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Enriching the Tactical Network Design of Express Service Carriers with Fleet Scheduling Characteristics

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Abstract

Express service carriers provide time-guaranteed deliveries of parcels via a network consisting of nodes and hubs. In this, nodes take care of the collection and delivery of parcels, and hubs have the function to consolidate parcels in between the nodes. The tactical network design problem assigns nodes to hubs, determines arcs between hubs, and routes parcels through the network. Afterwards, fleet scheduling creates a schedule for vehicles operated in the network. The strong relation between flow routing and fleet scheduling makes it difficult to optimise the network cost. Due to this complexity, fleet scheduling and network design are usually decoupled. We propose a new tactical network design model that is able to include fleet scheduling characteristics (like vehicle capacities, vehicle balancing, and drivers' legislations) in the network design. The model is tested on benchmark data based on instances from an express provider, resulting in significant cost reductions.

Key words: express service carriers, freight transportation, tactical hub network design, integer programming, fleet scheduling, heuristics.
JEL Classification System: C60, L91.

1. Introduction

Express service carriers provide time-guaranteed deliveries of parcels. Direct transport from sender to receiver is the fastest way of transport but this is in general not cost efficient. Therefore, express carriers operate a network in which parcels of many customers are consolidated. Parcels of several senders are consolidated at nodes (in practice called depots, terminals, etc.), transported to other nodes via the line-haul network and finally delivered to the consignees. We will now briefly describe how the express supply chain is organised. Then a description of network design is given followed by a discussion on fleet scheduling. At the end of this introduction, our research goals are stated.

1.1. Express Supply Chain

The first node at which a parcel arrives after pickup is called the *origin node* (or *origin*) of the parcel; the node from where the parcel is delivered to the consignee is called the *destination node* (or *destination*) of the parcel. The transport of parcels between origin node and destination node is called *line-haul*. Origin and destination node form an *od-pair*. For these od-pairs, several *services* are offered, defined in terms of promised delivery dates and times of the parcels. Parcels of an od-pair with the same service can always be transhipped together during line-haul transport. The number of parcels of one service to be transhipped between two nodes is called the *flow* of the *origin-destination service pair* (*od-service pair*); the total flow of parcels to be transported between two nodes is called the flow of the od-pair.

Cut off times form the connection between the pickup and delivery process and the line-haul process and guarantee the on-time delivery of parcels. That is, all parcels of one service collected in the pickup process have to be processed and loaded into line-haul vehicles before the *collection cut off time* of the corresponding service; the line-haul transport will start afterwards. The line-haul vehicles have to arrive at the destination nodes before the *delivery cut off time* of the corresponding service. The line-haul vehicles will be unloaded after arrival at the destination node and parcels will be processed such that the final delivery to consignees can start

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afterwards. Flows in the line-haul network are either directly transported between nodes or consolidated at *hub* locations. A hub is a sorting centre serving nodes and other hubs. Hubs in the express network are crucial in making fast and reliably connections. A *direct route* between nodes can be established if there is enough flow to create a (nearly) full vehicle load between two nodes. A direct route can also be used when none of the hub routes is able to meet the service requirements of the corresponding od-pair. A *hub route* is a route from node to node visiting hubs in between; note that hub routes result in detours of flow routing.

Carriers can use ground or air modes in their line-haul transport. Generally, road transport is preferred because of the lower cost involved. Air transport is used to establish services that can not be offered by ground transport. In this paper, we focus on road transport. However, the proposed method can also be used for air transport. Figure 1 gives an overview of the express supply chain.

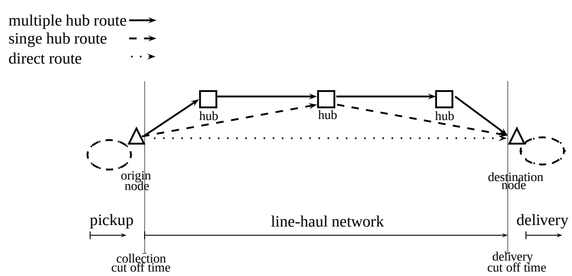

Figure 1: Express supply chain.

1.2. Hub network design

Consolidation at hub locations was introduced in literature by O'Kelly (1986). The construction of a line-haul network is better known as the *hub network design problem*. Generally, there are two decision levels in hub network design problems. The *strategic* hub network design problem of express carriers decides on the number and location of hubs in the line-haul network. The *tactical* hub network design problem concerns the assignment of nodes to hubs, determines arcs (i.e. line-hauls) between hubs, and routes flows through the network.

In general, strategic and tactical network design discussed in literature focus on minimisation of the sum of unit transport cost. It is generally assumed that consolidated transport between hub locations benefits from economies of scale such that unit transport cost of inter-hub flows can be discounted. The main restrictions in both strategic and tactical network design are *flow conservation* and *service commitment*. Flow conservation requires that all flow has to be transported between nodes; service commitment requires that flows are transported within predefined time limits. It is often assumed that the hub network is complete when a link between every hub pair is established, and that no direct routes are allowed (Alumur and Kara, 2008b). Besides, some literature assumes *capacitated* hub locations that can only deal with a limited amount of flow (e.g. Aykin (1994), Melkote and Daskin (2001)).

1.3. Fleet Scheduling

After tactical network design, vehicle schedules need to be created such that the flow can be transported. An important aspect of fleet scheduling is the inclusion of *waiting times* (Kara and Tansel, 2001): a vehicle can only depart once the flow scheduled on that vehicle has arrived and been processed. In particular, waiting times are important in case of the last vehicle moving via a certain arc. Flows can only be consolidated when there is enough time available for consolidation. This is illustrated in Figure 2: the cut off times imply that there are only 10 hours available to transport flows (a,b) and (c,d); as a result, consolidation of inter-hub flows is not possible. Note that cut off times not only define the available time of transport, but also define the moment of transport.

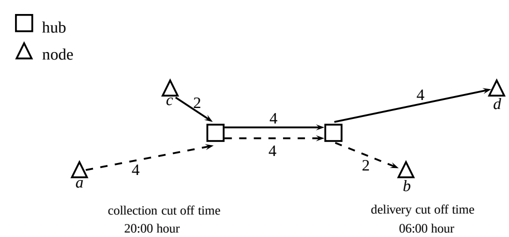

Figure 2: Consolidation not possible.

Another important aspect of fleet scheduling is *vehicle balancing*: since express carriers operate on a daily basis, the number of incoming and outgoing vehicles should be balanced for every node. A third aspect in fleet scheduling that needs attention concerns *drivers' legislations*. Maximum driving times and prescribed breaks may not be violated. If the driving time between two locations exceeds the maximum driving time of one driver, a second driver is required resulting in additional cost. In network design literature, the problem of fleet scheduling and balancing is referred to as the *fleet scheduling problem*.

1.4. Research goals

This paper concerns the tactical network design in road transport of express carriers. The research is inspired by practical considerations not yet dealt with in literature.

The first extension on existing literature concerns the cost function, which in practice turns out to be more complex than generally seen in literature. In the latter, the cost function results from unit transport cost and inter-hub transport is discounted. However, transport cost results from the dispatching of vehicles. Unit transport cost is therefore not linear as is often assumed, but results from a stepwise cost function based on the number of trucks needed (see Figure 3).

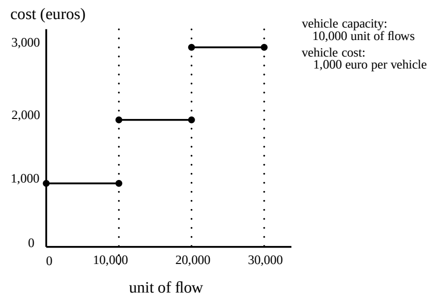

Figure 3: Step-wise cost function.

In our approach, we will therefore explicitly determine vehicle movements to determine the cost of the tactical network design. A second cost component that will be included in our network design is vehicle balancing cost. Since express providers often see imbalances in flows between industrial and non-industrial areas, vehicle balancing cost form a substantial part of the total costs of the express network. We will therefore include this cost in our tactical network design. Moreover, drivers' legislations may not be violated. Additional cost will be included if a second driver is required. Finally, variable handling cost at hub locations will be taken into account in the network design.

Express carriers offering next day services face tight time constraints. Literature discusses the usage of a cover radius (Kara and Tansel, 2003), which is a bound on transport time. However, the available time to transport flows depends on the service definition. The tactical network design model presented in this paper uses cut off times to derive the available time to transport flows so that multiple services can be included. However, the moment of transport is not taken into account during network design, i.e. it is not checked if combining flows is possible in time.

Routes that are allowed in our model can be varied, as long as service requirements can be satisfied with respect to the cut off times. We therefore do not have to assume a complete hub network, nor exclude direct routing.

Finally, we assume that hub locations can handle a limited amount of flow because hub locations are fixed and given in the tactical hub network design.

The remainder of the paper is organised as follows. Section 2 gives an overview of literature on hub network design. The modelling approach is presented in Section 3. Two network design models are presented, a traditional model and a new model. A fleet scheduling heuristic will be used to derive the final network cost so that the two models can be compared. The models are tested on data instances of an express provider. The results will be presented in Section 4. Finally our conclusions and directions for further research are given in Section 5.

2. Related literature

This section briefly discusses literature on the hub network design problem. Recent overviews on hub network design in express networks are given by Alumur and Kara (2008b). Overviews on hub network design in general are given by ReVelle et al. (2008) and Melo et al. (2009).

Hub consolidation was introduced in literature by O'Kelly (1986). In this, O'Kelly introduced the concept of economies of scale on inter-hub flows: the idea is that flows between hubs might enjoy a discounted transport rate arising from the greater volume on these arcs. This is modelled by discounting unit transport cost for inter-hub flows. The first strategic hub network design model is a quadratic model presented by O'Kelly (1987). Afterwards, several researchers studied strategic and tactical hub network design and several variants of the problem are proposed. The strategic hub network design selects the locations of hubs in the network such that the sum of unit transport cost is minimised (O'Kelly (1992), Aykin (1994), Aykin (1995), O'Kelly et al. (1996)), the largest transport time is minimised (Kara and Tansel (2001)), the number of hubs is minimised (Kara and Tansel (2003), Tan and Kara (2007), Yaman et al. (2007), Alumur and Kara (2008a)), or the total freight to be delivered to customers within a certain time bound is maximised (Yaman et al. (2008)). This paper focuses on the tactical hub network design. The remainder of this section concerns literature on the tactical hub network design problem.

The tactical hub network design in air transport is considered by Barnhart and Schneur (1996). Pick up and delivery aircraft routes and schedules are derived towards a single hub node. Each aircraft route begins at the hub, visits a set of destination nodes followed by an idle period, then visits a set of origin nodes before returning to the hub. The idle time in between can be used for ferrying (i.e. repositioning of aircrafts). Earliest pick up and latest delivery times are used at the nodes. Associated with the hub is a cut off time, which is the latest time an aircraft may arrive at the hub. Three service levels are defined in these models: next-day service (24 hours), second day service (48 hours) and deferred service (3-5 days). A system that determines aircraft routes, fleet assignments and package routings simultaneously has been described by Armacost et al. (2004). Like Barnhart and Schneur (1996), pick up and delivery routes towards a single air hub are derived including time windows for pick up and delivery. Armacost et al. (2002) and Armacost et al. (2004) use a composite variable formulation to solve a comparable model.

Multiple hub networks are considered by Lin (2001). Two algorithms to solve the tactical network design with time bounds are proposed. Service commitment is satisfied in the modelling by applying an origin-destination dependent time bound for transport. This model and solution approach is extended by Lin and Chen (2004) considering waiting times at hub locations as well. However, the model assumes that there is insufficient demand under tight time restrictions to fill up vehicles or aircrafts traversing via an arc, so that only one such vehicle or aircraft is dispatched on each arc.

The next section presents two models to solve the tactical network design problem of express carriers. Moreover, a fleet scheduling heuristic is presented that will be used to compare the results of the tactical hub networks design models.

3. Modelling

The modelling presented in this section solves the network design and fleet scheduling problem in two steps. First, a tactical network design model is run to derive flow routes. The tactical network design models that are used are discussed in Section 3.1. Two models are proposed, the first model is a traditional model that discounts economies of scale on inter-hub flow routing, and will be used for benchmarking. The second model is new and includes fleet scheduling characteristics in network design. In order to compare the results, a fleet scheduling heuristic is solved to determine the network cost (Section 3.2). The fleet scheduling heuristic will use the flow routes found by one of the network design models. However, the heuristic can also be applied on existing routes of an express provider. Figure 4 gives an overview of the modelling approach.

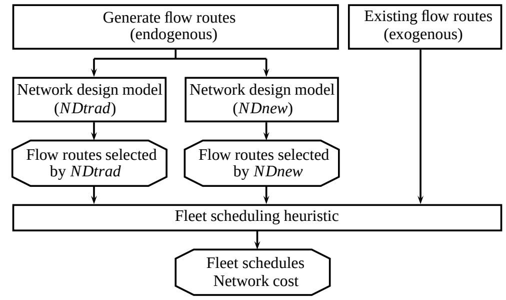

Figure 4: Overview modelling.

3.1. Network design model

The network design starts with a set of locations L containing hub locations $H \subset L$ and nodes $N \subset L$. Without loss of generality it will be assumed that each location is either a hub location or a node, i.e. $H \cap N = \emptyset$. Node i offers services s to customers guaranteeing a delivery time of parcels received at the node before the collection cut off time c^o_{is}; in order to satisfy the service, the parcel has to be delivered at the destination node j before the delivery cut off time c^d_{js}. It is assumed that services between nodes are only offered to the customers if their service requirements can be met. That is, the available time between collection cut off time and delivery cut off time of the od-service has to be larger than the driving time between these locations. The total flow of parcels of service s from node i to node j is denoted by f_{ijs}.

To simplify the problem, we assume that there is only one vehicle type available to transport the flows. This assumption hardly limits practical applications. The capacity of this vehicle is equal to v units of flow. Note that vehicle capacity and flow need to be expressed in the same unit (e.g. weight, volume, parcels, etc.). Vehicles move via the arcs A of the network; the start location of an arc is denoted by $s_a \in L$ and the end location is denoted by $e_a \in L$. The distance of arc $a \in A$ is given by d_a.

Drivers' legislations should be taken into account when determining the drivers cost, since maximum driving times and prescribed breaks may not be violated. When the driving time between two locations exceeds the maximum driving time of one driver, a second driver is required and this cost has to be incorporated. We will follow the European Regulations (EUR-lex, 2006) that prescribe a maximum driving time of 9 hours and an uninterrupted break of no less than 45 minutes, after a driving period of 4.5 hour. The total costs of a vehicle moving via arc a is denoted by C_a and includes vehicle transport cost and (second) drivers cost. All required cost information is available.

For each pair of nodes i, j with a positive flow $\sum_s f_{ijs} > 0$, routes will be generated. A route $r \in R$ is created via the arcs a of the network; the parameter u_{ra} equals 1 if route r uses arc a and 0 otherwise. Since route r starts at a node location i and ends at a node location j it can only be used to satisfy services of the corresponding pair of nodes. Besides, the route can only be used for service s of the node pair if it can leave node i after the collection cut off time (c^o_{is}) and arrives at node j before the delivery cut off time (c^d_{js}) taking transport time and hub sorting time into account. This results in a parameter p_{ijsr} that equals 1 if a route can be used to serve service s of od-pair i, j and 0 if it cannot. See Figure 5 for an illustration of the route generation.

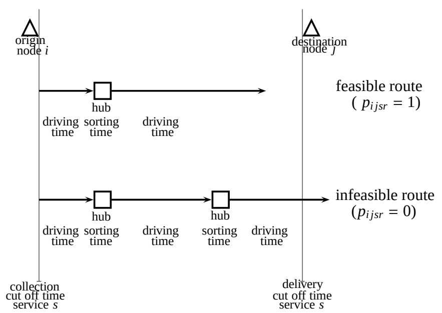

Figure 5: Route generation, route feasible?

A *direct route* $i \rightarrow j$ is a route that only uses a node-node arc (i.e. $s_a, e_a \in N$). It is not allowed to pass nodes other than the origin and destination node of the route, i.e. a route $i \rightarrow j \rightarrow k$ with $i, j, k \in N$ is not allowed. A *single hub route* $i \rightarrow h_1 \rightarrow j$ is a route that uses a node-hub arc (i.e. $s_a \in N$ and $e_a \in H$) and a hub-node arc (i.e. $s_a \in H$ and $e_a \in N$). A *multiple hub route* $i \rightarrow h_1 \rightarrow \ldots \rightarrow h_2 \rightarrow j$ can pass more than one hub and uses one node-hub arc, one or more hub-hub arcs (i.e. $s_a, e_a \in H$) and one hub-node arc. Routes are categorised by their number of hub touches n ($n = 0, 1, 2, 3, ...$); a route with n hub touches is referred to as type Hn route. Note that $n = 0$ refers to a direct route, $n = 1$ refers to a single hub route and $n > 1$ denotes multiple hub routes. The modeller can indicate which routes should be taken into account in the model. In general, when we say that we include Hn-routes, all possible routes with n hub touches are generated for each service of an od-pair.

It is assumed that each service of an od-pair can be satisfied by at least one of the routes generated. If none of the hub routes is able to meet the service requirements, the flow has to be routed directly from origin node to destination node. This flow that has to be routed directly because of tight time constraints is denoted by f^D_{ijs} and can be determined in a preprocessing phase of one of the network design models presented in the next sections. If some services of an od-pair i, j have to be routed directly while others can be routed via a hub route, it is possible to allow these services to use this direct route as well. In this, either all flow of these services can be routed via this direct route or only part of the flow can use this route. This will be discussed in more detail in the sections below. The remaining flow for which a route has to be determined by one of the network design models is denoted by f^R_{ijs} and equals $f_{ijs} - f^D_{ijs}$. An overview of the parameters is given below.

L	set of locations, index l
$N \subset L$	set of nodes, index i, j
$H \subset L$	set of hub locations, index h
S	set of services, index s
c^o_{is}	origin cut off of node i service s
c^d_{js}	destination cut off of node j service s
f_{ijs}	total flow from node i to node j of service s
f^D_{ijs}	flow from node i to node j of service s which has to be routed via a direct route
f^R_{ijs}	flow from node i to node j of service s for which a route needs to be determined
A	set of arcs, index a
s_a	start location of arc a
e_a	end location of arc a
d_a	distance of arc a
v	capacity of a vehicle
C_a	cost of one vehicle v moving via arc a
R	set of routes, index r
u_{ra}	1 if route r uses arc a and 0 otherwise
p_{ijsr}	1 if od-pair i, j can use route r for service s 0 otherwise

Sections 3.1.1 and 3.1.2 present the network design models that are used to determine the flow routes.

3.1.1. Network design model: traditional model

This section discusses a traditional model of the tactical network design problem of an express provider. Unit transport cost of a vehicle moving via arc a follow from dividing the cost of one vehicle moving via that arc by the capacity of the vehicle, i.e. $\frac{1}{v}C_a$. To incorporate economies of scales on inter-hub flow routing, a factor α_a is included such that $\alpha_a \leqslant 1$ for inter-hub arcs and $\alpha_a = 1$ for non-hub arcs.

As described above, it is possible that some flow has to be routed directly because of tight time constraints.

It is possible that some flow of an od-pair has to be routed directly while other services of the od-pair can be satisfied by a hub route. In that case, we will assume that all flow of the od-pair is routed directly. The parameters f^D_{ijs} and f^R_{ijs} are updated accordingly. Note that either f^D_{ijs} or f^R_{ijs} will be equal to 0.

The network design model will choose one route for each service s of od-pair i, j with a positive flow f^R_{ijs}. The variable x_{ijsr} equals 1 if od-service i, j, s uses route r. The flow conservation constraint can now be modelled as

$$\sum_r (p_{ijsr} x_{ijsr}) = 1, \forall i, j \in N, s \in S, f^R_{ijs} > 0.$$

The total costs of the network design can be formulated as

$$\sum_{ijsr} (\sum_a (\frac{1}{v} \alpha_a u_{ra} C_a) f^R_{ijs} x_{ijsr}).$$

An overview of the model and additional parameters and variables is given below. This network design model will be referred to as *NDtrad*.

parameters

α_a	discount factor on arc a for economies of scale

variables

x_{ijsr}	1 if od-pair i, j uses route r for service s, 0 otherwise

NDtrad-model

$$\min \sum_{ijsr} (\sum_a (\frac{1}{v} \alpha_a u_{ra} C_a) f^R_{ijs} x_{ijsr}) \tag{1}$$

$$\sum_r (p_{ijsr} x_{ijsr}) = 1, \quad \forall i, j \in N, s \in S, f^R_{ijs} > 0 \tag{2}$$

$$x_{ijsr} \in \{0, 1\}, \quad \forall i, j \in N, s \in S, r \in R. \tag{3}$$

3.1.2. Network design model: new model

Instead of incorporating a scaling factor for economies of scales, an upper bound on economies of scales can be obtained by determining the minimum number of vehicles required to transport the flows. This network design model selects a route for each service of an od-pair; the routes that can be selected need to satisfy the service requirements of the corresponding service of the od-pair. Since each chosen route is feasible, the model results in a minimum number of vehicles to transport the flows. If time constraints are tight, more vehicles will be needed to transport the flows. In case of loose time constraints, the number of vehicles determined by the network design model is sufficient to transport the flows. The model therefore results in an upper bound on achievable economies of scale.

If some flow of an od-pair must be routed directly because of tight time constraints the remaining capacity on the used vehicles will be available for transporting flow of the od-pair that could be routed via a hub route (i.e. f^R_{ijs}). However, this flow will only use the direct route if there is enough time for consolidation. The parameters f^R_{ijs} and f^D_{ijs} are updated accordingly. Note that f^R_{ijs} and f^D_{ijs} can be larger than 0 at the same time.

The network design model again will choose one route for each service s of od-pair i, j with $f^R_{ijs} > 0$. As in Section 3.1.1, the variable x_{ijsr} will be used to denote that od-pair i, j, service s uses route r. The flow conservation constraint is again modelled as

$$\sum_r (p_{ijsr} x_{ijsr}) = 1, \forall i, j \in N, s \in S, f^R_{ijs} > 0.$$

The total vehicle capacity on each arc has to be sufficient to transport the flow using that arc. By y^R_a we denote the number of vehicles needed to transport the flows f^R_{ijs} via arc a. This results in the constraint

$$\sum_{ijsr} (u_{ra} f^R_{ijs} x_{ijsr}) \leqslant v y^R_a, \forall a \in A.$$

The parameter $\bar{y}^D_a$ denotes the number of vehicles required to transport direct flows, and equals $\lceil f^D_{ijs}/v \rceil$. The required number of repositioning vehicles moving via arc a will be denoted by y^B_a. The vehicle balancing constraint now becomes

$$\sum_{a|s_a=l} (\bar{y}^D_A + y^R_a + y^B_a) = \sum_{a|e_a=l} (\bar{y}^D_a + y^R_a + y^B_a), \forall l \in L.$$

In practice, the amount of flow that can pass through a hub is limited to the capacity of the hub. We assume that hub h can handle at most Q_h units of flow. Note that it is never optimal to handle flows more than once in a hub, so that the restriction of capacitated hub locations is non-restrictive if $Q_h \geq \sum_{ijs} f^R_{ijs}$. Since routes are generated, it is known if hub h is passed by a route r; this will be denoted by the parameter q_{rh} that equals 1 if route r uses hub h and is equal to 0 otherwise. The hub capacity constraint can be modelled as

$$\sum_{ijsr} (f^R_{ijs} q_{rh} x_{ijsr}) \leq Q_h, \forall h \in H.$$

The total costs are the sum of the variable hub cost and the cost of vehicles moving via the arcs of the network.

The hubs that are passed by a route are known so that the variable cost of one unit of flow using route r can be derived. This cost is denoted by C^H_r. Some express providers subcontract vehicle movements (a discussion of subcontracting can be found in Krajewska and Kopfer (2009)). As a result, repositioning vehicle movements are sometimes bought at a lower rate when subcontractors can use the movement for other purposes. Now, the total costs of the network follow as (with repositioning vehicles discounted by a factor $\gamma \leqslant 1$)

$$\sum_r (C^H_r f^R_{ijs} x_{ijsr}) + \sum_a (C_a(\overline{y}^D_a + y^R_a + \gamma y^B_a)).$$

An overview of the model and additional parameters and variables is given below. This network design model will be referred to as *NDnew*.

parameters

γ	discount factor of repositioning vehicles moving via arc a
Q_h	maximum amount of flow which can pass through hub h
q_{rh}	1 if route r uses hub h and 0 otherwise
C^H_r	variable hub cost of using route r
$\overline{y}^D_a$	number of vehicles moving via arc a to transport flows f^D_{ijs}

variables

x_{ijsr}	1 if od-pair i, j uses route r for service s, 0 otherwise
y^R_a	number of vehicles moving via arc a to transport flows f^R_{ijs}
y^B_a	number of repositioning vehicles moving via arc a

NDnew-model

$$\min \sum_{ijsr} (C^H_r f^R_{ijs} x_{ijsr}) + \sum_a (C_a(\overline{y}^D_a + y^R_a + \gamma y^B_a)) \quad (4)$$

$$\sum_r (p_{ijsr} x_{ijsr}) = 1, \quad \forall ij \in N, s \in S, f^R_{ijs} > 0 \quad (5)$$

$$\sum_{ijsr} (u_{ra} f^R_{ijs} x_{ijsr}) \leqslant v y^R_a, \quad \forall a \in A \quad (6)$$

$$\sum_{a|s_a=l} (\overline{y}^D_a + y^R_a + y^B_a) = \sum_{a|e_a=l} (\overline{y}^D_a + y^R_a + y^B_a), \quad \forall l \in L \quad (7)$$

$$\sum_{ijsr} (f^R_{ijs} q_{rh} x_{ijsr}) \leq Q_h, \quad \forall h \in H \quad (8)$$

$$x_{ijsr} \in \{0, 1\}, \quad \forall i, j \in N, s \in S, r \in R \quad (9)$$

$$y^R_a, y^B_a \geq 0 \text{ and integer}, \quad \forall a \in A. \quad (10)$$

3.2. Fleet scheduling heuristic

The network design models of Section 3.1 determine a route for each od-service i, j, s. The fleet scheduling heuristic presented in this section determines the real number of vehicles required to transport the flow and derives fleet schedules. Post-processing will determine repositioning cost once fleet schedules are created. This heuristic will be used to test relative performance of *NDtrad* and *NDnew*.

The fleet scheduling heuristic uses the following rules for vehicle departures via arc a:

- a vehicle can depart if its departure is critical for the service requirements of one of the od-services for which flow is loaded on the vehicle;
- a vehicle can depart if all flow to be transported via arc a is available;
- a vehicle can depart if it has a full vehicle load.

The heuristic uses an *event list E* of possible departures. All flow is assumed to be available at the origin node at the collection cut off time. These collection cut off times c^o_{is} are the first possible departure times that are added to the event list. The second group of possible departure times that are added are the so-called *critical departure times*. All flow has to be available at the destination node before the delivery cut off time of its corresponding service. Since the flow route x_{ijsr} of od-service i, j, s is known, the latest departure time at each arc in the route can be determined via backwards computing, by starting at the delivery cut off time taking into account transport time and sorting time. The latest departure time of od-service i, j, s at location s_a of arc a is called the critical departure time, denoted by t^{crit}_{ijsa}. The last group of events, the availability time of flow at hub locations, results from the arrival of a vehicle: flow that arrives at a hub location needs further transport and this transport is possible after sorting. The time at which arrived flow can leave the hub location is called the *availability time*; the availability time of od-service i, j, s to be further transported via arc a is denoted by t^{avail}_{ijsa}. Every time a vehicle is scheduled to depart, flow can be transported. If there is more flow available than the capacity of the vehicle, flow with the earliest critical departure time at the corresponding departure location has highest priority to use this vehicle and is transported to the next location.

The heuristic starts with the first event time e in the event list. Then it checks: (1) do there exist arcs with flow having reached a critical departure time? If there is some flow, vehicles are scheduled to depart and the flow is transported. If there is none, the next question is: (2) do there exist arcs for which all flow has arrived? If there exists such an arc, vehicles are scheduled and flows are transported to the next location. Finally, it is checked: (3) do there exist arcs at which a full vehicle can be loaded? If this is the case, a vehicle will depart and the flow will arrive at the next location. Afterwards, e is removed from the event list and the next event in the event list will be considered. The heuristic terminates when all flow has arrived at its destination node.

Note that vehicle departures are caused because of flow arrivals in step (2) and (3): in step (2), the last flow to be transported via an arc has arrived, and in step (3), flow arrives resulting in a full vehicle load. However, in step (1), a departure does not need to be instigated by the arrival of flow. It might be that some flow is waiting for other flows to arrive, but at some moment (the critical time) it can no longer wait. Then, a vehicle is scheduled to transport this flow. However, this vehicle could already leave at the moment the last flow, which will be transported by this vehicle, arrived. This time will be referred to as time e^*. Note that e^* can be the availability time of the flow that causes the critical departure, or the availability time of other flow that arrived at this arc (after the arrival of the flow causing the critical departure). The vehicle will be scheduled at time e^*, which can be earlier than the critical event time (and therefore also earlier than the current event time, i.e. $e^* < e$). If this vehicle arrives at a hub location, the flow needs further transport. Recall that this flow becomes available for further transport at time t^{avail}_{ijsa}. Now notice that it is possible that the flow becomes available before the current event time e, because the vehicle might have been scheduled before this time. Since this could impact vehicles already scheduled between t^{avail}_{ijsa} and e, these vehicle departures need to be reconsidered. Therefore, the heuristic turns back in time so that the event list restarts at $e = t^{avail}_{ijsa}$. All vehicle departures scheduled after t^{avail}_{ijsa} are cancelled and the flow will be pushed backwards accordingly. This step will be referred to as a *reset* of the event list.

An overview of the heuristic is given in Figure 6.

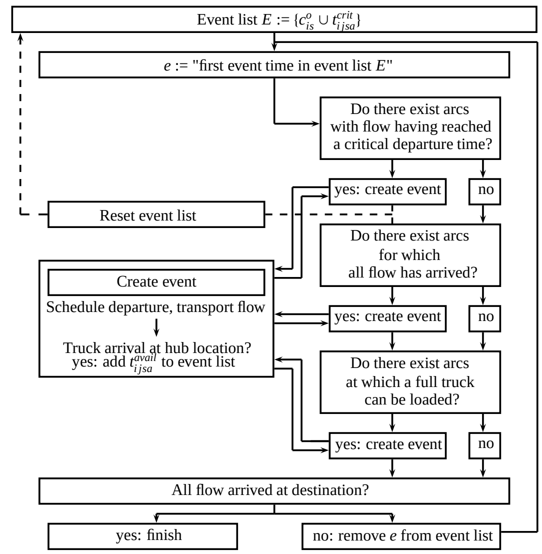

Figure 6: Fleet scheduling heuristic.

Postprocessing: Vehicle balancing

Vehicle balancing cost is not determined in the network design model *NDtrad*; the network design model *NDnew* determines vehicle balancing cost but due to tight time constraints, the real number of vehicles required to transport the flows can be higher. Therefore, vehicle balancing cost needs to be determined.

The fleet scheduling heuristic results in a number of vehicles moving via each arc; this will be denoted by $\overline{y}_a$. The required number of balancing vehicles moving via each arc (i.e. y^B_a) needs to be derived. The balancing constraint becomes

$$\sum_{a|s_a=l} (\overline{y}_a + y^B_a) = \sum_{a|e_a=l} (\overline{y}_a + y^B_a), \forall l \in L.$$

The repositioning cost needs to be minimised so that the resulting model becomes

parameters

γ	discount factor of repositioning vehicles moving via arc a
$\overline{y_a}$	number of transportation vehicles moving via arc a

variables

y^B_a	number of repositioning vehicles moving via arc a

Balancing model

$$\min \sum_a (\gamma C_a y^B_a) \tag{11}$$

$$\sum_{a|s_a=l}(\bar{y}_a + y_a^B) = \sum_{a|e_a=l}(\bar{y}_a + y_a^B), \forall l \in L \quad (12)$$

$$y_a^B \geq 0 \text{ and integer}, \forall a \in A. \quad (13)$$

3.3. Remark

Cut off times are used to determine the available time to transport flows in the network design models. However, the moment of transport is not taken into account (i.e. the possibility to combine flows in time is not checked during network design). The fleet scheduling heuristic does make this check on the possibility to combine flows in time; if flows cannot be combined, additional vehicles are required. The resulting cost after fleet scheduling are therefore in general higher than the cost found after network design, but the difference in cost depends on the routes given to the heuristic. As a result, a suboptimal solution of the network design model could give lower cost after fleet scheduling than the optimal solution of the network design model.

4. Computational study

The research was inspired by practical considerations of an express carrier. This section presents the results of the models applied to modified instance data of the express service carrier.

Data instances are created for two geographies (Geography *A* and *B*) which are inspired on actual countries. Data instances define the number and location of nodes and hubs, the cut off times and the services offered between nodes. An overview of the characteristics of the geographies can be found in Table 1. Geography *A* has 31 nodes and Geography *B* has 37 nodes; in both geographies, four hubs are available. Note that the largest distance and the average distance between od-pairs are larger in Geography *B* than in Geography *A*. There is a positive flow between each pair of nodes in Geography *B* while there are only 750 od-pairs with a positive flow in Geography *A*. In the latter, there is no flow between 180 od-pairs. However, the total flow in Geography *A* is larger than in Geography *B*.

In both geographies, two services are defined: services s_1 and s_2. In both geographies, 80% of the total flow is of service s_1 and the remaining 20% has service s_2. Parcels with an s_1-service are available at the origin node before 20:00h and have to arrive at the destination node until 07:00h in both geographies. In Geography A, s_2-parcels are available at the origin node before 21:00h and have to arrive at the destination node at 06:00h. In Geography B, s_2-parcels are available at the origin node before 20:00h and have to arrive at the destination node at 07:00h two days later. Note that s_2 is a faster service in Geography A, but a slower service in Geography B.

For both geographies, three cases are constructed varying in the demand for each service. For every geography, the total demand is the same in each case, however the geographical spread differs. The first case, *Case* 1, describes the situation in which there is equal demand for each service (i.e. f_{ijs_1} is the same for each i, j and f_{ijs_2} is the same for each i, j). *Case* 2 considers the situation with moderate fluctuations in demand for each service. Finally, *Case* 3 describes the situation with strong differences in demand for each service. The latter can be interpreted as a situation where a group of nodes represents net senders generating large flows to be transported to net receivers, while there is only small demand vice versa. In both geographies, 15 nodes are indicated as net senders and the remaining nodes are net receivers.

Balancing movements are discounted by 10% of a transport movement cost (i.e. $\gamma = 0.90$) and variable hub cost is €0.05 per kg (i.e. $C_r^H = 0.05$). Hub capacities are assumed to be non-restrictive and 60 minutes of sorting time is needed at each hub location.

Section 4.1 compares the results found by the traditional and the new network design model. Sensitivities of the new network design model are discussed in Section 4.2.

4.1. Comparison of the results

This section compares the results found by using *NDtrad*-routes or *NDnew*-routes. The *NDtrad* model will be used for benchmarking; we will therefore choose α in each case such that the *NDtrad* model gives lowest cost (considered values of α are $\alpha = 0.0, 0.2, 0.4, 0.6, 0.8$ or 1.0) to ensure a fair comparison. Of course, in practice α is input. The resulting values of α are 0.8 in all cases of Geography *A*, $\alpha = 0.00$ in *Cases B*1 and *B*2; *Case B*3 shows lowest cost when $\alpha = 0.20$. The results of *NDnew* are found by including direct routes, 1-hub routes, 2-hub routes, and 3-hub routes (i.e. we generate all feasible routes visiting respectively at most zero, one, two, or three hub locations).

Table 2 shows for each instance the results found by using *NDtrad*- or *NDnew*-routings and the percentage difference between them. The first column in the table displays the total cost; afterwards the total number of vehicle movements and the corresponding distance driven are presented. The last two columns of the table show the average number of hub touches per kg of flow, and the average hub throughput respectively. A cost

Table 1: Overview characteristics geographies.

	Geography A	Geography B
nr. of nodes	31	37
nr. of hubs	4	4
nr. of od-pairs	750	1,332
largest distance	909	1,428
average distance	372	626
total flow	750,000	350,000
$\%s_1$flow	80%	80%
$\%s_2$flow	20%	20%
$c^o_{is_1}$	day1-20:00	day1-20:00
$c^d_{is_1}$	day2-07:00	day2-07:00
$c^o_{is_2}$	day1-21:00	day1-20:00
$c^d_{is_2}$	day2-06:00	day3-07:00

breakdown in the three cost components (i.e. balancing cost, variable hub handling cost, and transport cost) is displayed in Figure 7(a). The division of flow over the kind of routes can be found in Table 3 and Figure 7(b).

Comparison of the cost shows that in all cases cost can be reduced by using the routes proposed by the new network design. On average, total cost can be reduced with 5.0% in Geography A and with 1.1% in Geography B. Recall that our new cost function includes three cost components: transport cost, variable hub cost, and balancing cost. The main cost savings are achieved by reducing variable hub cost and balancing cost: on average, 17.5% of the variable hub handling cost can be saved and 18.1% of the balancing cost can be saved. transport cost decreases in half of the cases, while it increases in cases $A1$, $B1$, and $B2$.

We see a decrease in number of vehicle movements in all cases except for *Case* $B1$. On average, we see that the total number of vehicle movements is reduced by 2.1%. The resulting total distance driven is on average reduced by 2.1%.

The changes in cost and vehicle movements are caused by changed flow routings. In general, the new routings show less hub touches. On average, the traditional model results in 18.4% of direct routes, 55.5% of 1-hub routes, and 26.1% 2-hub routes; the new model results in 25.1% direct routes, 63.0% 1-hub routes, 10.8% 2-hub routes, and 1.2% 3-hub routes (see Table 3). The resulting average number of hub touches and the average hub throughput are reduced with 17.5% when using the new network design model. Less hub routing immediately implies less hub handling cost. Balancing cost are reduced due to the inclusion of direct routes. The results of this section will be referred to as the 'base' results of the *NDnew* model.

4.2. Sensitivities NDnew-routings

This section shows the sensitivities of the results of *NDnew*-routings to kind of routes, hub capacities, variable hub cost, transport cost, and balancing cost. The results are compared based on cost and route usage. The "Cost overview"-figures that will be shown, present cost divided in transport cost, variable hub cost, and balancing cost. The "Routing overview"-figures show the percentage of flow that is routed per kind of route (i.e. direct route, 1-hub route, 2-hub routes, or 3-hub routes).

NDnew routings - Sensitivity to kind of routes

Here we show the results found by *NDnew*-routing, when varying the kind of routes. The kind of routes that can be included are direct routes, 1-hub routes, 2-hub routes, and 3-hub routes. Note that the 'base' results assume that all kind of routes may be used. The results are averages over the cases and are displayed in Figure 8.

First, only direct routes are feeded into the model. Afterwards, we expanded the set of routes with hub routes: each time we allowed one more hub touch (up to three hub touches). Additionally, cases are studied where direct routes are not possible anymore and possible hub routes are varied.

When we only allow direct routes, the cost are €712,653 which is about 2.6 times as high as the cases in which hub routes are allowed. However, note that including hub routes reduces transport cost but on the other hand leads to increasing handling cost and balancing cost. Including 2-hub routes reduces the cost with 4.7% when direct routes are allowed and with 6.2% when direct routes are not allowed. Apparently, inter-hub flow routing is profitable. However, the inclusion of 3-hub routes has only small impact: on average, 0.4% of the cost can be saved. When we compare the results of allowing direct routes to the results in which direct routes are not allowed, it can be seen that the cost on average are 1.1% higher if direct routes are forbidden. In this, transport cost remain almost at the same level but both variable hub handling cost and vehicle balancing cost show higher cost.

Concluding, hub routing leads to a large cost saving. However, in the used geographies, the cost effect of including 3-hub routes is only small when 1-hub and 2-hub routes are included. When allowing direct routings together with hub routings, cost can be further reduced due to lower handling cost and balancing cost. This implies that it is favorable to use more direct routes than in the traditional model.

NDnew routings - Sensitivity to hub capacities

This section shows the results of limiting hub capacities. Recall that the 'base' results assume non-restrictive hub capacities. The results are averages over the cases and are displayed in Figure 9.

Since maximum hub capacities are unknown, these capacities will first be derived as follows. In each case, the maximum hub capacity is derived as the maximum hub throughput found for one of the hubs in the 'base' results. We will refer to this as Q_{base}. Afterwards, fractions θ of these hub capacities are taken as bound on the maximum hub capacity, i.e. $Q_h = \theta Q_{base}$ for all hubs h. This is done for fractions $\theta = 0.20, 0.40, 0.60, 0.80$ and 1.00 of the maximum hub capacity.

It is easily understandable that cost decreases when θ increases. This is caused by decreasing transport cost. However, balancing cost and variable hub cost increase. In case only 20% of the hub capacity is available, cost are 37% higher than in the 'base' results. However, the cost level stabilizes as soon as 60% of the hub capacity is available. Apparently, the flow can be spread more evenly over the hub locations so that cost savings from consolidation can still be achieved. This can also be seen from the routings: only an additional 5.1% of the flow is routed directly in case $\theta = 0.60$ when comparing to the 'base' results.

Concluding, it can be said that there is a strong relation between hub routing and hub capacities. In particular, when hub capacities are restrictive, more direct routing is used, resulting in higher cost. However, cost stabilizes as soon as 60% of the hub capacity is available. Note that fixed hub cost is left out of consideration, although this is likely to depend on capacity.

NDnew routings - Sensitivity to variable hub cost

The sensitivity of the results is tested against varying variable hub cost C_r^H. The results are averages over the cases and are displayed in Figure 10.

First, the model is run excluding variable hub cost (i.e. $C_r^H = 0.00$). Afterwards, variable hub cost is increased to $0.05, 0.10, 0.15, 0.20, 0.25$. Compared to the 'base' results (i.e. $C_r^H = 0.05$), more flow is routed via multiple hub routes. In case variable hub cost is excluded, flows are more consolidated. Overall, there is a strong relation between variable hub cost and routing: increasing variable hub cost results in decreasing number of hub touches in flow routing. As a result, all cost components show increases as soon as C_r^H increases. When we look at the hub capacities, we see that the maximum flow passing through a hub decreases when C_r^H increases: when $C_r^H = 0.25$ the maximum flow through a hub decreases with 29.8% compared to Q_{base}.

It can be concluded that there is a strong relation between variable hub cost and flow routing: when variable hub cost increases, hub routing is less preferred. As a result, required hub capacities are strongly impacted by variable hub cost: there will be an overcapacity of 29.8% when variable hub cost increases to €0.25 (compared to €0.05).

NDnew routings - Sensitivity to transport cost

Finally, the influence of the varying transport cost C_a is investigated. Again, the results are averages over the cases and are displayed in Figure 11.

The model is run for increasing transport cost C_a. These cost are increased to $1.5C_a$, $2.0C_a$, $2.5C_a$, $3.0C_a$, and $3.5C_a$. Compared to the 'base' results (i.e. $1.0C_a$), we see that all cost components increased. It was expected that increasing transport cost would result in more hub routing, since consolidation of flows reduces the number of vehicle movements. But the results show that only a small percentage of the flow will use more hub routing: when transport cost are 3.5 times as high, direct routing decreases only with 2.8% and 1-hub routing decreases with 1.7%. That means that direct routing and 1-hub routing is still attractive even when transport cost is high. Finally note that hub capacities need to increase: when we multiply C_a with 3.5, we see an increased hub capacity of 8.3% compared to Q_{base}.

Two effects need to be taken into consideration to explain the impact of transport cost on hub routing: first, more hub routing results in higher total transport cost due to increasing variable hub cost and the detour of flow; second, more hub routing results in lower total transport cost as a result of more consolidation. Note that varying transport cost has both a positive and negative effect on the total transport cost. The results show that there is only small impact of increasing transport cost on hub routing. That indicates that the cost savings of more consolidation are only small compared to the increasing cost due the detour of flow routing and the increasing variable hub cost. As a result, direct and 1-hub routing is still profitable even when transportation cost strongly increase.

NDnew routings - Sensitivity to discounting of balancing cost

Finally, the sensitivity of the results is tested against varying discounting of balancing cost γ. In the 'base' results, it is assumed that balancing cost is discounted with 10% ($\gamma = 0.90$). The results are again averages over the cases and are displayed in Figure 12.

The results are shown for decreasing discounting of balancing cost. Considered values of γ are $0.00, 0.25, 0.50, 0.75$, and 1.00. From the cost it can be seen that cost increases when γ increases, but the largest differences are caused by increasing balancing cost. However, there is a small increase in transport cost when balancing cost increases. Besides, observe that more flow is routed directly. This can be explained as follows. Suppose some flow can be routed via a hub route, consolidated with other flows so that it does not generate additional transport cost (it only generates variable hub cost). However, due to imbalances of flow, a repositioning vehicle will be required to drive between origin node and destination node. On the other hand, the flow can be routed directly, but in that case a vehicle has to be scheduled resulting in additional transport cost. No repositioning vehicle is required in that case. It is obvious that the first option, routing via hub locations, is preferred when repositioning is (strongly) discounted; the last option is preferred otherwise.

Concluding, it can be said that there is only a small dependency between direct routing and balancing cost.

This section showed the results of applying the network design models on modified data instances of an express service carrier. The next section will state our conclusions and recommendations for further research.

5. Conclusions and directions for further research

This paper proposes a new tactical network design model for express carriers.

The model is tested on modified instance data of an express carrier. Test cases are created for two geographies, and for each such geography three test cases are generated varying in the geographical spread of demand. In each test case, cost savings can be achieved if routes proposed by the new network design are used instead of the traditional routes. The first geography shows an average cost saving of 5.0% and the second geography shows an average cost saving of 1.1%. The main cost savings are achieved by reduced variable hub cost and reduced balancing cost.

Furthermore, the sensitivity analyses showed that the cost is 2.6 times as low when consolidation is used to transport flows compared to only direct driving. These savings can still be achieved even when only 60% of the hub capacity is available. Of all cost components, variable hub cost influences hub routing the most: increasing variable hub cost leads to a strong decreasing hub routing. Higher balancing cost leads only to a small increase in direct routing; higher transport cost results in a small increase in (multiple) hub routing.

This article showed cost reductions by including fleet scheduling characteristics in the tactical network design of express service carriers. The models are tested on modified instance data of two geographies. The results of the geographies differ; it should be further investigated how characteristics of a geography affect the routings. Final fleet schedules are derived after flow routing. Further cost reductions are expected if fleet schedules and flow routings are determined simultaneously. This article focused on the tactical network design of express carriers. More research needs to be done to show the impact of fleet scheduling on the strategic network design of express carriers.

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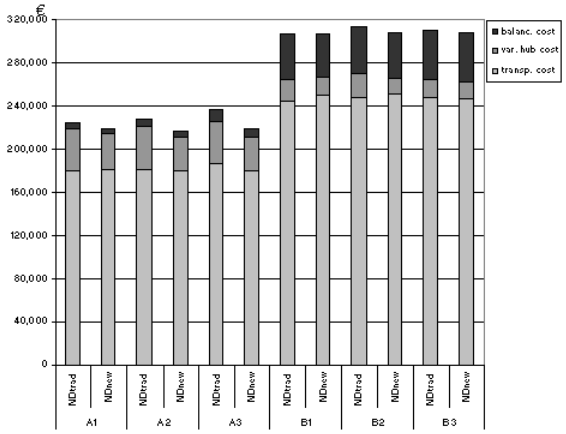
Table 2: Results comparison: cost overview.

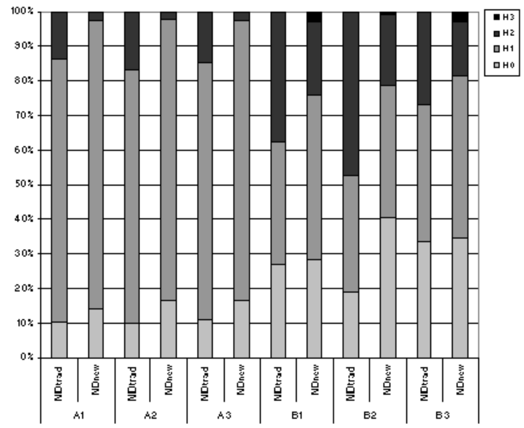
	Tot. Cost (*euro*)	Tot. nr. Mov.	Tot. Distance (*kms*)	Avg. nr. Hub Touches per KG	Avg. Hub Throughput
CaseA1 - NDtrad	224,636	359	155,511	1.03	193,406
CaseA1 - NDnew	219,307	350	155,425	0.89	166,632
CaseA1 - difference	**-2.4**%	**-2.5**%	**-0.1**%	**-13.8**%	**-13.8**%
CaseA2 - NDtrad	228,519	368	157,661	1.07	200,490
CaseA2 - NDnew	216,042	353	153,637	0.86	160,534
CaseA2 - difference	**-5.5**%	**-4.1**%	**-2.6**%	**-19.9**%	**-19.9**%
CaseA3 - NDtrad	236,317	392	165,476	1.04	194,508
CaseA3 - NDnew	219,351	363	156,540	0.86	161,651
CaseA3 - difference	**-7.2**%	**-7.4**%	**-5.4**%	**-16.9**%	**-16.9**%
CaseB1 - NDtrad	307,510	582	292,951	1.11	96,772
CaseB1 - NDnew	306,751	596	293,830	0.99	86,367
CaseB1 - difference	**-0.2**%	**2.4**%	**0.3**%	**-10.8**%	**-10.8**%
CaseB2 - NDtrad	314,175	606	296,546	1.28	112,322
CaseB2 - NDnew	308,065	599	298,396	0.82	71,541
CaseB2 - difference	**-1.9**%	**-1.2**%	**0.6**%	**-36.3**%	**-36.3**%
CaseB3 - NDtrad	310,906	597	299,770	0.93	81,586
CaseB3 - NDnew	307,796	596	297,650	0.87	75,872
CaseB3 - difference	**-1.0**%	**-0.2**%	**-0.7**%	**-7.0**%	**-7.0**%
CaseGeography A - difference	**-5.0**%	**-4.7**%	**-2.7**%	**-16.9**%	**-16.9**%
CaseGeography B - difference	**-1.1**%	**0.4**%	**0.1**%	**-18.0**%	**-18.0**%
CaseOverall - difference	**-3.0**%	**-2.1**%	**-1.3**%	**-17.5**%	**-17.5**%

Table 3: Results comparison: routing overview.

	H0 (%)	H1 (%)	H2 (%)	H3 (%)
NDtrad - average	18.4	55.5	26.1	0.0
NDnew - average	25.1	63.0	10.8	1.2

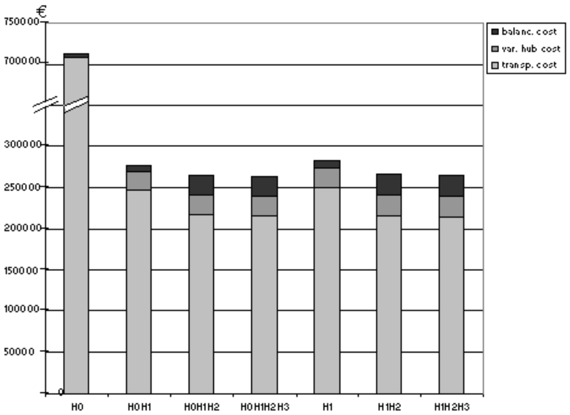


(a) Cost overview.

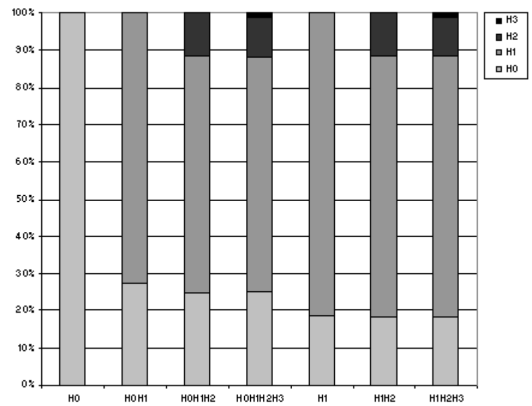


(b) Routing overview.

Figure 7: Results comparison *NDtrad*-routes and *NDnew*-routes.

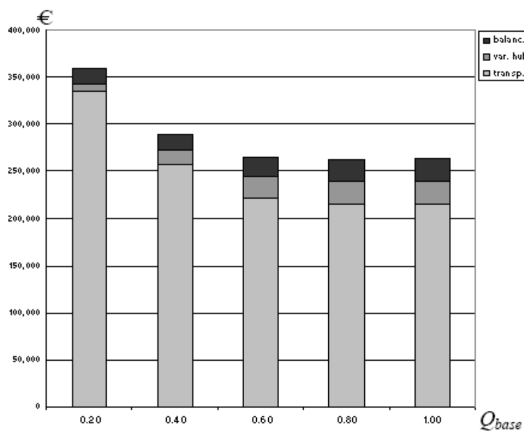


(a) Cost overview.

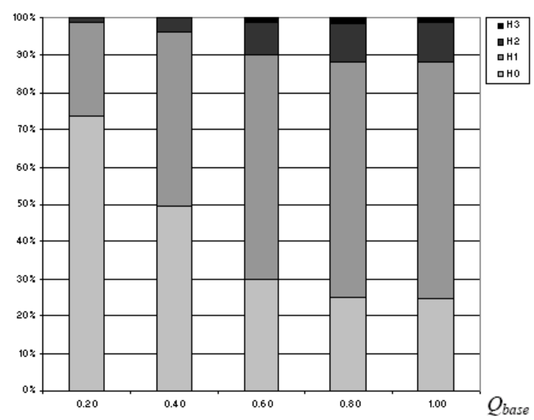


(b) Routing overview.

Figure 8: Results *NDnew* - Sensitivity kind of routes.



(a) Cost overview.



(b) Routing overview.

Figure 9: Results *NDnew* - Sensitivity hub capacities.

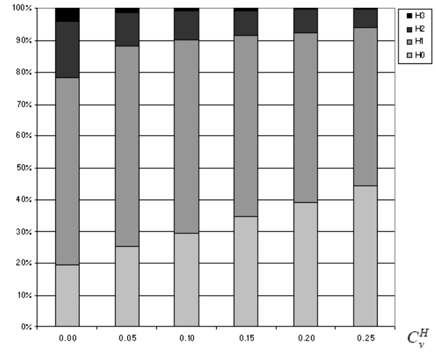


Figure 10: Results *NDnew* - Sensitivity variable hub cost.

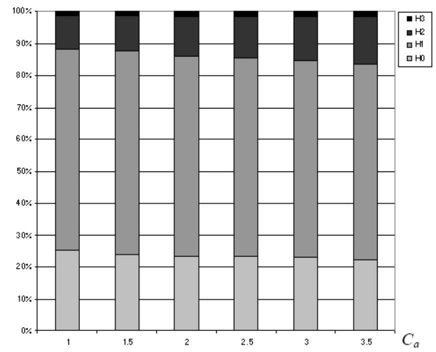


Figure 11: Results *NDnew* - Sensitivity transport cost.

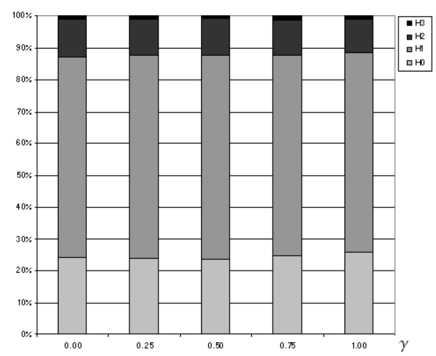


Figure 12: Results *NDnew* - Sensitivity discounting of balancing cost.