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Abstract

Networks with transshipments facilitate the efficient transportation of freight. The realization of high fill rates is essential to remain competitive as a carrier. We concentrate on operational order consolidation in networks with transshipments, such as intermodal networks. We introduce a k-shortest path matching algorithm to consolidate less-than-truckload orders in a dynamic setting. Based on an enumerative leg-expansion procedure, multiple high-quality routes are generated and stored for each order. For each incoming order, we aim to combine one of the k best routes for the order at hand with open orders that have been scheduled, but not yet delivered. We identify overlap in the utilized legs, thereby taking into account idle capacity, time restrictions, handling operations and characteristics of the various transport means. Based on these properties, we determine the combination of orders that yields the highest cost reduction. It is expected that good routes yield the best consolidation opportunities. We therefore only assess k routes per order for consolidation opportunities, as such limiting the size of the search space. The algorithm takes into account the time schedules and available capacity on all legs in the routes. Experiments on various virtual problem instances show cost savings up to 14%. Experiments using a data set of a leading logistics service provider based in the Netherlands show a 29% improvement in the average fill rate compared to the case where only the best routes are considered for consolidation purposes, achieving a cost reduction of 9% for the orders that were consolidated.

1 Introduction

Freight transportation via networks with transshipments is becoming an increasingly important alternative to direct transportation. Developments in real-time information provisioning, planning systems, governmental regulation, and more consideration to external costs, make transportation via networks with transshipments both increasingly relevant and competitive. In this paper, we consider the case in which the logistics coordination in an intermodal setting is in the hands of a Logistic Service Provider (LSP). This is a central agent that does not necessarily own transport resources, but instead matches incoming orders to contracted transporters, i.e., carriers. An order is defined as a request by a shipper to transport a certain load from a specified pickup location to a specified delivery location. Time windows specify at what times

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the order can be picked up and must be delivered. In an intermodal setting, multiple routes between the pickup location and the delivery location can be constructed by combining various route segments (legs), each operated by a separate vehicle. We distinguish between two sorts of legs. Main legs are fixed connections between two hubs, and are operated by one modality type. The modalities may operate following a timetable. Free legs are connections between any two points in the network, and are operated by trucks that can be commissioned at any desired time. Vehicles on free legs generally have high flexibility, short travel distance, and small capacity when compared to trains and barges. Therefore, vehicles operating on the free legs generally charge higher transportation costs per kilometer than their counterparts operating on main legs.

The multitude of potential leg combinations in even moderate-sized networks allows the generation of many distinct routes. Both financial and non-financial goals (e.g., minimizing emission and duration) can play a role in selecting the most suitable route. Transshipments between vehicles take place at transfer hubs. Also, the reallocation of goods – i.e., splitting or merging loads – can be performed at these hubs. In a typical intermodal setting, a load is picked up by a truck at the customer, transshipped at a transfer hub, then transported via one or more legs – which can be operated by any type of transport means – and finally distributed by truck from the final transfer hub towards its destination location.

For the LSP, the financial attractiveness of intermodal transport depends on a high fill rate of the utilized transport means (e.g., truck, train, barge), provided that the decrease in marginal costs is sufficiently reflected in the price charged by the carrier. Direct road transport from pickup to delivery location generally results in a shorter travel distance than intermodal transport does. However, due to the opportunity to bundle orders at the transfer hub, the transport means operating on the main legs may be able to utilize their capacity more efficiently. Transfers taking place at the hubs require transshipment costs and possibly storage costs. To be financially competitive to direct road transport, these costs should at least be compensated in terms of lower transportation costs (Trip and Bontekoning, 2002). Furthermore, high penalties for lateness can be detrimental to the financial competitiveness of intermodal transport. Besides financial costs, an LSP may also explicitly consider external costs. Such external costs could for example be incorporated in a multi-criteria analysis on which routing decisions are based, or by quantifying external costs in monetary units. Such an analysis is outside our scope, but is likely to be more favorable towards intermodal transport than a purely financial approach. In this study, we solely assess the potential cost reduction for the LSP by means of consolidation.

Although the concept of freight consolidation is strongly embedded in the classic vehicle routing problem, attention for consolidation in networks with transshipments remains limited. In this paper, we aim to contribute to this knowledge domain, more specifically the operational planning of consolidated routes in a dynamic environment. We present a scheduling algorithm that is able to efficiently identify and plan consolidated routes for networks with transshipments. We adopt a financial perspective for the evaluation of the algorithm, focusing on the reduction of total transportation costs. The key tradeoff we consider is between the reduction in transportation costs and joint transshipment operations on the one hand, and increasing costs due to detours and additional handling on the other hand. We illustrate our approach using a case study at a leading LSP based in the Netherlands, that is active in the European transportation market.

The remainder of the paper is structured as follows. We provide a literature review in Section 2, assessing studies on several topics that are relevant to our work. In Section 3, we outline our problem setting and the corresponding approach, followed by a description of the consolidation algorithm in Section 4. We conduct experiments on several networks, measuring the performance of our algorithm under a variety of circumstances (Section 5). We finish with conclusions in Section 6.

2 Literature review

In this study, we assess the consolidation of goods in an intermodal transportation setting. Intermodal transportation is formally defined as the transportation of goods via at least two legs that are operated by distinct transport means, with transshipments taking place at transfer hubs (Dewitt and Clinger, 2000; Crainic et al., 2006). Examples of such hubs are rail yards, harbors, inland terminals, and airports (Bektas and Crainic, 2007). Commonly, the scope in intermodal transportation literature is limited to container transport. Due to their ease of handling and seamless fit with various types of transport means, containers are particularly suitable for intermodal transport. However, the concept is widely applied to other forms of transportation as well (Crainic et al., 2006). In Less-than-Truckload (LTL) transport, intermodal principles are fully incorporated. The use of different transport means for pickup, line-hauling, and delivery is common in this field (Powell, 2003), although distinct types of transport means are not necessarily involved. Another example of multimodality is found in urban logistics, where hubs embedded in one-tier or two-tier networks are used to transfer goods to city freighters. Despite the increasing number of applications of networks with transshipments, Veenstra and Zuidwijk (2010) point out that serious knowledge deficits exist in the research fields of multi-modality, network design and operational planning.

The key benefit of intermodal transport is that it facilitates the convergence of many low-volume, low-frequency transport flows into a small amount of high-volume, high-frequency streams. Generally, these high-volume streams take place over a longer distance; this practice is also known as line-hauling (Janic, 2007). In its basic form, the transformation of transport streams is achieved by collecting the goods at a transfer hub (bundling), transporting the combined goods by utilizing the same transport means, and distributing the goods via another hub (unbundling). The collection of goods before the first hub and the distribution from the last hub are also known as drayage or first/last-mile logistics, and often take place with smaller vehicles (Macharis and Bontekoning, 2004). In our research, we consider line-hauling to take place on the main legs, while free legs account primarily for transport over shorter distances. Due to the practice of bundling and unbundling, intermodal transport allows for a high service frequency and better utilization of transport capacity, the latter resulting in lower marginal costs. The drawback is that the travel distance is increased and more transshipments are required. To be a viable alternative for direct road transport, the higher transshipment costs and possible storage costs of intermodal transport should at least be less than the reduction of transportation costs

(Konings, 1996; Trip and Bontekoning, 2002).

In the context of this paper, a transportation unit is the resource used by a single truck to contain goods, e.g., a container or trailer. For illustrational purposes, henceforth we will always refer to a transportation unit as a container. Based on the observations of Crainic et al. (2006), we distinguish between two container operations at the transfer hub. A transshipment entails moving a container from one transport means to another, and handling considers moving goods from one container to another. The latter allows combining different orders for part of a route, such that goods can be consolidated even when they have geographically distant origins and/or destinations. A common feature in intermodal transportation is the use of fixed timetables, particularly in railroad- and waterway transportation (Macharis and Bontekoning, 2004). To incorporate departure times based on timetables in an operational planning problem, two main approaches exist. The first is to create a time-expanded graph, where each arc is characterized by a time component (Ford Jr and Fulkerson, 1958; Köhler et al., 2002). A distinct leg is generated for each departure time in the timetable, allowing to include specific properties such as the realized fill rate on the vehicle. The major drawback of a time-expanded graph is that it can become very large, although this disadvantage is partially mitigated by the need to consider the graph only over a limited time interval. Furthermore, potentially many geographically identical routes are generated, differing only in their departure times. The alternative approach is to consider a time-dependent graph (Ding et al., 2008; Delling and Wagner, 2009). The graph itself is then defined only in space; time-dependent leg characteristics are taken into account by applying a function with the departure time as input. In this paper, we restrict ourselves to the case where the only time-dependent characteristic is the departure time itself, i.e., properties such as travel times and cost functions remain unaltered. Although the time-dependent graph provides a denser representation than the time-expanded graph, it may be more difficult to incorporate the same level of detail.

Macharis and Bontekoning (2004), Caris et al. (2008), and SteadieSeifi et al. (2014) provide overviews of the research done on intermodal transport, all indicating that only few studies have been performed on operational planning. We mention some notable ones. Boardman et al. (1997) make use of a k-shortest path algorithm to perform intermodal planning, evaluating multiple routes before selecting the route that best fits the established criteria. By coupling a vector of path length estimates to each vertex and using these estimates as a criterion whether or not to evaluate a route, the authors keep computational time limited. Ziliaskopoulos and Wardell (2000) explicitly take into account timetables and transfer times in their planning algorithm, making use of Bellmans optimality principle while working backwards from the destination vertex to the origin vertex. While these works focus on the transportation of single orders only, elements of their approaches are applied in this study.

Additional insights can be obtained from the conceptually closely-related fields of dial-a-ride and ride-sharing problems. In these fields, the combination of picking up and dropping off persons with the fixed schedules of public transport is assessed, as well as transfers between different transport means. The subclass with fixed timetables is generally referred to as the integrated version of the problem. Horn (2004) provides a leg-expansion approach for this integrated problem. He starts by generating routes consisting of only a single leg, and gradually increases the number of legs in a route while simultaneously establishing upper bounds. He states that this procedure generally leads to an optimal schedule quickly, because good routes tend to contain only few legs. An intuitive explanation for this is that each transshipment increases handling costs, while it is likely that the travel distance and travel time increase as well. This result could be formalized by, e.g., applying a branch-and-bound algorithm; for a certain amount of handling costs it becomes impossible to financially compete with direct transportation, regardless of the reduction in transport costs that may be achieved. Horn (2004) compares the costs of the best constructed multi-leg route to the costs of the direct route from origin to destination; from these two the least expensive route is selected.

Whereas the literature described so far focuses on optimizing the transportation of a single order (or person) through an intermodal network, we are interested in minimizing the total transportation costs of all orders combined from the viewpoint of the LSP. As we are dealing with LTL orders, these objectives are not equivalent. Routing decisions made at a certain point in time have an impact on the profitability of later orders (Powell, 1987). Factors such as container capacity and departure times that are fixed in current routing decisions may impede consolidation opportunities for orders arriving at a later time, such that the sum of costs for all optimal routes for single orders is unlikely to be the lowest attainable global solution. In Figure 1, we illustrate how routing decisions affect consolidation opportunities. Although in the bottom panel a detour is made for both order 1 and order 2, the total travel distance is reduced by consolidating on the first main leg. Would we have fixed the shorter route for order 1 in advance (upper panel), finding an improving consolidation opportunity when order 2 arrived later would have been unlikely. According to Kotzab et al. (2012), LSPs tend towards self-interest when having conflicting interests with their shippers. Following the associated line of reasoning, they may decide to compromise the quality of individual routes to the benefit of the full schedule. However, the goals of shippers and the LSP will often be mutual; the reduction of transportation and handling costs can be beneficial to both parties. The shipping fees charged by the LSP are outside the scope of this research.

Crainic et al. (2006) define consolidation in an intermodal setting as a system where one vehicle or convoy serves to move freight for different customers with possibly different initial origins and final destinations. Bontekoning and Kreutzberger (1999) identify several forms of consolidation networks, differing primarily on the points of bundling and unbundling and the number of tiers. Consolidation in first and last mile logistics is well-studied, as it is the basis of many less-than-truckload (LTL) vehicle routing problems. In particular, the pickup-and-delivery problem (see Savelsbergh and Sol, 1995) is relevant in this setting. Objectives such as minimizing the total costs or the number of vehicles tend to result in schedules with high utilization of vehicle capacity. Consolidation on liner services (i.e., the main legs) on the other hand, is a subject that has not received much attention from the academic community. Partially, this deficit may be attributed to the common focus on container transport, which often entails full truckloads without reallocations or order combinations at intermediate hubs. Also, research on intermodal transport in general tends to focus on strategic and tactical problems rather than operational planning. To the best of our knowledge, generally accepted models for LTL transport in networks with transshipments do currently not exist.

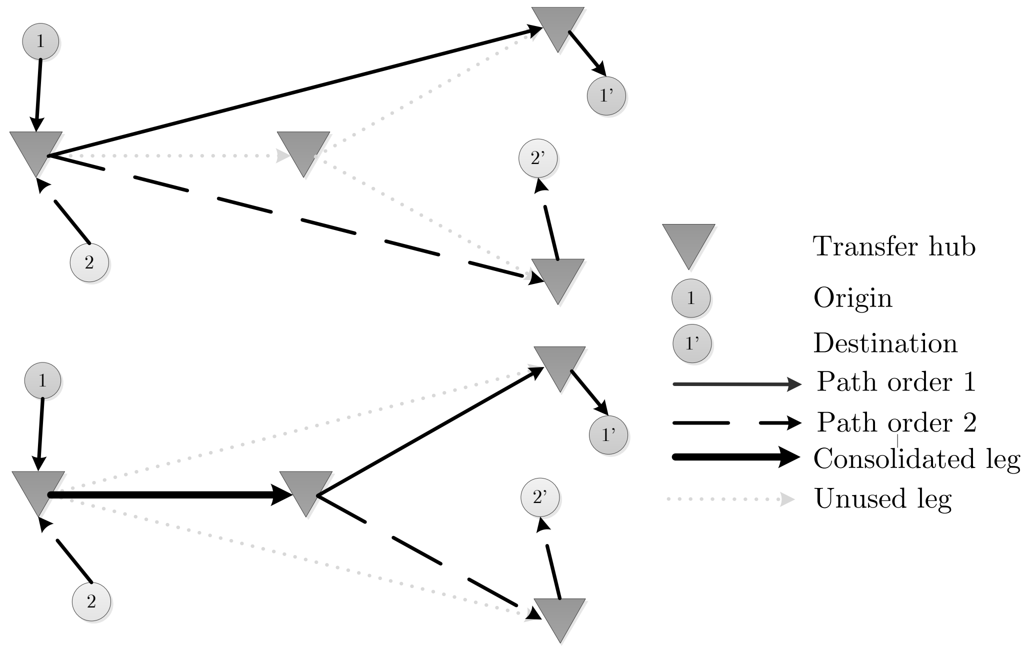

Figure 1: Example of the consolidation of two orders. The top panel illustrates the individually least expensive routes for both orders. The bottom panel shows how consolidation reduces the total travel distance, but introduces additional handling operations as well.

Crucial to the attractiveness of consolidation on the main legs is the cost of transportation. We discuss the topic from the carrier point of view, allowing to distinguish between costs and prices at the carrier level. Note that the price function used by the carrier is the cost function for the LSP. Powell (2003) distinguishes between three forms of pricing performed by carriers: static pricing, contract pricing and spot pricing. Static prices are standard market rates set for transporting freight on a given lane; these prices are not affected by the state of the system. Contract prices are prefixed price agreements between shippers and carriers based on the expected volume to be transported over a given period of time. Finally, spot prices are determined for a specific order at a specific time, based on the prevailing state of the system. According to Caplice (2007), the vast majority of carriers set prices based on static pricing principles, utilizing a fixed price function per shipment or per lane. For LTL transport, it is common to let prices in some way depend on the fill of the container. However, Neumann (2007) states that loads in LTL transport are heterogeneous; loads can be pallets, boxes, unpacked items, etc. Consequently, it is difficult to apply a uniform measure on the size of LTL loads, such as weight, volume, or loading meters.

Berwick and Dooley (1997) and Krajewska and Kopfer (2006) mention economies of utilization (i.e., lower costs due to higher utilization of assets) as an opportunity for carriers to reduce transportation costs. This is because fixed asset costs can then be allocated across more units of output. If this decreasing cost function for the carrier is properly reflected in the prices they charge, the LSP would be able to benefit from higher utilization as well. However, prices agreed upon between shippers and carriers do not necessarily reflect the actual costs that are made to provide the service. Precise cost allocation may be difficult, as operational transportation costs depend on many factors (Yan et al., 1995). A cost function may, amongst others, depend on average fill rate, haul length, shipment size, percentage of LTL traffic, and composition of output (Spady and Friedlaender, 1978). Such factors might only partially be reflected in the prices charged by the carrier. In container transport, for example, it is common to charge a flat rate per container rented, regardless of its fill rate. Clearly, such price functions give the LSP a strong incentive to attain a high fill rate. On the other end of the spectrum, the rates charged by parcel services usually are insensitive to volume (Klausner and Hendrickson, 2000). The associated price function, which is linear in the number of packages, would make an LSP almost indifferent about consolidating. In LTL, linear price functions starting with a certain minimum tariff and setting a maximum fill rate (e.g., 80%) after which a container is considered to be full, are more common. A price function used primarily in theory is the logarithmic price function, reflecting monotonically decreasing marginal costs. As each carrier may adopt a unique price function, it is possible that an LSP faces multiple price functions on a single route. Clearly, the larger the cost reduction when combining loads into the same container, the more beneficial it becomes for the LSP to actively consider consolidation opportunities.

In this study, we expand on the intermodal planning literature in two ways. First, we present an algorithm to schedule the transport of LTL freight via intermodal networks, thereby contributing to the limited amount of studies focusing on operational planning. Second – by combining the k-shortest path principle with a leg-expansion approach – we present an efficient method to identify consolidation opportunities in a limited state space.

3 Problem demarcation and solution approach

The problem that we are concerned with is a dynamic planning problem. In this context, *dynamic planning* means that an order is planned immediately upon becoming known. On the other hand, *static planning* entails waiting for a certain time period before jointly planning the orders that arrived during the passed time period. Our choice to consider dynamic planning instead of static optimization (over a rolling horizon) is motivated by experience. Typically, the time between pickup and delivery in an intermodal setting spans several days. When modalities with low travel speed or low departure frequencies are considered, a delay of the actual planning moment might exclude routes of longer duration. This eliminates certain opportunities for consolidation. Furthermore, planners at an LSP generally want to be able to directly quote the expected pickup and delivery times to a shipper. For these reasons, we plan orders immediately when the shipper poses a request. An order can be replanned when consolidation opportunities arise, which typically happens when new orders arrive.

We make a number of key assumptions. First, we only address consolidation opportunities on the main legs. Nonetheless, VRP models could be well integrated into our algorithm to allow for consolidation on the free legs. Particularly for first-mile and last-mile logistics, the added value of vehicle route planning can be readily appreciated. More generally, based on the slack in departure times on a free leg, a VRP could be run at any planned free leg to see whether consolidation is achievable within the time constraints. The consequence of running VRPs in parallel with the planning for liner services is that waiting policies become more complex, as this requires making a tradeoff between (1) consolidation on the long haul and (2) collection and distribution. This aspect is beyond our current research scope, as it diverts attention from the consolidation process on the main legs. Our second key assumption is that all travel times and transshipment times are deterministic. This assumption effectively eliminates the need to consider timeliness of delivery and advanced waiting policies. In addition, we assume that transshipments with handling and without handling take the same amount of time. A final simplifying assumption is that handling costs are independent of the size of the set of orders that is moved from one container to the other, such that it is irrelevant which orders are reallocated.

Our proposed solution to the described planning problem is to keep multiple routing opportunities open until the time of departure, or until a consolidated solution has been scheduled. For all these routes, a feasible departure window is attached to each transfer hub, allowing to identify orders that may depart on the same time. The marginal cost savings achieved on the joint legs could then justify replacing the best individual solutions by a route set yielding lower overall costs. The route set contains one route per order; every order (if more than one) shares at least one container on one leg with another order for which a corresponding route is in the route set. The implication of such a set is that consolidating on one leg potentially affects all routes in the set, we discuss the route set in more detail in Section 4.3. Once the final decision to combine routes has been made, the determined routes can no longer be altered. Further expansion of the combined route set remains an option, as well as adjustments to the departure windows for the sake of consolidation. However, it is not possible to undo a consolidated schedule in terms of routing. Decomposition of routes might require re-optimizing the schedule of other orders in the set, which would essentially involve generating a new static schedule at each order arrival. In a dynamic planning environment, such a procedure would be too computationally intensive.

To incorporate timetables in our model, we make use of a time-dependent graph, considering the case in which the departure time is the only varying component (e.g., travel times and costs remain constant). Time-expanded graphs may require a large value for k in order to maintain sufficient diversity in the routes, although the unique legs would allow for quicker evaluation. In a time-expanded graph, consolidation opportunities could already be assessed during route generation, i.e., the costs on a leg may be conditioned to its current fill rate. However, the time-dependent graph allows for a more generic approach towards our planning problem. Particularly when departures are frequent, the time-dependent graph provides a more compact representation than the time-expanded graph. The main reason for choosing time-depending graphs is that the departure windows allow for flexibility in the departure time even after consolidating. To realize this, we apply a mapping function which generates a set of feasible departure times based on the corresponding timetable, if such a table exists. The mapping function only needs to be applied when mutual legs with overlapping departure windows are identified. Such an evaluation is somewhat more complex than for a time-expanded graph, but allows a more efficient search.

Having set the scope of our research and motivated our solution approach in this section, we proceed to outline our algorithm in the Section 4.

4 Consolidation model

In this section, we describe our consolidation algorithm. In Section 4.1, we provide an introduction to the network setting, the planning problem, and a global concept of our solution approach. Subsequently, we outline the three key steps of our algorithm: planning k individual routes for an incoming order (Section 4.2), constructing a decision tree with all the consolidation possibilities per leg (Section 4.3), and verifying the feasibility of solutions (Section 4.4).

4.1 Network and planning problem

Our representation of the intermodal network is as follows. Let $\mathcal{G} = \{\mathcal{V}, \mathcal{A}\}$ be a directed graph with $\mathcal{V}$ the set of vertices and $\mathcal{A}$ the set of arcs, henceforth called legs. The subset $\mathcal{H} \subset V$ represents the transfer hubs in the network. The remaining vertices signify the subset of order origins, $\mathcal{O} \subset V \setminus \mathcal{H}$, and the subset of order destinations, $\mathcal{D} \subset \mathcal{V} \setminus \mathcal{H}$. The set of legs can be divided into a subset of free legs and a subset of main legs. The free legs connect every vertex pair in the graph, and are operated by vehicles without time schedules. Free legs can therefore be used to link origins and destinations either to each other or to transfer hubs, but can also facilitate transport between hubs. The counterparts of the free legs are the main legs. These main legs are predetermined connections between vertices of the subset $\mathcal{H}$, operated by specific transport means and possibly operating on a timetable. There can be multiple legs between the same hub pair, for example representing various modalities or carriers.

Each leg $l \in \mathcal{A}$ in the network is described by the tuple (v_l, v'_l, m_l, μ_l), where $v_l \in \mathcal{V}$ is the starting vertex of the leg, $v'_l \in \mathcal{V}$ is the end vertex of the leg, m_l represents the mode that is utilized, and μ_l is the deterministic travel time (based on the transport means operating the leg). Denoting the set of modes operating in the network as $\mathcal{M}$, the mode $m_l \in \mathcal{M}$ is in turn a doublet $(c_{m_l}, p_{m_l}(f))$. Here, $c_{m_l} \in \mathbb{N}$ is the capacity of the vehicle expressed in FTLs (in this paper, an FTL equals the capacity of a container). $p_{m_l}(f)$ is a function providing the transportation costs per km, depending on the fill rate of the container $0 < f \leq 1$.

Let $i, j \in \mathbb{N}, i \neq j$ be order indicators, with order i representing an order that just became known, and order j an open order (i.e., an order that has not yet arrived at its destination). Let $\mathcal{I}$ be the set of all open orders, excluding order i. Each order i can be described by a tuple $(v_i^{ori}, v_i^{des}, t_i^{arr}, t_i^{min}, t_i^{max}, f_i)$. Here, $v_i^{ori} \in \mathcal{O}$ is the origin vertex and $v_i^{des} \in \mathcal{D}$ the destination vertex. Order i becomes known at the arrival time t_i^{arr} (i.e., the LSP receives the request from the shipper), and is tentatively scheduled at that point. The order has an earliest pickup time t_i^{min}; from this time onwards the order can be retrieved from the origin v_i^{ori}. Furthermore, it has a strict deadline t_i^{max}; the order must arrive at its destination v_i^{des} at or before this time. The time parameters are subject to $t_i^{arr} \leq t_i^{min} < t_i^{max}$. Finally, the order has a size f_i expressed in terms relative to the container capacity required, i.e., $0 < f_i \leq 1$. A vehicle may have a capacity $c_{m_l} > 1$, i.e., the vehicle may be able to carry more than one shipping container.

We now briefly explain the general idea behind our matching algorithm. The algorithm is triggered by every new order arrival. First, a large preset number of unconsolidated routes is generated for the order i, of which the k best are stored. For each hub in these routes, a departure window is given, indicating all feasible departure times. Subsequently, for each of the

k routes, we construct a decision tree that combines all possible consolidation opportunities on the various main legs. This tree allows to evaluate the effect of all consolidation decisions in conjunction. From the routes corresponding to open orders, we select all matching main legs, i.e., having mutually feasible departure times and sufficient capacity in the container. Each distinct consolidation opportunity is represented by a node in the decision tree, while each path represents a unique combination of consolidation opportunities. The combination of routes yielding the largest savings is then updated in terms of departure windows and fill rates. If the solution being assessed contains more than one main leg, this procedure also verifies whether the solution is feasible. Feasible combinations of orders on different legs do not necessarily yield a feasible route, e.g., due to timing restrictions. This check is performed after constructing the decision tree, such that evaluation is only required until the best feasible solution is identified. A preliminary check would reduce the size of the decision tree, but requires more time to construct the tree, as every path needs to be verified before inclusion. When a solution is both improving and feasible, it is tentatively scheduled, with the best solution being fixed after solving the decision trees for all k routes. The main structure of the algorithm is described in the flowchart in Figure 2. Throughout this section, we make use of a running example to illustrate the working of the algorithm. The pseudocode for the consolidation algorithm can be found in Appendix A.

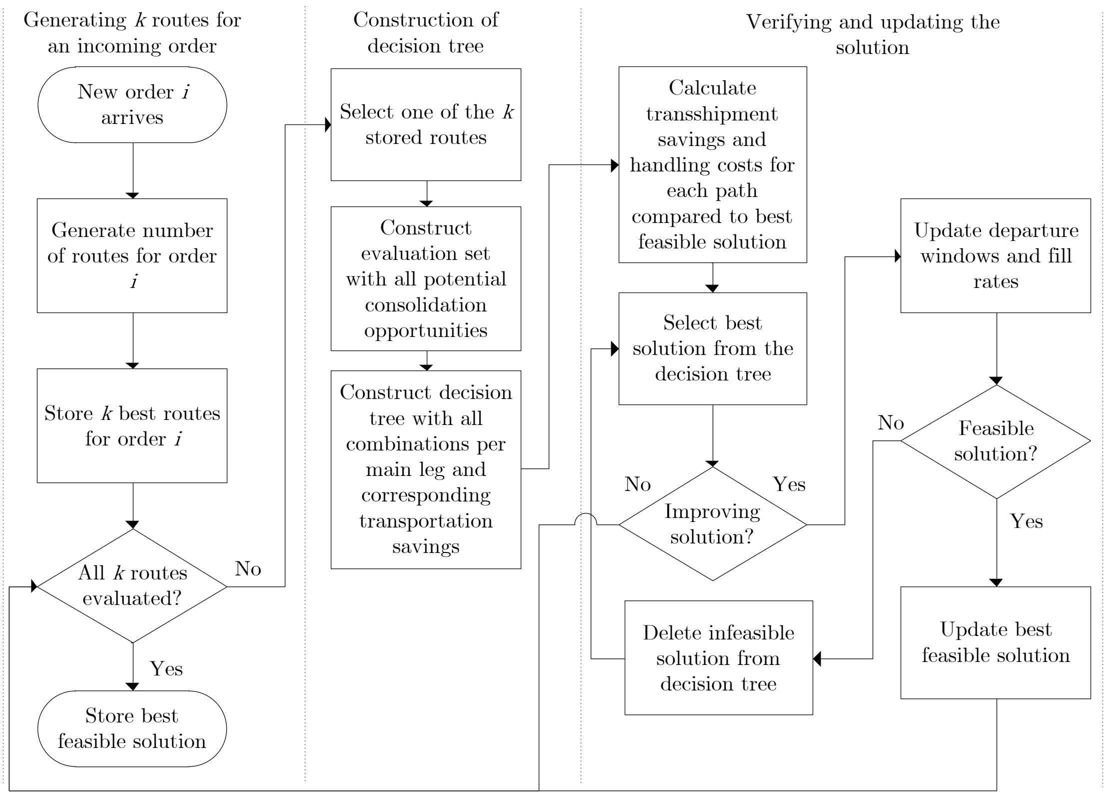

Figure 2: Flowchart with the main steps of the consolidation algorithm. The algorithmic procedure for each column is outlined in the subsequent sections.

4.2 Generating k routes for an incoming order

For each incoming order i, we start by generating routes using a procedure based on iteratively expanding the number of main legs in a route. We start by generating the direct route from the origin to its destination via a free leg, i.e., a route without main legs. We then proceed by constructing routes containing one main leg, two main legs, etc.[1] Only time-feasible routes are incorporated in the solution set. Furthermore, we exclude routes that are too costly. For this purpose, we set a dynamic threshold on the route costs based on the costs of the least expensive route obtained so far, multiplied by a factor $\beta > 1$. Routes that exceed the threshold – summing up the costs up to the last main leg of the route, considering both main legs and connecting free legs – are not included in the solution set and so are not expanded further. We continue enumerating routes up to a preset maximum ($\geq k$). Each route description contains the utilized legs ordered in terms of precedence, the earliest departure time and final possible departure time at each leg, and the utilized container capacity on the main legs. The first and final departure times together form the departure window for a given leg. Timetables may result in slack in the schedule, departure policies determine where this slack will be located. After generating the routes, the k least expensive routes – not taking into account any consolidation opportunities yet – are stored. The least expensive route is then tentatively incorporated in the schedule.

We introduce some mathematical notation to formally describe the properties of a route. Let R_i denote the set of all k stored routes for order i. A route $r_{i,n} \in R_i$, with $n \in \{1, \ldots, k\}$, is defined as an ordered set of legs (both main legs and free legs) connecting v_i^{ori} to v_i^{des}. We define an indicator $z \in \{1, 2, \ldots, |r_{i,n}|\}$, allowing the precedence of the legs in the routes to be specified. We refer to the z^{th} leg incorporated in $r_{i,n}$ as $l_{i,n,z} \in r_{i,n}$. Each leg in the route is characterized by its departure window; departing at any point in time within this window ensures that the destination is reached before the delivery deadline, given the remaining legs in the route. Each leg in the route is characterized by an earliest and latest departure time, possibly depending on a timetable. To provide the transshipment times between adjacent legs $l_{i,n,z-1}$ and $l_{i,n,z}$, we define a function $\delta(l_{i,n,z-1}, l_{i,n,z})$. Recall that handling has no influence on transshipment time here. We observe that the information about the origin hub, destination hub and modalities incorporated in the leg description allows the calculation of unique transshipment times. A container description q_l – defined by the doublet (Ω_{q_l}, f_{q_l}) – is used to distinguish between containers transported via a given main leg l. Ω_{q_l} is the set of orders currently assigned to the container and f_{q_l} the currently attained fill rate. The doublet changes after every consolidation action. For a given modality, there may be multiple vehicles leaving within the departure window. We allow orders to be placed on any of these vehicles, and change vehicle if a consolidation opportunity requires this. Therefore, orders are assigned to a specific container on the main leg rather than to a specific vehicle. Finally, the earliest departure time $t_{l_{i,n,z}}^{ed}$ at each leg $l_{i,n,z}$ is given by the earliest departure time at the preceding leg plus the subsequent travel time and transshipment time. At the start of the first leg – which in our setting is

[1]This phase can be completed more efficiently by first pre-processing the network. Based on the geographical distances between hubs, origin and destination, distant hubs can be removed, leaving a reduced network to run the planning algorithm on.

always a free leg, because $\mathcal{O} \cap \mathcal{H} = \emptyset$ – the earliest departure time is set to be equal to the pickup time, i.e., $t_{l_{i,n,1}} = t_i^{min}$. We then proceed to iteratively calculate the earliest departure times for each leg, where the departure time from the timetable serves as input for the calculation of the first feasible departure time of the subsequent leg. Similarly, the latest departure time $t^{ld}_{l_{i,n,z}}$ is determined by working backwards from t_i^{max}.

The departure window at each leg is given by $[t^{ed}_{l_{i,n,z}}, t^{ld}_{l_{i,n,z}}]$. Leaving at any departure time falling within this window ensures that the route is time-feasible. If no timetable exists for the leg (e.g., a free leg), every departure time within the window is feasible. If multiple departure times are feasible for the same route, we set a tentative departure time based on a tie-breaking policy (e.g., an earliest or latest departure policy). As we remember the departure window, the actual time of departure can still be changed when deciding to consolidate prior to departure at the leg. Observe that the chosen departure policy impacts the consolidation opportunities on the route when we seek to consolidate while the route is being executed. For example, a latest departure policy increases the opportunities for consolidation on the selected leg, but limits consolidation opportunities for any subsequent legs.

Example 1: Route structure for incoming orders

Consider the network and order-destination pair as described in Figure 3, where order 1 has a load size of 0.3. Suppose $k = 4$. We denote each route as an ordered set of legs; every free leg is referred to as 0. In this example, the route 0-1-0 is the least expensive option, such that this route is set as the initial solution. Being the second route in the list (see Table 4.1), we refer to this route as $r_{1,2}$.

Order	1
Fill quantity	0.3
Route(s)	0
	0-1-0
	0-1-2-0
	0-1-3-0

Table 4.1: Characteristics and k routes for order 1.

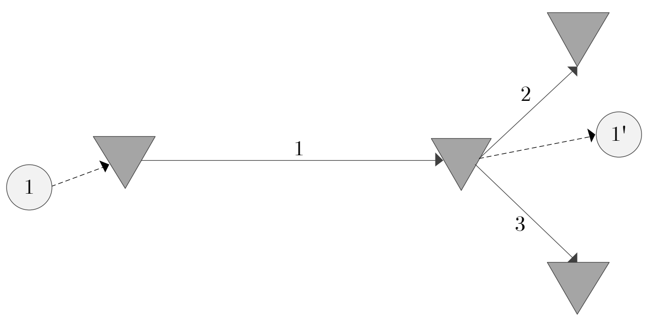

Figure 3: Initial solution for order 1, utilizing only main leg 1.

Order 1 has an earliest pickup time of 11.40 and a latest delivery time of 20.00 on the same day. Assume that vehicles traverse main leg 1 with an hourly departure, that traversing this leg takes two hours, and that the transshipment time is always half an hour. In Figure 4, the corresponding time schedule for the route is provided, given a latest departure policy. In this figure, window 1 indicates the time interval in which departure on main leg 1 yields a feasible schedule.

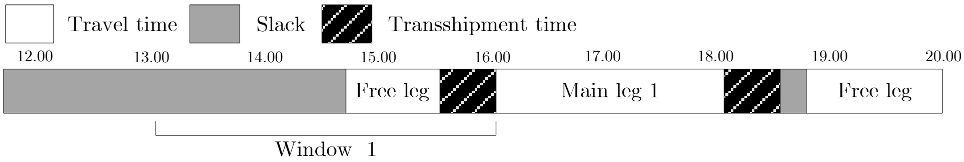

Figure 4: Gantt chart for route $r_{1,2}$ *under a latest departure policy, indicating the departure window for main leg 1.*

4.3 Construction of decision tree

After generating and storing k routes for the new order i, we seek to improve our initial solution by means of consolidation. For each of the k stored routes and for every main leg in each route, we check whether it is possible to combine order i with another order j. Order j may already have been consolidated with other orders; in this case the route characteristics of order j (e.g., fill rate, departure windows) have already been updated. For all open orders – i.e., orders that have not reached their destination yet – we check for consolidation opportunities for stored routes having at least one main leg in common. It is feasible to consolidate on a main leg if (1) the main leg is included in both routes, (2) a mutually feasible departure time exists for this leg, and (3) sufficient idle capacity is available to combine the loads on the operating transport means in a specified container. Closer assessment is required to see whether consolidation would be beneficial in terms of reducing the total costs, as this can only be determined with certainty in conjunction with the consolidation decisions on the other main legs in the route. We refer to the set containing all routes of open orders that allow for consolidation as the *evaluation set*. All k routes have a distinct evaluation set.

In case of multiple main legs contained in route $r_{i,n}$, it may be possible to consolidate with distinct orders on the various main legs. The decision whether to consolidate on a selected leg affects opportunities for consolidation on other legs in the route of order i; narrowing down the departure window for one leg might render consolidation opportunities on other legs infeasible. Particularly when combining multiple orders with distinct routes, it is challenging to oversee the impact of one particular consolidation action on the quality of the overall solution. Our proposed solution to this problem is to construct a decision tree for each of the k routes of order i, where each stage in the tree assesses all feasible order-container combinations for one main leg in a stored route for order i. At each branch, the consolidation on the selected main leg with a particular order (set) and the impact on the corresponding routes is evaluated. At each end node of the decision tree, where the end node represents a combination of orders and containers over all main legs in route $r_{i,n}$, the total costs of the corresponding route set can be calculated. We note that the number of paths in such a tree may increase exponentially with the number of main legs in the route. In a practical setting, however, routes containing more than two main legs are rare, keeping the decision tree at a well-manageable size.

As we solve the decision tree for all $r_{i,n} \in R_i$, we must construct an evaluation set $\mathcal{T}$ for every given route $r_{i,n}$. This set $\mathcal{T}$ contains all route sets corresponding to open orders $j \in \mathcal{I}$ containing routes that have at least one main leg in common with $r_{i,n}$, and consolidation is feasible on this leg. As multiple containers may be transported over the same leg of the same route set – thereby representing distinct consolidation opportunities – the container description q_l is also required for evaluation. Hence, each element in the evaluation set consists of both a route set and a corresponding container description. In addition to the option to combine orders in a container, 'not consolidating' is a feasible choice for every leg (both main and free) as well, such that we have at least one decision for every leg in $r_{i,n}$. Let $\mathcal{T}_{l_{i,n,z}} \subseteq \mathcal{T}$ denote the subset of routes that contain a leg equal to $l_{i,n,z}$ (i.e., the same main leg), and where the departure windows and container capacity allow for consolidation with order i on leg $l_{i,n,z}$. Furthermore, let $m \in \{1, \ldots, k\}$. If an open order j has already been consolidated, then adjusting the departure window and fill rate for the selected leg in route $r_{j,m}$ also has an effect on the routes that are interrelated with $r_{j,m}$. In this context, *interrelated* is a broader definition than *consolidated*; an interrelated route may have no main legs in common with $r_{j,m}$, but still be affected by the changes made in r_j. To illustrate this, consider a route $r_{1,1}$ containing main leg 1, $r_{2,1}$ containing both main legs 1 and 2, and $r_{3,1}$ containing main leg 2. Suppose that orders 2 and 3 are already consolidated on leg 2. If orders 1 and 2 are consolidated on leg 1, updating the departure window on leg 1 may have an impact on the departure window at leg 2 as well, thereby indirectly affecting the schedule for order 3. To describe the set that contains route $r_{j,m}$ and all routes interrelated with this route (if any), we use the symbol $\mathcal{R}_{j,m}$. Hence, we have $r_{j,m} \in \mathcal{R}_{j,m}$, with $\mathcal{R}_{j,m} = \{r_{j,m}\}$ when order j has not been consolidated yet. Observe that if $|\mathcal{R}_{j,m}| > 1$ (i.e., order j has been consolidated with at least one order), then $k = 1$ for all orders having a route contained in $\mathcal{R}_{j,m}$. An element $(\mathcal{R}_{j,m}, q_l)$ is included in evaluation set $\mathcal{T}_{l_{i,n,z}}$ if the following four conditions are met for a main leg $l_{i,n,z} \in r_{i,n}$:

1. The main leg $l_{i,n,z}$ is also included in at least one route $r_{j,m} \in \mathcal{R}_{j,m}$.
2. At least one mutually feasible departure time exists for both orders on $l_{i,n,z}$.
3. There is sufficient spare capacity to add order i to container q_l (with $j \in \Omega_{q_l}$) on the main leg.
4. The element $(\mathcal{R}_{j,m}, q_l)$ is not yet included in the evaluation set. This condition implies that a route set can be included more than once in the evaluation set. For example, multiple containers may be transported on the same train, representing distinct consolidation opportunities on the same leg.

When we identify a route $r_{j,m}$ for which consolidation is feasible on the selected leg, it is ensured that consolidating orders i and j on the selected leg and container is also feasible due to the departure window constraints. After completing the evaluation set per main leg, we combine the evaluation sets per main leg in all possible ways in the decision tree. Every stage in the tree represents a main leg in $r_{i,n}$, every branch in the stage represents a unique consolidation opportunity $(\mathcal{R}_{j,m}, q_l) \in \mathcal{T}_{l_{i,n,z}}$. Every consolidation opportunity in a stage can be combined with all consolidation opportunities of other stages; a path in the tree describes a unique solution. The decision tree contains $\prod_{z=1}^{|r_{i,n}|} |\mathcal{T}_{l_{i,n,z}}|$ paths. Even though all individual consolidation opportunities in the tree are feasible (i.e., each branch), after updating the departure windows the combination of multiple consolidation opportunities (i.e., consolidation on multiple legs) is not necessarily feasible. However, as the savings for each path are already known, we only need to check the feasibility of solutions until we encounter the best improving solution that is feasible. Non-improving solutions are never selected, and therefore need not to be evaluated.

From the evaluation set, an upper bound to the achievable savings by consolidating on a specific route can be calculated. We can use this upper bound to reduce the size of the decision tree by excluding routes in the tree construction phase. Based on the evaluation set for a specific main leg, we may already be able to tell whether a specific order-container combination may or may not be able to yield a saving. Consider a route set $\mathcal{R}_{j,m}$ incorporated in the evaluation set, which contains a specific route $r_{j,m} \in R_j$ that allows for consolidation on leg $l_{i,n,z}$. To determine the upper bound, we first calculate the cost difference (without consolidation with order i) between executing route $r_{j,m}$ and the least expensive route $r^*_{j,m'} \in R_j$, with $m' \in \{1, \ldots, k\}$. We then compute the cumulative savings (based on the updated transportation costs and transshipment costs) if we were to consolidate with order i on *all* mutual main legs between $r_{i,n}$ and $r_{j,m}$ that allow for consolidation, which can be derived from the evaluation set $\mathcal{T}$. If the cost difference between $r_{j,m}$ and $r^*_{j,m'}$ exceeds the potential savings stemming from consolidation, then consolidating on any leg in $r_{j,m}$ is never an improving solution. Even if some decision tree path that includes legs from $r_{j,m}$ would yield a saving, we could always improve on this saving by *not* consolidating on these legs. Therefore, all main legs in $r_{j,m}$ can be discarded, and need not to be included in the decision tree. Unfortunately, this upper bound is rather weak for multi-leg routes, as it ignores the cost difference between $r_{i,n}$ and $r^*_{i,n'} \in R_i$, where $n' \in \{1, \ldots, k\}$ and $r^*_{i,n'}$ is the cheapest route in R_i. The reason that we cannot include the latter cost difference is that consolidation with different order sets may be possible, such that the cost difference cannot be fully allocated to a specific consolidation action.

Example 1 [Continued]: Construction of a decision tree

Cycling through all k routes for order 1, assume we now arrived at route $r_{1,3}$, with trajectory 0-1-2-0. Suppose three open orders (2,3 and 4) have main legs in common with this route, that are feasible in departure time and capacity, and therefore included in the evaluation set. Orders 2 and 3 were already consolidated in an earlier stage, hence only one route remains for both of these orders. Order 4 still has four available routes, Figure 5 shows the current schedule, Table 4.2 shows all available routes for the orders.

In Table 4.3, the timetable corresponding to the relevant main legs is presented, giving the departure times with the routes that are eligible for leaving at each departure time between parentheses. The transshipment times at the transfer hubs are 30 minutes, no extra time is assumed for handling.

When constructing the evaluation set, we see that consolidation at main leg 1 is feasible for

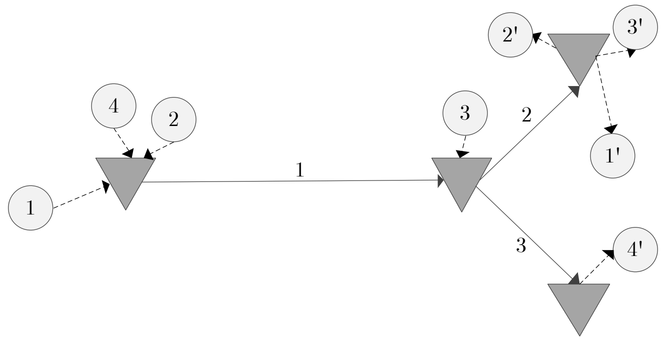

Figure 5: Current routes for orders 1, 2, 3, and 4.

Order	1	2	3	4
Fill quantity	0.3	0.4	0.3	0.5
Route(s)	$r_{1,1}$: 0	$r_{2,1}$: 0-1-2-0	$r_{3,1}$: 0-2-0	$r_{4,1}$: 0
	$r_{1,2}$: 0-1-0			$r_{4,2}$: 0-1-0
	$r_{1,3}$: **0-1-2-0**			$r_{4,3}$: 0-1-2-0
	$r_{1,4}$: 0-1-3-0			$r_{4,4}$: 0-1-3-0

Table 4.2: Order properties for orders 1, 2, 3, and 4.

three routes of order 4, corresponding to two nodes in the decision tree. On main leg 2, consolidation is possible with $r_{2,1}$, $r_{3,1}$, and $r_{4,3}$. Observe that since orders 2 and 3 utilize the same container on main leg 2, this consolidation opportunity needs to be assessed only once. Finally, on both legs we can also choose not to consolidate, leaving the original time window intact. With five options on main leg 1 and three on main leg 2 (including not consolidating), we have fifteen combinations to assess. However, not all of them are feasible. It is not possible to combine different routes for order 4 in the same schedule, while it is not possible either to consolidate both on main leg 1 with $r_{2,1}$ and on main leg 2 with $r_{4,3}$ due to time constraints. When updating the route combinations in the next step (Section 4.4), such infeasible combinations are identified and discarded. The decision tree in Figure 6 shows all combinations. By calculating the savings corresponding to each path, the decision maker can determine the consolidation opportunity with the largest feasible saving.

Main leg	Feasible departure time with corresponding route sets	Travel time
1	13.00 $\{r_{1,3}\}$, $\{r_{4,2}\}$, $\{r_{4,3}\}$, $\{r_{4,4}\}$	2 hours
	14.00 $\{r_{1,3}\}$, $\{r_{4,2}\}$, $\{r_{4,4}\}$	
	15.00 $\{r_{1,3}\}$, $\{r_{2,1}\}$, $\{r_{4,2}\}$, $\{r_{4,4}\}$	
2	15.30 $\{r_{1,3}\}$, $\{r_{4,3}\}$	1 hour
	16.30 $\{r_{1,3}\}$, $\{r_{2,1}, r_{3,1}\}$	
	17.30 $\{r_{1,3}\}$	

Table 4.3: Timetable on main legs 1 and 2, showing the feasible departure times for orders 1, 2, 3 and 4.

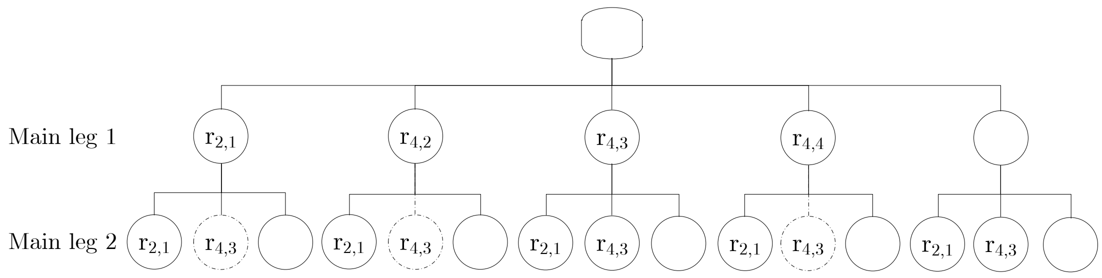

Figure 6: Decision tree containing all feasible combinations of consolidation opportunities for route $r_{1,3}$. The empty nodes represent the option not to consolidate. The dotted nodes represent infeasible solutions.

Our decision tree allows only for consolidation with one order (set) on each branch. Would we assess all combinations of orders at once, the tree could quickly grow unfeasibly large. However, after consolidating by selecting the best solution from the tree, it may be possible to further expand the updated route set by utilizing the remaining capacity of the container. Using the best solution acquired from the decision tree as input, with updated departure windows and fill rates, we may therefore construct an updated tree to check whether more orders could be added to the main legs. Note that if it was an improvement to consolidate open orders on a given leg, this would have been done in a previous point in time. Hence, only changes in the marginal cost structure can render previously non-improving solutions as improving solutions. The additional benefits of additional loops are therefore generally expected to be limited in comparison to the first loop. The algorithm terminates when it is unable to find a feasible improving solution in the decision tree, this procedure is described in Section 4.4.

4.4 Verifying and updating the solution

After completing the decision tree, we update the route sets corresponding to the path that yields the largest savings. If the solution proves to be feasible, it is stored as the new best solution. If not, the path is deleted and the next best solution is assessed; this procedure is repeated until the best feasible path in the tree has been identified. In this section we outline the updating procedure after a consolidation action; simply checking whether the latest departure time on a leg remains greater than (or equal to) the earliest departure time is sufficient to verify the feasibility of the solution.

For each branch in the path – where the branch represents a consolidation opportunity on a specific main leg found in both $r_{i,n}$ and $r_{j,m} \in \mathcal{R}_{j,m}$ on a certain container – the departure windows are updated. First, the departure windows at the selected leg needs to be updated, followed by those for all other legs in the routes incorporated in $\mathcal{R}_{j,m}$. This is required for the assessment at the subsequent legs in $r_{i,n}$; consolidation may no longer be possible after narrowing the departure window. Also when future orders arrive, it is important that each leg has the correct departure window to properly assess consolidation opportunities. Defining $z' \in \{1, 2, \ldots, |r_{j,m}|\}$ as the precedence indicator for $r_{j,m}$, synchronization of the departure windows at $l_{i,n,z}$ and $l_{j,m,z'}$ is done by selecting the maximum earliest departure time and minimum latest departure time of the two. After obtaining the adjusted departure windows for $l_{i,n,z}$ and $l_{j,m,z'}$, we update the departure windows of the remaining legs in both $r_{i,n}$ and $\mathcal{R}_{j,m}$. The departure windows of routes contained in $\mathcal{R}_{j,m}$ that do not contain $l_{j,m,z'}$ need to be recalculated as well. We do this by identifying common main legs, and use the departure window of the updated main leg as input to adjust the departure windows of any other main legs in the route.

For all stages in the decision tree after the first – representing the consolidation opportunities for a subsequent main leg in $r_{i,n}$ – the departure windows as identified in the evaluation set can no longer directly be applied. This is because consolidation on the first main leg potentially alters the subsequent departure windows, meaning that we must find mutual departure times within the updated departure window for $l_{i,n,z}$. If we seek to consolidate with an order in $\mathcal{R}_{j,m}$ again (i.e., on a different main leg from the same route set as a preceding branch), we must therefore use the updated departure times for $\mathcal{R}_{j,m}$ as well. Repeating the procedure of updating subsequent departure windows and identifying feasible mutual departure times, we advance to the end nodes of the decision tree. If no feasible departure time can be found for any of the legs, the solution is infeasible and therefore discarded. We then proceed to the next best solution, and repeat the same steps until we find a feasible solution or no more improving solutions exist.

Example 1 [Continued]: Updating the departure windows after consolidation

Based on the decision tree as constructed in the preceding section, we decide to consolidate $r_{1,3}$ *on main leg 1 with* $r_{4,4}$ *and on main leg 2 with* $\{r_{2,1}, r_{3,1}\}$*. In this example, we describe how the departure windows are updated for consolidation, and how updating affects the rest of the schedule. We again assume that departures are tentatively scheduled as late as possible; however, earlier departure times can be selected to facilitate consolidation. In Figure 7, the vertical dotted lines represent the mutually feasible departure times on both legs.*

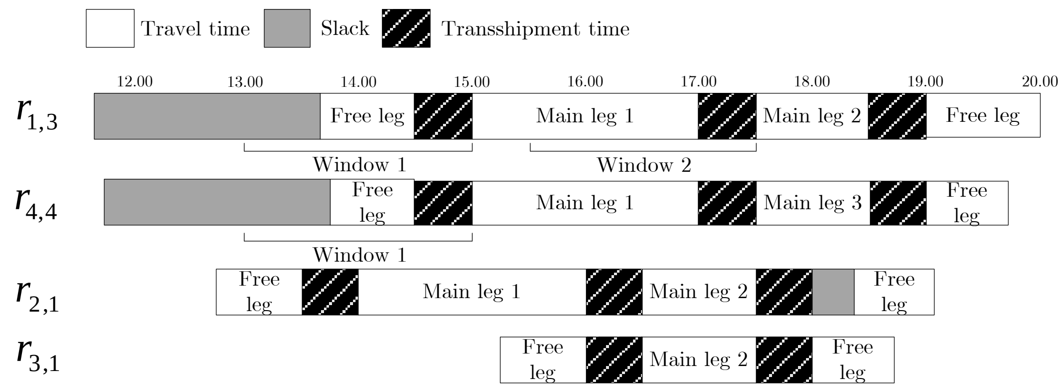

Figure 7: Gantt charts of routes before consolidation. A mutually feasible departure time must exist for consolidation.

It can be seen that 13.00, 14.00 and 15.00 are feasible departure times for both order 1 and 4. However, when selecting 15.00, consolidation at main leg 2 would no longer be possible. Hence, 13.00 and 14.00 are the only feasible departure times for this particular combination. The departure window is therefore narrowed, causing scheduled slack after the second main leg. The schedule after consolidation for order 1 is shown in Figure 8.

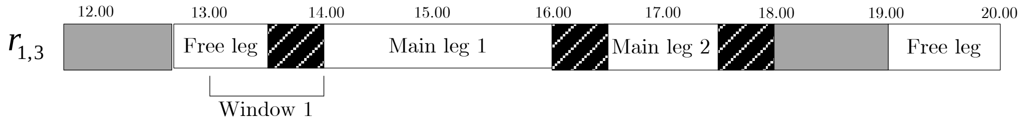

Figure 8: Gantt chart on route $r_{1,3}$ after consolidation on both main legs

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As we are interested in reducing the total costs, the combination of orders should have lower costs than those of the best individual solutions added up. Let $X = \{1, 2, \ldots, \prod_{z=1}^{|r_{i,n}|} |\mathcal{T}_{l_{i,n,z}}|\}$ be the set of indices for the unique paths in the decision tree of route $r_{i,n}$, with $x \in X$ referring to a specific path in the decision tree. Let $\mathcal{R}_x$ be the set containing route $r_{i,n}$ and all route sets corresponding to a specific path in a decision tree. Every branch in the path may relate to a distinct route set and/or container, the costs of the solution can only be determined if all these sets are considered in conjunction. The total costs of a route set are composed of three elements with their own cost functions: the transportation costs $c^p(\mathcal{R}_x)$, the transshipment costs $c^t(\mathcal{R}_x)$, and the handling costs $c^h(\mathcal{R}_x)$. Once the algorithm terminates and has identified the best improving solution (if any) for order i, we store the corresponding route set permanently, such that we have $\mathcal{R}_x = \mathcal{R}_{i,n}$. The purpose of this action is threefold. First, in case $|\mathcal{R}_{j,m}| > 1$, rescheduling a single order from $\mathcal{R}_{j,m}$ may have a strong impact on the solution quality of other orders in $\mathcal{R}_{j,m}$. It might then be better to reschedule other orders in $\mathcal{R}_{j,m}$ as well. Potentially, a complete re-optimization of the scheduling problem could be invoked at each new order arrival. Second, by fixing routes after a consolidation decision, the physical route of the order is altered at most once during the planning phase. In a practical setting, allowing continuous change might be detrimental to the planning process. Finally, fixing consolidated routes allows deleting the remaining $k-1$ routes, effectively reducing the search space. This vastly improves the computational speed required for planning new orders. Note that, although we fix the consolidated route, further expansion on a consolidated route remains possible. By adding orders arriving in the future or by combining with currently non-improving orders, the fill rate on the fixed route can be increased.

5 Numerical experiments

In this section, we describe the experiments that were completed with our algorithm. Our aim is to provide insight into the behavior of our algorithm under various circumstances. We use three benchmarks to measure the added value of our algorithm, namely (1) direct transport from origin to destination (single free leg), (2) the best route (including intermodal options) without consolidation, and (3) the best route for each order with consolidation allowed (i.e., we set $k = 1$ such that alternative consolidation opportunities cannot be identified).

We performed experiments on four virtual networks, each one representing generalizations of common consolidation scenarios. In addition, we did experiments on a real case with a reduced European transportation network. In Figure 9, panel a) shows a cluster with pickup locations, a cluster with delivery locations, transfer hubs in the center of both clusters, and a main leg connecting these two hubs. A practical form of this representation would be a liner service operating between an industrial area and an urban area. Panel b) shows a network consisting of a single origin cluster and two distant destination clusters. Panel c) shows a triangular network, where making a detour could yield additional consolidation opportunities. Finally, panel d) shows a scaled-down version of a semi-random network. Our actual networks consist of 20 randomly generated transfer hubs and 40 main legs, all directed towards the right. The pickup points and distributions are uniformly generated within a distance of $\frac{1000km}{\#hubs}$ from the nearest hub, based on the notion that hubs tend to be positioned within areas of high demand and vice versa. As opposed to the other virtual networks, the semi-random network allows for a large number of distinct routes, making the selection for k the most relevant. Orders generated have a preset minimum distance of 250km between origin and destination, and always move to the right. The semi-random network could for example correspond to a European corridor. In addition to the network with 20 hubs and 40 main legs, we also perform tests with networks containing 15 hubs and 30 legs, and 20 hubs and 100 legs respectively.

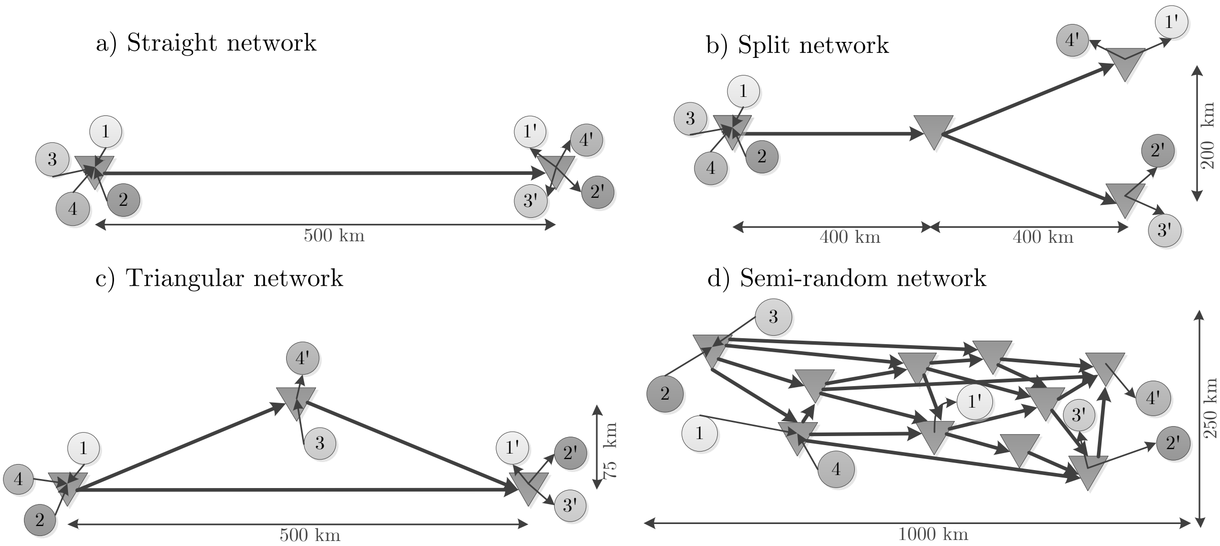

Figure 9: Graphical representation of the four virtual networks used in the experiments. Four order-destination pairs are shown for each network, in the actual experiments many orders are available at the same time.

We do not explicitly consider the transport means operating on the main legs, but rather define an abstract modality based on average properties of barge, truck, and train. We presume there is no limit on the number of containers a vehicle can carry, and set the travel speed at 50 km/hour. A preset cost is paid for each amount of container capacity to be transported. In accordance with dominant practice, we incorporate static pricing principles, based on the fill rate of the container. Although in reality costs may also differ based on the number of container carried, we assume that only the fill quantity of the container itself impacts the costs. In Figure 10, we show the two cost functions evaluated in our experiments; a logarithmic cost function $\frac{ln(63.62)\cdot f_{q_{l_{i,n,z}}}}{6.51}$ (standard setting) and a flat cost function 0.5. The flat cost function provides the strongest incentive to consolidate. For the logarithmic cost function, the benefits of consolidation marginally decrease with the fill rate. For comparative purposes, the logarithmic function is established in such a way that the integral of both functions is the same. This way, on average and without consolidation, the costs are the same when order sizes are uniformly distributed.

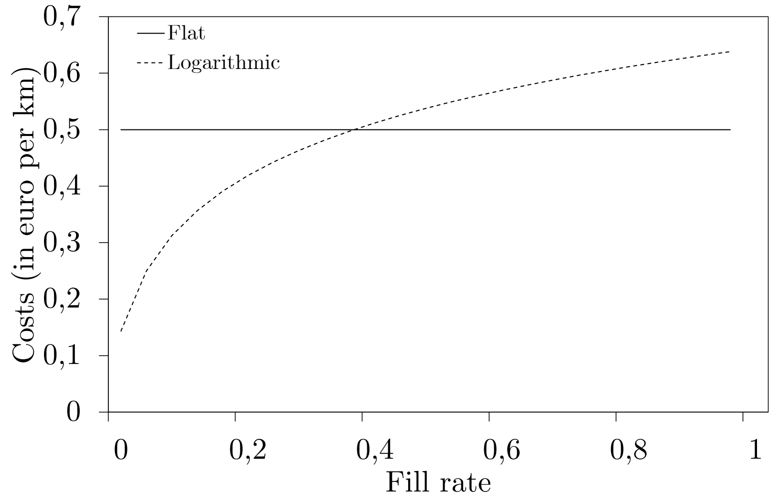

Figure 10: Flat and logarithmic cost functions, providing a transportation cost per km based on the container fill rate.

In Table 5.1, we provide the standard settings for the experiments on the four virtual networks. These settings are based on experiences in several practical cases. The order size is selected from the indicated range based on a uniform distribution. Furthermore, we test different settings for three variables. Varying the maximum horizontal distance between hubs allows us to determine the minimum distance required to make consolidation a feasible alternative for direct road transport. Finally, we vary the number of routes stored (k) to assess the impact of storing an additional route, i.e., to gain insight in the tradeoff between solution quality and computation time. The experiments are done for every network with both cost functions. The number of orders per run and the warm-up period are determined based on the graphical procedure of Welch (1983), using the average costs of transporting an order as the KPI. We use 6 replications with a run length of 650 to achieve a relative error of at most 5% for the 95% confidence intervals.

We apply our algorithm on a data set of the Dutch LSP. The order set at hand consists of 1006 orders transported over a quartile in 2013, which were shipped from several locations in the Netherlands to a variety of locations in Germany, Austria, Switzerland and Italy. The actual locations, pickup- and delivery times are used. The order sizes – provided in loading meters – are slightly adjusted; we consider a full container to be equivalent to a full truckload. The average order size for this set is 0.33 container. For transport to the delivery areas, the LSP utilizes a network consisting of 37 hubs connected by 110 waterway and railroad legs. These legs are operated by contracted carriers that make use of fixed timetables. As an alternative, it is always possible to transport by truck. The corridor is directed towards Italy; intermodal transportation options towards Germany are therefore limited. Also, the distances for the orders shipped from the Netherlands to Germany are generally too short to consider intermodal transport. In line with practice, a flat rate is charged for each container transported over a main leg. Transportation costs are normalized for confidentiality reasons. The cost for transporting a full container via a free leg is set at 1.00 per km for a full container. A linear capped cost function (i.e., piecewise linear) with a start rate of 0.30 and a cost cap at a fill rate of 0.90 is applied. For barges a flat rate of 0.33 is used, for trains this flat rate is 0.51. As the LSP requires only a relatively small amount of barge or train capacity, we assume no constraints on the number of containers that these modalities can carry.

Variable	**Standard setting**	**Experimental variables**
Cost function (main legs and free legs)	Logarithmic	Flat
Maximum horizontal distance between hubs	500km (straight) 800km (split/triangular) 1000km (semi-random)	100,250,...,600km (straight)
Time between order arrivals (Poisson distributed)	3 hour mean	
Number of orders per run	650	
Warm-up/cool-down period (in # of orders)	25	
Travel speed (all vehicles)	50km/hour	
Departure policy	Latest departure	Earliest departure
Earliest pickup time (after arrival)	0 days	
Latest delivery time (after arrival)	5 days	
Costs free leg per km (flat rate for full container)	1.00	
Costs main leg per km (flat rate for full container)	0.50	
Costs transshipment operation	22	
Costs handling operation	35	
Number of routes stored per order (i.e., k)[2]	2 (straight/split) 3 (triangular) 5 (semi-random)	1,2,...,10 (semi-random)
Order size	0.04-1.00	
Vehicle capacity (all vehicles)	1.00	

Table 5.1: Settings for the numerical experiments on the virtual networks.

We first describe the key results for the experiments on the virtual networks, using the standard settings. In Table 5.2, we provide the attained fill rate with (1) consolidation compared to the best route without consolidation, (2) the average detour compared to the best routes, and (3) the relative cost reductions per network. For the latter, we use three benchmarks: the free leg from origin to destination (Direct), the best route without consolidation (Best), and consolidation possible on the best route only ($k = 1$). It can be seen that the benefits are greatest for well-connected areas of demand and supply. For the first three networks, we note that the (rounded-off) improvement compared to $k = 1$ is 0%. Due to the small diversity in routes for these networks, the algorithm is generally able to combine best routes of orders when

[2]For the straight, split and triangular network, the best identified settings for k are used. Due to the small amount of routes in these networks, experiments could be run for all values of k.

consolidating, such that storing more than one route has a negligible impact.

When comparing the performance under an earliest departure policy with that of a latest departure policy, the latter clearly performs better (Table 5.3). These differences can be explained by the reduction of solution space when applying earliest departure, which discards later departure times and alternative routes by fixing the route upon order arrival. Note that new orders may still be added during execution of the route, such that waiting at intermediate hubs remains possible.

From our tests on the straight network (Figure 11) consolidation actions start to occur frequently if average distances between origins and destinations are about 200km. Smaller distances result in direct routes via a free leg, as the tradeoff between transportation costs and transshipment costs is no longer beneficial. Therefore, main legs with a length under 200km are unlikely to be utilized. Fill rates stabilize around 500km; larger distances do not yield an increase in consolidation actions.

In Figure 12, we provide an experimental instance of the realized savings for a semi-random network, distinguishing between four values for k. The savings are split out per route, where the *Route#* refers to the position of the route when sorted on costs (e.g., the third best route has *Route#* 3). In this setup, $k = 3$ yields the highest overall savings. Similar results – a certain non-maximum value for k providing the best solutions on average – consistently occurred during our experiments. As our algorithm is a greedy heuristic and we solve a dynamic problem, increasing the value of k needs not to continuously lead to improving overall solutions. Consolidating on low-quality routes might yield a small saving which would not be identified with smaller k, but possibly eliminates more suitable schedules when new orders arrive. The optimal setting for k depends on the composition of the order set and the structure of the network.

Figure 13 shows the outcomes for applying $k = \{1, 2, \dots, 10\}$ on three semi-random networks; 15 hubs with 30 main legs, 20 hubs with 40 main legs, and 20 hubs with 100 main legs. The savings structure of the first two networks are rather similar, achieving their best results at $k = 3$ and $k = 4$ respectively. For the 20/100 network, $k = 5$ yields the best results. The number of attractive alternative routes tends to increase the best setting for k. As the quality of routes is then higher as well – due to stored routes being closer together in terms of costs – overall savings are also higher.

Network	Cost function	Increase fill rate (achieved fill rate)	Detour	Cost reduction compared to		
				Direct	Best	$k = 1$
Straight	Logarithmic	78% (0.92)	0%	43%	18%	0%
Straight	Flat	73% (0.91)	0%	48%	27%	0%
Split	Logarithmic	76% (0.92)	1%	48%	23%	0%
Split	Flat	75% (0.91)	1%	53%	30%	0%
Triangular	Logarithmic	75% (0.91)	1%	44%	18%	0%
Triangular	Flat	74% (0.91)	1%	49%	26%	0%
Semi-random	Logarithmic	52% (0.79)	3%	31%	10%	2%
Semi-random	Flat	52% (0.79)	4%	34%	14%	5%

Table 5.2: Key results from numerical experiments under the standard settings. Shown are the average increase in fill rate, the average increase in route length, and the average cost reduction.

Finally, we discuss the results of our experiment based on the real LSP data. As a bench-

Network	Earliest departure		Latest departure		Absolute difference between policy performances	
	Cost reduction compared to *Best*	Increase fill rate	Cost reduction compared to *Best*	Increase fill rate	Cost reduction	Fill rate
Straight	14%	60%	18%	77%	4%	17%
Split	20%	67%	23%	75%	3%	8%
Triangular	15%	56%	19%	72%	4%	16%
Network	4%	15%	10%	49%	6%	34%

Table 5.3: Differences in performance between earliest departure policy and latest departure policy. The latest departure policy consistently outperforms its counterpart; due to retaining flexibility it is more often able to identify good solutions.

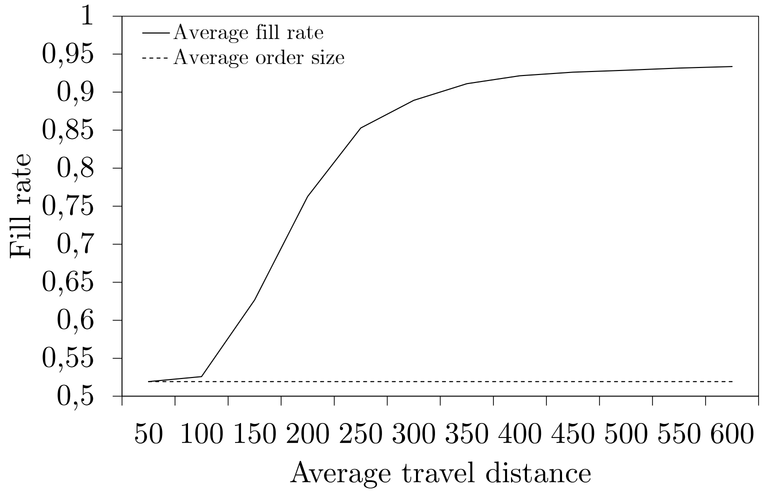

Figure 11: Attained fill rates on the straight network with various main leg lengths. For main legs shorter than 200km consolidation does not take place; the handling and transshipment costs then outweigh the lower transportation costs.

mark: the average transportation cost per order is 321 when only considering direct transport. Accounting for transport via the intermodal network already yields an average cost reduction of 9.1%. In that case, 215 routes (out of 1006) utilize main legs. However, when allowing for consolidation with $k = 1$, the additional benefits from consolidation are negligible, with only 20 orders that can be consolidated. As the 215 routes make use of 28 distinct main legs, the chance of finding a match in terms of main leg, departure window and capacity is limited when $k = 1$. In a case like this, the added value of storing multiple paths can be observed. Table 5.4 shows the improvement in performance for various settings for k. These results show how the flexibility acquired by storing multiple routes improves the average fill rates and reduces logistics costs.

Despite the promising initial results, we note a few practical limitations of our algorithm. First, handling operations will take more time than just transshipping. This means that routes may no longer be feasible when requiring additional handling time, requiring an additional feasibility check. Second, not all hubs allow for handling; some hubs only tranship full con-

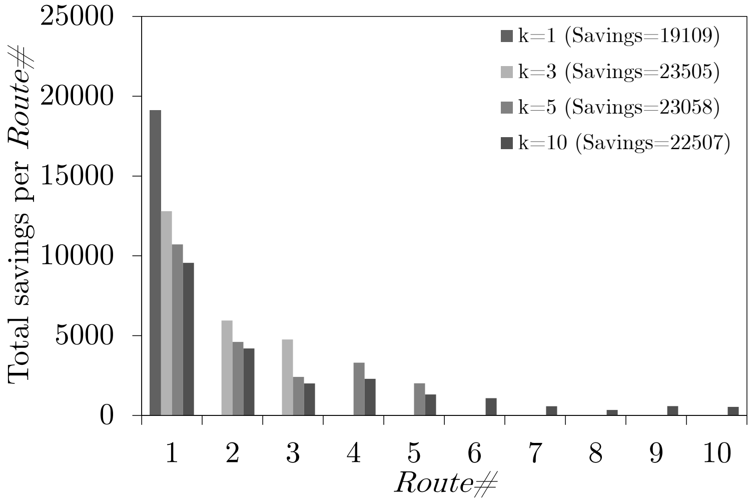

Figure 12: Savings for $k = \{1, 3, 5, 10\}$, compared to the best solution without consolidation, split out per route. As route quality diminishes for large k, marginal savings decrease with k. The choice for k impacts the global solution quality.

k	No. consolidated (out of 1006 orders)	Cost reduction for consolidated orders (compared to $k = 1$)	Overall cost reduction (compared to $k = 1$)	Overall improvement fill rate
k=1	20	0%	0%	1%
k=2	102	2.1%	0.4%	4%
k=3	143	5.6%	0.7%	7%
k=5	205	6.5%	1.8%	14%
k=10	270	6.9%	2.5%	20%
k=15	326	7.1%	2.8%	26%
k=20	371	8.9%	3.2%	29%

Table 5.4: Computational results for the LSP experiment, using various settings for k

tainers. This feature can be added as an additional constraint that limits the solution space. Third, travel times and transshipment times are not deterministic in practice. Incorporating stochasticity is particularly relevant when lateness at the customer must be taken into account. Penalty functions could then be used to assess the tradeoff between consolidation opportunities and lateness. The number of transshipments in a route will likely have a greater impact, as missing a planned departure time results in significant delays. As an alternative to stochastic travel times, we could also employ the time-dependent mapping function to incorporate time-dependent travel times. Finally, we do not consider consolidation on the free legs. Our algorithm could be integrated with a VRP-algorithm, such that tours composed of free legs could be constructed. The implementation of this aspect would benefit from more advanced waiting policies than deployed in this paper.

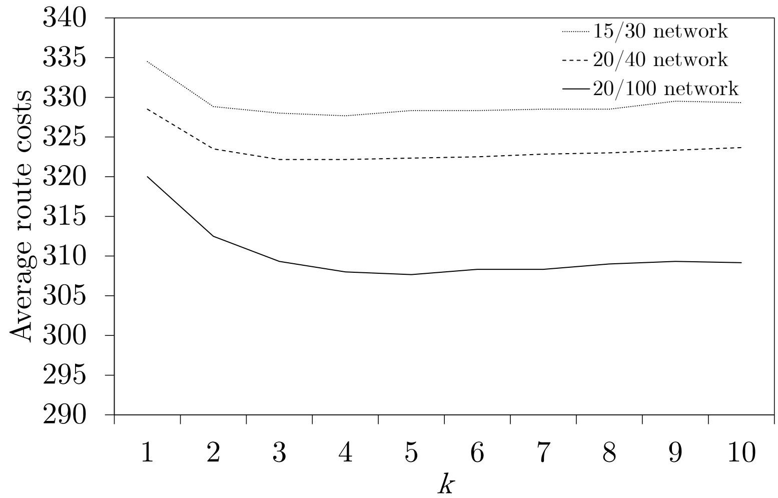

Figure 13: Average route costs for three semi-random networks, measured for $k = \{1, 2, \ldots, 10\}$. It can be seen that the network containing 20 hubs and 100 main legs benefits most from the algorithm, due to the higher variety in good routes.

6 Conclusions

With the algorithm presented in this paper, we explore operational scheduling of consolidated routes in networks with transshipments. We introduce a new method to assess consolidation opportunities in a dynamic planning environment. By using a time-dependent graph that allows for multiple departure times, we facilitate the scheduling of routes with consolidated orders. We create flexibility in both space and time, by (1) storing k routes for every order and (2) using departure windows instead of fixed departure times. The storage of the k best routes for each order yields a high-quality search space for the consolidation algorithm. The matching procedure only takes place on the controlled search space, allowing the algorithm to be used in an online planning environment.

Our algorithm is based on three key design choices that bring computation speed to a level suitable for dynamic planning, but reduce the chances of finding the optimal solution. First, by setting k smaller than the total number of possible routes, not all consolidation opportunities are evaluated. Second, the loop structure that sequentially solves decision trees considers consolidation with one order (set) at a time, and might therefore deviate from the optimal assignment of orders. Third, by removing $k-1$ solutions after consolidating, future consolidation opportunities on other routes are discarded. The first two aspects in particular are necessary to guarantee that the algorithm can be used in a practical setting. The final restriction might be relaxed, but introduces additional complexities and would make the algorithm less suitable for instances where computation time is limited. Static re-optimization techniques may be more fitting for such an approach.

The number of routes that is stored for each order determines the tradeoff between solution quality and computation time. The more routes we store, the larger the probability of finding an efficient consolidation option. However, as the algorithm is greedy, storing too many routes may decrease the solution quality. A large set of routes per order increases the probability of finding a consolidation opportunity, but the routes that allow for such a solution may be of poor quality, such that only minor savings are obtained. These savings would not have been found for small values for k, but at the same time eliminate potential future opportunities of higher quality (i.e., consolidation while using better routes). It is therefore recommended to calibrate the algorithm to a given network and order properties. An important influence on the computation time is the number of main legs in a route, as additional legs causes an exponential growth of the decision tree. Despite the theoretical problems with computational time, in none of our experiments we encountered search spaces of a magnitude that would hamper real-time planning.

Our experiments on semi-random networks showed cost savings between 10 and 14%, using transportation via the best route without consolidation as a benchmark. The LSP experiment in particular showed how memorizing multiple routes contributes to the quality of the solution. When only storing the best route for each order (i.e., $k = 1$), only 2% of the orders could be consolidating. When $k = 20$, we could consolidate 37% of the orders, achieving a 9% cost reduction on these orders. However, in most cases storing the best route of each order contributes most to the savings. The flexibility acquired by leaving departure windows open already greatly contributes to consolidation opportunities. In more complex networks, the added value of variety in physical routes can be observed as well. Diversity in both space and time are therefore important attributes when considering the operational planning of consolidation.

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A Pseudocode for consolidation algorithm

```
Consolidation algorithm
for each route in route set for new order i do

  % Preprocessing of routes feasible for evaluation
  for each leg in route for order i do
    for each leg in set of available legs open orders do
      if selected legs order i and j are the same and
          feasible departure time within mutual departure window exists and
          sufficient capacity to combine orders and
          no order from consolidated route set order j in evaluation set or
          vehicle on selected leg not in evaluation set[3] then
          Incorporate route (set) in evaluation set;
      end if
    end for
  end for

  % Tree construction
  InitSolution := BestSolution; [sets initial route as starting point for evaluation]
  for each leg in route for order i do
    for each representation in evaluation set do
      if no consolidation on different route for order j in preceding branch and
          feasible departure time within mutual departure window exists then
          Update departure window for selected leg;
          Update fill quantity on selected leg;
          Update other departure windows in routes containing the selected leg;
          Update departure windows remaining routes in set;
          Update costs on selected leg;
      end if
    end for
  end for

  % Tree evaluation
  for all end nodes do
    if Cost(NewSolution)<Cost(BestSolution) [lower costs of consolidated route set than current best solution] and
      NewSolution is feasible then
      BestSolution := NewSolution;
    end if
  end for
end for
```

Table A.1: Pseudocode for consolidation algorithm.

[3] Same order set can be incorporated more than once if multiple vehicles operate on the same leg.

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