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Integrating passenger and freight transportation: Model formulation and insights

Veaceslav Ghilas, Emrah Demir and Tom Van Woensel

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Integrating passenger and freight transportation:  
Model formulation and insights

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Abstract
Integrating passenger and freight flows creates attractive business opportunities because the same transportation needs can be met with fewer vehicles and emissions. This paper seeks an integrated solution for the transportation of passenger and freight simultaneously, so that fewer vehicles are required. The newly introduced problem concerns scheduling a set of vehicles to serve the requests such that a part of the journey can be carried out on a scheduled passenger transportation service. We propose an arc-based mixed integer programming formulation for the integrated transportation system. Computational results on a set of instances provide a clear understanding on the benefits of integrating passenger and freight transportation in the current networks, considering multi-modality of traditional passenger-oriented transportation modes, such as taxi, bus, train or tram.

Keywords: Integrated passenger and parcel transport networks, routing & scheduling, multi-modal transportation, pickup and delivery problems.

1. Introduction

A successful integration of passenger and freight transportation creates a seamless movement for the people and parcels. This integration achieves socially desirable transport options economically viable in urban areas as it reduces congestion and air pollution. Actual integration is being already observed in long-haul freight transportation: passenger aircrafts and ferries, such as Norwegian Hurtigruten carry freight and people at the same time (Levin et al., 2012; Hurtigruten, 2013). In short-haul transportation, however, people and freight rarely share transportation modes although they largely share the same infrastructure, indicating the potential efficiency gains for an integrated approach (Lindholm and Behrends, 2012). To our knowledge, an integrated transport solution to short-haul transportation has not been sufficiently taken into consideration in the literature.

In this paper, we propose novel conceptual and mathematical models for the integrated transport solution of passenger and freight transportation networks. Note that this integrated
solution has various potentials for regions with shrinking population sizes as well. Usage of public transport in these areas has significantly decreased (Santos et al., 2010) and delivery routes to individual consumers and retailers consist of fewer stops over longer distances (Harms et al., 2010). Integrating passenger and freight transport increases the capacity utilization and gives opportunity to public transportation companies. Various stakeholders (e.g., public transport companies, shippers, etc.) are consulted and actively participate in this line of research, highlighting the potential benefits for real-life applications.

This paper particularly investigates the opportunity to make use of available public transportation as a part of the freight journey, which operates according to predetermined routes and schedules. Generally during off-peak hours, the capacity utilization of fixed scheduled line (FSL) vehicles is relatively low. Transferring freight requests to fixed scheduled lines could then be beneficial for the whole transportation system. Therefore, such a request can be picked up by a pickup and delivery (PD) vehicle and transported to a station-hub, which is assumed to be located nearby. From there, the request continues its journey on a scheduled public transportation system. Afterwards, the same request can be picked up again by another PD vehicle to be delivered to its destination point.

A successful synchronization of PD vehicles with scheduled public transportation is directly related to both coordination (timing) and consolidation (volume). The coordination is the key factor that makes each leg’s movement precise, well-timed, and well organized. The latter one is also required to make a whole system more efficient. In order to minimize the number of individual packages handled at the station-hubs, bundling of parcel requests should be considered. In this sense, each station-hub can be seen as a consolidation point for packages. Specifically, we consider an extension of the pick-up and delivery problem with time windows in which transfers of any request to a fixed line is permitted. A part of the request’s journey can thus be carried out on a public scheduled transportation. In addition, two types of requests are considered: passengers and packages. These two types of requests should be treated differently according to their specific customer requirements. For example, a total trip time of a passenger request is usually more crucial, whereas packages can be more flexible. In the proximity of each station-hub, both direct and indirect flows are considered. Direct flows represent cases where a request uses only door-to-door transportation (by using a PD vehicle). The latter represents a situation where a request is transported by a fixed line as a part of the total trip. In this paper, we denote this specific transportation problem as Pickup and Delivery Problem with Fixed Scheduled Lines (PDP-FSL). A schematic overview of the considered network is shown in Figure 1.

Assume a request has its pick-up and destination points close to two different station-hubs (e.g., requests in Figure 1). It would make sense to use a fixed line service that connects these two transfer points, instead of using one PD vehicle. Hence, a reasonably less travel time of PD vehicles can be expected and consequently reduction can be achieved in operating costs, the level of congestion and the amount of \( CO_2 \) emissions.

The contributions of this paper are the following: (i) we introduce a mixed-integer formulation for the PDP-FSL, (ii) we analyze the benefits of using fixed scheduled lines in a PD environment by comparing and testing different coordination scenarios amongst various actors.

The remainder of the paper is structured as follows. Section 2 provides a brief review of the existing works. Section 3 presents an illustrative example for the proposed environment. Section 4 formally introduces a mixed-integer programming formulation of the PDP-FSL. Section 5 presents three families of valid inequalities for the proposed model. Section 6 reports the
Section 2 presents simulated coordination and cooperation scenarios. Conclusions are stated in Section 8.

2. Literature review

This section reviews pick-up and delivery problems (PDPs), dial-a-ride problems (DARPs) and ride-sharing problems. To the best of our knowledge, a limited literature exists on the problem discussed in this paper, particularly on transfer options to fixed line services. Moreover, a research on integration of passenger and freight transportation systems is quite new. Thus, our paper is one of the first attempts to investigate integrated passenger and freight transportation from an operational level of planning perspective.

We refer to Berbeglia et al. (2007) for a survey on the solution methodologies for static PDPs, where static planning concerns the environment with all the information assumed to be known in advance. The authors describe three main groups of the PDPs based on origins and destinations of the requests. The first group, many-to-many, is characterized by the fact that each commodity is associated with several origins and destinations. The second group, one-to-many-to-one, is characterized by some requests that need to be transported to the depot and others originate from the depot. Finally, the last group, one-to-one, considers each request is described by one origin and one destination point (see, for example, Qu and Bard (2012)). In a related work of Berbeglia et al. (2010), dynamic one-to-one PDPs are reviewed. The authors focus on the dynamic nature of the problems, meaning that some of the information is revealed over time.

A special case of PDPs where users need to be transported from their origin to their destination is called a dial-a-ride problem (DARP). The transportation of elderly and disabled people can be seen as a main application area of the DARP. More extensive information related to the DARP can be found in Cordeau and Laporte (2007). The authors provide an overview on models and solution methodologies for single as well as multiple vehicles. Parragh (2010) investigated heterogeneity in vehicles and passengers along with waiting time of passengers in the context of DARP. Branch & Cut (B & C) and variable neighborhood search algorithms are
proposed to solve the DARP. Computational results show that a reasonable reduction in total waiting times are possible without increasing the total operating costs by more than 6%.

One of the PDP extensions considers transfer opportunity between PD vehicles at station-hubs (PDP-T). Hence, a request can be picked up by one vehicle and delivered by another one. Shang and Cuff (1996) is one of the earliest studies on PDP with transfers in health sector, with a special focus on patients’ records transportation. The authors propose an insertion heuristic algorithm which lead to an improvement of up to 37%, compared to the manual plans. Cortes et al. (2010) proposed an exact decomposition method, namely B & C for solving PDP-T. Their proposed algorithm proved savings of up to 90% in terms of CPU time, compared to traditional Branch & Bound (B & B). In another work, Masson et al. (2012) introduced an adaptive large neighborhood search (ALNS) to solve the PDP-T. Their results proved savings of up to 9% in terms of travel time by using intermediate transfers. In addition, Masson et al. (2014) proposed an ALNS for the dial-a-ride problem with transfers (DARPT), with transfer-node-related neighborhoods. They argued that using transfers between vehicles may lead to significant savings in terms of operating costs, specifically up to 8%.

Public transportation vehicles operate strictly according to fixed routes and timetables. An integration of PDP with such transportation systems has been studied to some extent. One of the first attempts to integrate fixed line services with DARP was done by Liaw et al. (1996). The authors formulate the problem where transshipments to public scheduled transportation are allowed for passengers and wheel-chaired persons and proposed two types of heuristics: online and offline. Their computational results show that improvements of up to 9% in terms of number of serviced requests can be obtained using static planning and up to 7% with the help of online decision support, compared to manual plans. Hall et al. (2009) introduced a mixed-integer program to solve an integrated dial-a-ride problem (IDARP). The authors consider transfers to fixed lines without modeling the schedule of the public transportation. Trentini et al. (2012) investigated a two-echelon VRP with transshipments in the context of passenger and freight integrated system. The authors propose to use public transportation to ship the goods from a central distribution center to predefined stations (transshipment points). From there, a number of tricycles are used to deliver products to their final destinations. The authors propose ALNS along with MIP formulation for the solution. Based on their results, proposed system proved the use of tricycles instead of trucks to serve the customers, hence be more environmentally friendly.

Ride-sharing (pooling) is another concept used in passenger transportation to improve transport’s efficiency (Cepolina and Farina, 2012). Deakin et al. (2010) investigated a case of Berkeley, California in ride-sharing under different circumstances. The authors conducted a statistical analysis on the data obtained from surveys. Their results suggest that ride-sharing is an attractive option for people living in Berkeley. In a work of Agatz et al. (2012), the authors investigated the dynamic aspects of the ride-sharing such that a part of information is known in advance. They showed the challenges in developing decision support systems for such environments, as well as the potential societal and environmental benefits. Li et al. (2013) proposed a model which considers integrated package and passenger transportation in the context of DARP. The computational results show that customer satisfaction and number of served parcels are in a trade-off. According to their results, a taxi-sharing option proved to be promising in terms of cost benefits for urban areas.

Tretinni and Mahlene (2010) studied an overview of solutions for combining freight and passenger transportation used in practice. The authors divide solutions in three categories:
shared road capacities (multi-use lanes, night deliveries, etc.), shared public transport services (buses, subway, etc.) and finally shared consolidation facilities (delivery bays, lockers, etc.).

Table 1 provides an overview of the related literature. Note that all papers consider time windows.

Table 1
Overview of related literature

<table>
<thead>
<tr>
<th>Research</th>
<th>Multi-depots</th>
<th>Heterogeneous fleet</th>
<th>Transfers among vehicles</th>
<th>Transfers to fixed lines</th>
<th>More types</th>
<th>Dynamics</th>
<th>Solution approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shang and Cuff (1996)</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Heuristics</td>
</tr>
<tr>
<td>Cortes et al. (2010)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td></td>
<td>-</td>
<td>B&amp;C</td>
</tr>
<tr>
<td>Masson et al. (2012)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>ALNS</td>
</tr>
<tr>
<td>Masson et al. (2014)</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>-</td>
<td>ALNS</td>
</tr>
<tr>
<td>Liaw et al. (1996)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>Heuristics</td>
</tr>
<tr>
<td>Hall et al. (2009)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>-</td>
<td>B&amp;B</td>
</tr>
<tr>
<td>Trentini et al. (2012)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>-</td>
<td>ALNS</td>
</tr>
<tr>
<td>Li et al. (2013)</td>
<td>✓</td>
<td>-</td>
<td></td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>B&amp;B</td>
</tr>
<tr>
<td>This paper</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>B&amp;B</td>
</tr>
</tbody>
</table>

3. dynamic aspects of the problem considered, 4. no schedule of the fixed lines is considered, 5. schedule of the fixed lines is considered, 6. different types of requests considered. “✓” the aspect is considered, “-” the aspect is not considered.

3. An illustrative example

Consider a 6-node network (see Figure 2) with a length of each arc shown (in kilometers). We assume two depots ($g_1$ and $g_2$) are operated with one PD vehicle each. Moreover, we consider one request with its origin $o$ and destination $d$. Time windows at every node are neglected in this example, along with a schedule of the fixed line ($T_1$ – $T_2$). Thus, we assume a request is transported by fixed line services as soon as it arrives to a station-hub ($T_1$ or $T_2$). In this example, our objective is to minimize the total traveled distance by all PD vehicles.

In a standard PDP, there are two optimal routes shown in the first row of the Table 2. An optimal solution using PDP-FSL would be the one shown in row PDP-FSL. Basically, both PD vehicles are used such that one picks up the request and transfers it to a fixed line and the second PD vehicle picks the request from the end of the fixed line and delivers it to its destination. The request flows as follows ($o$, $T_1$, $T_2$, $d$), such that first part of the journey ($o$, $T_1$) is carried by a PD vehicle, then fixed line between $T_1$ and $T_2$, and finally another PD vehicle completes the route ending at $d$.

Table 2 shows that using fixed lines yields an outcome of up to 16.6% savings in terms of total traveled distance (100 km), compared to the original PDP (120 km). In addition, savings
Table 2
Solutions to PDP and PDP-FSL

<table>
<thead>
<tr>
<th>Problem</th>
<th>Route</th>
<th>Distance</th>
<th>CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDP</td>
<td>([g_1 - a - d - g_1]) or</td>
<td>120</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td>([g_2 - a - d - g_2])</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDP-FSL</td>
<td>([g_1 - a - T_1 - g_1]) and</td>
<td>100</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>([g_2 - T_2 - d - g_2])</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

of 9.89% with regards to CO₂ emissions are achieved, where PD vehicles are considered to be taxis. Used CO₂ factors are obtained from Milieubarometer (2011).

Note that in the aforementioned example, PDP-FSL solution leads to more used vehicles than as in PDP solution. This is explained by fact that only one request is considered, where specifically no integration takes place. For cases with more than one request (of both types), the number of used PD vehicles in PDP solution can be used as an upper bound for the number of used PD vehicles in the PDP-FSL.

4. Mathematical model for the PDP-FSL

In this section, we introduce a mixed-integer programming formulation for the PDP-FSL. In this environment, all information (demands, travel time, etc.) is assumed to be known in advance. Thus, an initial plan for the whole planning horizon (e.g., one day) is generated. There are two types of requests, namely passenger and package requests. A solution to our model is a routing plan for the PD vehicles, such that each request is served. Additionally, a time schedule for the PD vehicles and requests to be served is produced. The objective function is the total operating costs. These include: (i) operating costs of the PD vehicles, and (ii) the number of bundles of package requests carried out by fixed line services. First, we describe used definitions and assumptions and afterwards we introduce the PDP-FSL model.

4.1. Definitions and assumptions

Request. A request \(r\) has an origin, \(o_r\), and a destination, \(d_r\). Each request is associated with two desired time windows: one for the origin \((l_{o_r}, u_{o_r})\), and one for the delivery point \((l_{d_r}, u_{d_r})\). A set of all requests is given by \(\mathcal{P}\), such that request \((r)\), has destination node \((r + n)\), where \(n\) is the number of requests. Moreover, two types of requests are considered: passengers and packages, such that \(\mathcal{P}\) is composed of \(\mathcal{P}^1\) - a subset of passenger requests and \(\mathcal{P}^2\) - a subset of package requests \((\mathcal{P}^1 \cup \mathcal{P}^2 \equiv \mathcal{P}\) and \(\mathcal{P}^1 \cap \mathcal{P}^2 \equiv \emptyset\)). Furthermore, demand quantity \((h_r)\) is known for each request.

Vehicle. A set of vehicles is given by \(\mathcal{V}\). In addition, each vehicle \(v\) has the information of passenger carrying capacity \((e_1^v)\), parcel capacity \((e_2^v)\) and its origin \((g_v)\).

Travel and service time. Travel and service times are known before-hand and remain unchanged during a planning horizon. The travel time between nodes \(i\) and \(j\) is denoted by \(c_{ij}\) and service time at node \(i\) is represented as \(s_i\).

Fixed line. A set of all physical fixed lines is given as \(\mathcal{E}\), which is defined by the arc between start and end of the line \((i, j)\). In addition, each fixed line has a set of departure times \(\mathcal{K}_{ij}^w\) from \(i\) (the start of fixed line), such that departure is given as \(p_{ij}^w\), \(\forall w \in \mathcal{K}_{ij}^w\), \((i, j) \in \mathcal{E}\). Note that each fixed line may have different frequencies than other lines, thus a size of the \(\mathcal{K}_{ij}^w\) may differ. Furthermore, it is assumed that FSL vehicles are designed to carry a limited amount of packages, thus implying a finite carrying capacity \(k_{ij}\), \(\forall (i, j) \in \mathcal{E}\).
Note that each station-hub is considered as a coordination and consolidation point for packages (e.g., DHL-Packstation (2013)). In other words, a storage space for packages that need to be shipped on a fixed line is available. Packages can be stored until their departure time at these stations. In addition, some passengers transferred to/from a fixed line may wait a reasonable time at a station-hub.

We define a digraph $G = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ represents a set of nodes and $\mathcal{A}$ represents a set of arcs. A small example of a fixed line with two requests ($r_a$ and $r_b$) is given in Figure 3. Each physical station-hub (nodes 1 and 2 in Figure 3a) is replicated $n$ times ($n$ - the number of requests) as in Hall et al. (2009). As such, a number of decision variables is increased. This is the cost for modeling multiple visits and waiting times of the PD vehicles at the transfer locations. As in this example there are only two requests, two copies of the original fixed line are made (see Figure 3b). Each replicated fixed line is assigned to one request, and only that request can travel on that specific fixed line. This is done to keep the number of decision variables reasonable (see Section 4.3).

![Figure 3](image_url)

Figure 3 An illustration of a replicated fixed line

Now consider the same example and assume two parcel requests $r_a$ and $r_b$ using a fixed line (1, 2). As explained earlier, original fixed line (1, 2) is replicated twice for each request, thus virtual fixed lines (1a, 2a) for $r_a$ and (1b, 2b) for $r_b$ are generated. It is assumed that two requests depart at time $T$ from 1a and 1b, respectively, on the replicated arcs. Hence, a bundle of parcels will be shipped together on the (original) fixed line (1, 2) at time $T$.

If requests cannot depart on the fixed line at the same time (due to time windows constraints), $r_a$ and $r_b$ may be shipped at different times (e.g., $T$ and $T_1$). Hence, two bundles (made of one package each) may be shipped on the (original) fixed line (1, 2) at times $T$ and $T_1$, respectively.

Note that the proposed model is not limited to one fixed line only (e.g., (1, 2) and (2, 1)). Different topologies may be considered, such as square, triangle, star networks. Furthermore, the requests are allowed to be shipped from a fixed line to the next line. The additional parameters used in our model are given in Table 3.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>Number of depots</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Number of replicated station-hubs</td>
</tr>
</tbody>
</table>
\[ f_i^r \begin{cases} 1 & \text{if node } i \text{ is destination node of request } r, \\ 0 & \text{if node } i \text{ is intermediate node}, \\ -1 & \text{if node } i \text{ is the origin of } r. \end{cases} \]

\( \theta_r \) Maximum ride time of the passenger \( r \)

\( \phi \) Weight in the objective function of PDP routing

\( \eta \) Weight in the objective function of the number of parcel bundles sent on fixed lines

Using the aforementioned parameters, sets can be represented as in Table 4.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{P} )</td>
<td>Set of pick-up nodes, ( \mathcal{P} \equiv [d + 1, \ldots, d + n] )</td>
</tr>
<tr>
<td>( \mathcal{D} )</td>
<td>Set of drop-off nodes, ( \mathcal{D} \equiv [d + n + 1, \ldots, d + 2n] )</td>
</tr>
<tr>
<td>( \mathcal{Q} )</td>
<td>Set of depots, ( \mathcal{Q} \equiv [1, \ldots, d] )</td>
</tr>
<tr>
<td>( \mathcal{T} )</td>
<td>Set of transfer nodes (station-hubs), ( \mathcal{T} \equiv [d + 2n + 1, \cdot \cdot \cdot, d + 2n + n\tau] ) (see nodes 1a, 1b, 2a and 2b in Figure 3b)</td>
</tr>
<tr>
<td>( \mathcal{N} )</td>
<td>Set of nodes in the graph ( \mathcal{G} ); ( \mathcal{P} \cup \mathcal{D} \cup \mathcal{Q} \cup \mathcal{T} \equiv \mathcal{N} )</td>
</tr>
<tr>
<td>( \mathcal{O}^t )</td>
<td>Set of replicated transfer nodes associated with transfer node ( t ) (e.g., in Figure 3b, ( \mathcal{O}^{2a} = {2b}, \mathcal{O}^{1a} = {1b}, \text{etc.}) )</td>
</tr>
<tr>
<td>( \mathcal{R}^1 )</td>
<td>Set of nodes which represents requests ( (\mathcal{P} \cup \mathcal{D}) )</td>
</tr>
<tr>
<td>( \mathcal{R}^2 )</td>
<td>Set of nodes which represents requests and depots ( (\mathcal{P} \cup \mathcal{D} \cup \mathcal{Q}) )</td>
</tr>
<tr>
<td>( \mathcal{R}^3 )</td>
<td>Set of nodes which represents requests and station-hubs ( (\mathcal{P} \cup \mathcal{D} \cup \mathcal{T}) )</td>
</tr>
<tr>
<td>( \mathcal{A}^1 )</td>
<td>Set of arcs ( (i, j) ) in ( \mathcal{G} ), ( \forall i, j \in \mathcal{R}^1 )</td>
</tr>
<tr>
<td>( \mathcal{A}^2 )</td>
<td>Set of arcs ( (i, j) ) in ( \mathcal{G} ), ( \forall i \in \mathcal{R}^1 ) and ( \forall j \in \mathcal{T} )</td>
</tr>
<tr>
<td>( \mathcal{A}^3 )</td>
<td>Set of arcs ( (i, j) ) in ( \mathcal{G} ), ( \forall i \in \mathcal{T} ) and ( \forall j \in \mathcal{R}^1 )</td>
</tr>
<tr>
<td>( \mathcal{A}^4 )</td>
<td>Set of arcs ( (i, j) ) in ( \mathcal{G} ), ( \forall i \in \mathcal{T} ) and ( \forall j \in \mathcal{O}^t )</td>
</tr>
<tr>
<td>( \mathcal{A}^5 )</td>
<td>( \equiv \mathcal{A}^1 \cup \mathcal{A}^2 \cup \mathcal{A}^3 \cup \mathcal{A}^4 )</td>
</tr>
<tr>
<td>( \mathcal{A} )</td>
<td>Set of arcs in ( \mathcal{G} ) defined by arc ( (i, j) ), ( \forall i, j \in \mathcal{N} ), (note that ( \mathcal{A} \setminus \mathcal{A}^5 \equiv \mathcal{F} \cup \mathcal{U}<em>{(i, j) \in \mathcal{R}^1} \cup \mathcal{U}</em>{(i, j) \in \mathcal{Q}}(i, j))</td>
</tr>
<tr>
<td>( \mathcal{F}^r )</td>
<td>Set of replicated fixed lines which is defined as ( (i, j) ), with associated ( \mathcal{L}^{ij} )</td>
</tr>
<tr>
<td>( \mathcal{L}^{ij} )</td>
<td>Set of departure times from replicated station-hub ( i ) on fixed line ( (i, j) \in \mathcal{F} )</td>
</tr>
<tr>
<td>( \mathcal{F}^t )</td>
<td>Set of replicated fixed lines associated to a request ( r ) (e.g., in Figure 3, ( \mathcal{F}^a = {(1a, 2a), (1b, 2b)}, \text{etc.})</td>
</tr>
<tr>
<td>( \mathcal{F}^i )</td>
<td>Set of replicated fixed lines connected to a station-hub ( t ) (e.g., in Figure 3, ( \mathcal{F}^{1a} = {(1a, 2a), (2a, 1a)}, \text{etc.})</td>
</tr>
</tbody>
</table>
| \( \mathcal{F}^{ij} \) | Set of replicated fixed lines associated with a physical fixed line \( (i, j) \in \mathcal{E} \) (e.g., in Figure 3, \( \mathcal{F}^{1,2} = \{(1a, 2a), (1b, 2b)\}, \mathcal{F}^{2,1} = \{(2a, 1a), (2b, 1b)\} \)

The decision variables used to handle routing and scheduling of the PD vehicles, along with the flow and the timing of the requests are given in Table 5.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{ij}^v )</td>
<td>A binary variable equal to 1 if arc ( (i, j) ) is used by PD vehicle ( v ), 0 otherwise, ( \forall (i, j) \in \mathcal{A}, v \in \mathcal{V} )</td>
</tr>
<tr>
<td>( \alpha_v )</td>
<td>A continuous variable which shows a time at which vehicle ( v ) returns to its depot, ( \forall v \in \mathcal{V} )</td>
</tr>
<tr>
<td>( \beta_i )</td>
<td>A continuous variable which shows a departure time of a vehicle from node ( i ), ( \forall i \in \mathcal{N} )</td>
</tr>
</tbody>
</table>
| \( y_{ij}^r \) | A binary variable equal to 1 if arc \( (i, j) \) is used by request \( r \),
4.2. Mathematical formulation

The PDP-FSL can be formalized as the following mixed-integer formulation:

\[
\min \phi \sum_{(i,j) \in A} \sum_{v \in V} c_{ij} x_{ij}^v + \eta \sum_{(i,j) \in E} \sum_{w \in \mathcal{K}^{ij}} z_{ij}^w
\]

Term (1) minimizes the total traveled time of the PD vehicles and the number of bundles of parcel requests sent on the fixed lines.

subject to

**Routing and flow constraints**

\[
\sum_{i \in \mathcal{N}} \sum_{v \in V} x_{ij}^v = 1 \quad \forall j \in \mathcal{R}^1
\]

\[
\sum_{i \in \mathcal{R}^3} x_{g,v,i}^v \leq 1 \quad \forall v \in \mathcal{V}
\]

\[
\sum_{i \in \mathcal{N}} \sum_{v \in V} x_{it}^v \leq 1 \quad \forall t \in \mathcal{T}
\]

\[
\sum_{j \in \mathcal{N}} x_{ij}^v - \sum_{j \in \mathcal{N}} x_{ji}^v = 0 \quad \forall i \in \mathcal{N}, v \in \mathcal{V}
\]

\[
\sum_{r \in \mathcal{P}} y_{ij}^r - \sum_{r \in \mathcal{R}^3} y_{ji}^r = f_i^r \quad \forall r \in \mathcal{P}, i \in \mathcal{R}^3
\]

\[
\sum_{i \in \mathcal{N}} \sum_{v \in V} x_{it}^v \leq \sum_{r \in \mathcal{P}} \sum_{(i,j) \in \mathcal{F}^t} y_{ij}^r \quad \forall t \in \mathcal{T}
\]

\[
\sum_{r \in \mathcal{P}^1} h_r y_{ij}^r \leq \sum_{v \in \mathcal{V}} e_{ij}^1 x_{ij}^v \quad \forall (i, j) \in \mathcal{A}^5
\]

In the first block of constraints, constraints (2) assure that all nodes related to the requests (pick-up and drop-off nodes) are visited exactly once. Constraints (3) make sure that each vehicle leaves its depot at most once and (4) assure that each transfer node is visited only once. Flow conservation for PD vehicles is considered in constraints (5). Constraints (6) assure flow conservation for the paths of each request. Constraints (7) assure that if a request uses a fixed line, a PD vehicle should pick it up/drop it off at a station-hub related to that specific fixed
line. Constraints (8) and (9) force the capacity of each PD vehicle is not exceeded for both types of requests.

The scheduling constraints

\[
\gamma_i^r \geq \gamma_i^r + c_{ij} + s_j - M_i^{ij}(1 - y_{ij}^r) \quad \forall r \in \mathcal{P}, i, j \in \mathcal{R}^3 \tag{10}
\]

\[
\beta_j \geq \beta_i + c_{ij} + s_j - M_i^{ij}(1 - \sum_{v \in \mathcal{V}} x_{ij}^v) \quad \forall i \in \mathcal{N}, j \in \mathcal{R}^3 \tag{11}
\]

\[
\alpha_v \geq \beta_i + c_{ij} + s_j - M_i^{ij}(1 - x_{ij}^v) \quad \forall v \in \mathcal{V}, j \in \mathcal{Q}, v \in \mathcal{V} \tag{12}
\]

\[
\beta_i + c_{i,i+n} + s_{i+n} \leq \beta_{i+n} \quad \forall i \in \mathcal{P} \tag{13}
\]

\[
l_i \leq \beta_i - s_i \leq u_i \quad \forall i \in \mathcal{R}^1 \tag{14}
\]

\[
l_{g_v} \leq \alpha_v - s_{g_v} \leq u_{g_v} \quad \forall v \in \mathcal{V} \tag{15}
\]

\[
\sum_{w \in \mathcal{L}^{ij}} q_{ij}^{rw} = y_{ij}^r \quad \forall r \in \mathcal{P}, (i, j) \in \mathcal{F}^r \tag{16}
\]

\[
\gamma_i^r - p_{ij}^w \leq M_i^{ij}(2 - q_{ij}^{rw} - y_{ij}^r) \quad \forall r \in \mathcal{P}, (i, j) \in \mathcal{F}^r, w \in \mathcal{L}^{ij} \tag{17}
\]

\[
\gamma_i^r - p_{ij}^w \geq -M_i^{ij}(2 - q_{ij}^{rw} - y_{ij}^r) \quad \forall r \in \mathcal{P}, (i, j) \in \mathcal{F}^r, w \in \mathcal{L}^{ij} \tag{18}
\]

\[
\sum_{r \in \mathcal{P}^2} \sum_{(a,b) \in \mathcal{F}^{ij}} q_{ab}^{rw} \leq k_{ij} \quad \forall (i, j) \in \mathcal{E}, w \in \mathcal{K}^{ij} \tag{19}
\]

\[
\gamma_{r+n}^r - \gamma_r^r \leq \theta_r \quad \forall r \in \mathcal{P}^1 \tag{20}
\]

Timing for each request is considered in constraints (10). Similarly for PD vehicles, scheduling is updated in constraints (11) and (12). Constraints (13) assure that pick-up node is visited before drop-off nodes of each request and (14), (15) force the time windows to be respected. Constraints (16) – (18) assure that if a request uses a fixed line, it departs at a scheduled departure time. Constraints (19) update the variable which states whether a parcel request is sent by fixed lines or not and make sure that the package carrying capacity on the fixed line is not exceeded. Constraints (20) assure that maximum ride constraint for passenger requests is not violated. \(\theta_r\) is assumed to be dependent on the direct trip time for each passenger request \((s_r + c_r + s_{r+n} + s_{r+n})\) multiplied by a factor \(\sigma \geq 1\). \(M_i^{ij}\) can be substituted by \((u_i + s_i + s_j + c_{ij})\) and \((u_i + s_i)\) can be used instead of \(M_i^2\).

The synchronization constraints

\[
\gamma_i^r - \beta_i \leq M_2^i(1 - \sum_{j \in \mathcal{R}^3} y_{ij}^r) \quad \forall r \in \mathcal{P}, i \in \mathcal{T} \tag{21}
\]

\[
\gamma_i^r - \beta_i \geq -M_2^i(1 - \sum_{j \in \mathcal{R}^3} y_{ij}^r) \quad \forall r \in \mathcal{P}, i \in \mathcal{T} \tag{22}
\]

\[
\gamma_i^r - \beta_i \leq M_2^i(1 - \sum_{j \in \mathcal{R}^3} y_{ij}^r) \quad \forall r \in \mathcal{P}, i \in \mathcal{R}^1 \tag{23}
\]

\[
\gamma_i^r - \beta_i \geq -M_2^i(1 - \sum_{j \in \mathcal{R}^3} y_{ij}^r) \quad \forall r \in \mathcal{P}, i \in \mathcal{R}^1 \tag{24}
\]
\[\gamma_{r+n} - \beta_{r+n} \leq M_{2r+n}(1 - \sum_{i \in \mathcal{R}^3} y_{r,i,r+n}) \quad \forall r \in \mathcal{P} \] (25)

\[\gamma_{r+n} - \beta_{r+n} \geq -M_{2r+n}(1 - \sum_{i \in \mathcal{R}^3} y_{r,i,r+n}) \quad \forall r \in \mathcal{P} \] (26)

\[\gamma_i - \beta_t \leq M_i (1 - y_{r,tj}) \quad \forall r \in \mathcal{P}, t \in \mathcal{T}, j \in \mathcal{O}^t \] (27)

\[\gamma_i - \beta_t \geq -M_i (1 - y_{r,tj}) \quad \forall r \in \mathcal{P}, t \in \mathcal{T}, j \in \mathcal{O}^t \] (28)

Set of constraints (21) – (28) assure the synchronization between requests’ and vehicles’ scheduling. Constraints (21) and (22) force departure times of requests and vehicles from a transfer node to be equal if there is a request flow from that node towards a pick-up/delivery node. Constraints (23) and (24) force departure times of requests and vehicles from a pick-up/drop-off node to be equal if there is a request flow from that node. Constraints (25) and (26) force arrival time at the destination node of a request be equal to departure time of a vehicle from that node. Constraints (27) and (28) assure time synchronization between vehicles and requests within each transfer node, with regards to flow between replications of the original station-hub.

**Decision variable domains**

\[x_{ij} \in \{0, 1\} \quad \forall (i, j) \in \mathcal{A}, v \in \mathcal{V} \] (29)

\[y_{ij} \in \{0, 1\} \quad \forall i, j \in \mathcal{R}^3, r \in \mathcal{P} \] (30)

\[\alpha_v \in \mathbb{R}^+ \quad \forall v \in \mathcal{V} \] (31)

\[\gamma_i \in \mathbb{R}^+ \quad \forall i \in \mathcal{R}^3, r \in \mathcal{P} \] (32)

\[\beta_i \in \mathbb{R}^+ \quad \forall i \in \mathcal{N} \] (33)

\[q_{ij}^{rw} \in \{0, 1\} \quad \forall r \in \mathcal{P}, (i, j) \in \mathcal{F}^r, w \in \mathcal{L}^{ij} \] (34)

\[z_{ij}^{rw} \in \{0, 1\} \quad \forall (i, j) \in \mathcal{E}, w \in \mathcal{K}^{ij} \] (35)

Since PDP-FSL is an extension of the PDP with time windows (PDP-TW), it is clearly an NP-hard problem. Considering the explosion in complexity along with instance size, a certain preprocessing needs to be implemented in order to reduce graph size. Thus, next section will introduce several elimination rules.

### 4.3. Preliminaries

Preprocessing was implemented in order to reduce the number of decision variables. Hence, some of the infeasible arcs in graph \(G\) are removed.

- A vehicle can leave from and return to its own depot.
- No vehicle can travel from the destination to the origin of same request.
- No PD vehicle can travel between node \(i\) and \(j\), if \((i, j) \in \mathcal{F}\).
- No request \(r\) can travel between origin and destination of a fixed line, other than arc \((i, j) \in \mathcal{F}^r\).
- No request \(r\) can travel from the destination to the origin of any request.
• No request is allowed to travel to/from any depot.
• No flow is allowed between node $i$ and $j$, if $l_i + s_i + c_{ij} > u_j$.
• No request can travel from its dropoff node to any other node.
• No request can travel to its pickup node from any other node.

Cordeau (2006) proposed elimination rules for DARP with time windows and some of them can be used for PDP-FSL to reduce the number of binary variables.

• No flow can be performed on arcs $(i, j)$ and $(j, i + n)$ with $i \in P$, $j \in R^3$ if $s_i + c_{ij} + s_j + c_{j,i+n} + s_{i+n} > \theta_i$;
• No flow is possible on $(i, j + n)$ if path $\{j, i, n+i, n+j\}$ is infeasible;
• Arc $(i + n, j)$ is infeasible if path $\{i, i + n, j, n + j\}$ is infeasible;

In addition, some elimination rules related to transfer nodes can be applied.

• No flow can be performed to a transfer node $t$, respectively from transfer node $t_1$ for passenger request $i$ if $s_i + c_{it} + s_t + c_{t,t_1} + s_{t_1} + c_{t_1,i+n} + s_{i+n} > \theta_i$, $\forall i \in P^1$, $(t, t_1) \in F^1$;
• An arc $(t, t_1)$ is infeasible if $s_i + c_{it} + s_t + c_{t,t_1} + s_{t_1} + c_{t_1,i+n} > u_{i+n}$, $\forall i \in P^2$, $(t, t_1) \in F^1$;

A number of departure times on the fixed lines for each request can be reduced by considering time windows. Thus, no request $r$ can depart at a time earlier than $(l_r + s_r + c_{rt} + s_t)$ on the fixed line $(t, t_1)$, $\forall r \in P$, $(t, t_1) \in F^r$. Similarly, no request $r$ can depart at a time later than $(u_{r+n} - s_{r+n} - c_{t,r+n} - s_t - c_{t_1,t} - s_{t_1})$ on a fixed line $(t_1, t)$, $\forall r \in P$, $(t_1, t) \in F^r$.

5. Model tightening

As the proposed model grows very rapidly in size with the number of requests, number of fixed lines and departure times on each line, some more additional constraints (valid inequalities) may be added to improve computation time. This section introduces three cuts to improve model’s computational efficiency.

5.1. Vehicle-request flow constraints

We state Proposition 5.1 as follows:

**Proposition 5.1.** The following inequality is valid for the PDP-FSL:

$$\sum_{v \in V} x_{ij}^v \geq y_{ij}^r \quad \forall (i, j) \in A^5, r \in P$$ (36)
Proof. Let \((i, j) \in \mathcal{A}^5\). In addition, let \(x_{ij}^v, \forall v \in \mathcal{V}, (i, j) \in \mathcal{A}\) and \(y_{ij}^r, \forall r \in \mathcal{P}, i, j \in \mathcal{R}^3\) be binary variables. We consider two cases: (i) PD vehicle does not traverse \((i, j) \in \mathcal{A}^5\) (i.e. \(\sum_{v \in \mathcal{V}} x_{ij}^v = 0\)) and (ii) PD vehicle travels on \((i, j) \in \mathcal{A}^5\) (i.e. \(\sum_{v \in \mathcal{V}} x_{ij}^v = 1\)).

In case (i), due to capacity constraints (8) and (9), no request can travel on \((i, j)\) (i.e. \(y_{ij}^r = 0, \forall r \in \mathcal{P}\)). In case (ii), any request may travel on \((i, j)\) as long as constraints (8) and (9) are satisfied. Therefore, \(y_{ij}^r \in \{0, 1\}, \forall r \in \mathcal{P}\) ensures that \(\sum_{v \in \mathcal{V}} x_{ij}^v \geq y_{ij}^r, \forall r \in \mathcal{P}\). □

Example. Let there be a flow between \(i\) and \(j\) traversed by a vehicle \(v\) of capacity two. In addition, two requests of the same type, \(r_1\) and \(r_2\), each having demand one travel on the same arc. Assume an LP solution with following values: \(x_{ij}^v = 0.2, y_{ij}^{r_1} = 0.3\) and \(y_{ij}^{r_2} = 0.1\). Hence, constraints (8) and (9) are satisfied (0.3 + 0.1 ≤ 2 × 0.2). By using constraints (36), \(x_{ij}^v\) is restricted to be at least 0.3 and \(y_{ij}^{r_1} = 0.3\) and \(y_{ij}^{r_2} = 0.1\), respectively. The resulting inequality is valid (0.3 + 0.1 ≤ 2 × 0.3) and is illustrated in Figure 4.

\[
\begin{align*}
\sum_{i \in \mathcal{N}} x_{ir}^v - \sum_{i \in \mathcal{N}} x_{r+n,i}^v & \leq \sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r & & \forall r \in \mathcal{P}, v \in \mathcal{V} \\
\sum_{i \in \mathcal{N}} x_{ir}^v - \sum_{i \in \mathcal{N}} x_{r+n,i}^v & \geq - \sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r & & \forall r \in \mathcal{P}, v \in \mathcal{V}
\end{align*}
\]

5.2. Vehicle pickup strengthening

A second proposition is given in Proposition 5.2.

Proposition 5.2. The following inequalities are valid for the PDP-FSL:

\[
\begin{align*}
\sum_{i \in \mathcal{N}} x_{ir}^v - \sum_{i \in \mathcal{N}} x_{r+n,i}^v & \leq \sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r & & \forall r \in \mathcal{P}, v \in \mathcal{V} \\
\sum_{i \in \mathcal{N}} x_{ir}^v - \sum_{i \in \mathcal{N}} x_{r+n,i}^v & \geq - \sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r & & \forall r \in \mathcal{P}, v \in \mathcal{V}
\end{align*}
\]

Proof. Let \(r \in \mathcal{P}\) and \(v \in \mathcal{V}\). In addition, let \(x_{ij}^v, \forall v \in \mathcal{V}, (i, j) \in \mathcal{A}\) and \(y_{ij}^r, \forall r \in \mathcal{P}, i, j \in \mathcal{R}^3\) be binary variables. We consider three cases: (i) \(r\) is served by PD vehicle \(v\); (ii) \(r\) is served by two different PD vehicles, \(v\) and e.g., \(v_1 \in \mathcal{V}\); (iii) \(r\) is served by other PD vehicle(s) \(v_1\) and/or \(v_2 \in \mathcal{V}\).

In case (i), due to constraints (2), pickup \((\sum_{i \in \mathcal{N}} x_{ir}^v = 1)\) and dropoff nodes \((\sum_{i \in \mathcal{N}} x_{r+n,i}^v = 1)\) of \(r\) are visited by \(v\), hence the left-hand side (LHS) of the constraints (37) and (38) take a value of zero. Furthermore, \(\sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r \geq 0\) ensures that even request \(r\) is served by \(v\), it may still use a fixed line as part of its journey.

In case (ii), the pickup or the dropoff node of \(r\) is visited by \(v\). Hence, LHS of constraints (37) and (38) may take two values: -1 and 1. In order to satisfy constraints (7), \(\sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r > 0\), which implies that \(r\) must use a fixed line as part of its journey.

In case (iii), PD vehicle \(v\) does not visit pickup or dropoff nodes of \(r\), thus LHS gets zero. Hence, \(\sum_{(i,j) \in \mathcal{F}^r} y_{ij}^r \geq 0\) guarantees that \(r\) can use a fixed line, as it may be served by one or two other PD vehicles. The result follows from these cases. □
5.3. Depot strengthening

A depot related valid inequality is given in Proposition 5.3.

**Proposition 5.3.** The following inequality is valid for the PDP-FSL:

\[ M \sum_{j \in R^3} x_{g_v,j}^v - \sum_{i \in R^3} \sum_{j \in R^3} x_{ij}^v \geq 0 \quad \forall v \in V \]  

(39)

**Proof.** Let \( v \in V \) and \( x_{ij}^v, \forall v \in V, (i,j) \in A \) be binary variable. Assume that each vehicle starts and ends its operating day at its depot (i.e. \( g_v \)). We know that no node \( i \in R^3 \) can be visited before leaving the depot. Due to the timing constraints (11) and (12), this assumption holds and the departure of \( v \) from its depot should be smaller than departure time from any other node. More specifically, if \( \sum_{i \in R^3} \sum_{j \in R^3} x_{ij}^v > 0 \), then \( \sum_{j \in R^3} x_{g_v,j}^v \) gets a value of 1 \( \implies \) inequality (39) holds. \( \Box \)

**Example.** Assume a part of an LP solution with two PD vehicles, namely \( v, v_1 \in V \) and \( i, j \in R^3 \) and \( g_v = g_{v_1} = 0 \) (see Figure 5). This LP solution satisfies constraints (2) - (28).

![Flow of the vehicle v](image1.png)

![Flow of the vehicle v1](image2.png)

**Figure 5** An example of violation for constraint (39)

Constraints (39) make sure that \( x_{0i}^v > 0 \) and/or \( x_{0j}^v > 0 \). Thus, LP solution given in the above figure violates constraints (39). In addition, note that \( M \) can be substituted by \( |R^3| \), which implies that a PD vehicle can visit each node in \( R^3 \) at most once.

6. Computational results

This section presents results obtained from solving the proposed formulation of the PDP-FSL using CPLEX (IBM ILOG, 2013). The model is implemented in NetBeans IDE 7.1.1 using the corresponding CPLEX 12.1 libraries. Furthermore, all experiments are run on an Intel Core i5 processor with 4 GB of memory.
6.1. Instance description

Three instance sets are generated based on realistic asymmetric driving times between locations in The Netherlands (LLC, 2013). The planning horizon covers 10 working hours (600 minutes) and a minute is set to be one unit of time. Each set contains six instances with five to ten requests and each request has a demand of one unit. Each set represents a scenario and starts with a 5-request instance. We iteratively add one more request at a time, until we get 10 requests. Furthermore, two types of requests have different setting in terms of time windows at the pickup and dropoff nodes. Table 6 illustrate the logic of time window setting for passenger requests.

Table 6
Time window setting for passenger request \( r \)

<table>
<thead>
<tr>
<th>( l_r )</th>
<th>( l_r + 30 )</th>
<th>( l_r + s_r + c_{r,r+n} + s_{r+n} )</th>
<th>( a_{r+n} + \sigma(s_r + c_{r,r+n} + s_{r+n}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_r )</td>
<td>( l_r + 30 )</td>
<td>( l_r + s_r + c_{r,r+n} + s_{r+n} )</td>
<td>( a_{r+n} + \sigma(s_r + c_{r,r+n} + s_{r+n}) )</td>
</tr>
</tbody>
</table>

The time windows of the package requests are set to be relatively wider than passenger requests’ time windows (i.e. must be picked up in the first part of the planning horizon and delivered until the end of the day). In addition, each instance has two depots with one heterogeneous vehicle each. A fixed line between two station-hubs is considered, \((i, j)\) and \((j, i)\) \( \in \mathcal{E} \). A FSL vehicle departs from each station once in half an hour (30, 60, ..., 540). Later departures are not taken into consideration because PD vehicle needs to be back at its depot before the end of the planning horizon. This leaves a reasonable time for the PD vehicle to go back to depots.

Table 7 presents further details regarding instances. The column Instance shows the identification of the instance (e.g., \( s_{1.1} \) can be decoded as scenario 1 – instance 1), sets sizes, number of constraints and variables in the resulting MIP formulation and finally, objective function value of the LP relaxation. Corresponding values are computed with and without proposed preprocessing in section 4.3. The improvement of the lower bound (LP) is on average 33.03%.

Table 7
The structure of instances

| Instance | \( |Q| \) | \( |V| \) | \( |P^1| \) | \( |P^2| \) | \( |\mathcal{E}| \) | \( \cdot |\mathcal{K}_{ij}| \) | Without preprocessing | With preprocessing |
|---|---|---|---|---|---|---|---|---|---|
| \( s_{1.1} \) | 2 | 2 | 4 | 1 | 2 | 36 | 4047 | 2932 | 145.98 | 1116 | 557 | 171.30 |
| \( s_{1.2} \) | 2 | 2 | 4 | 1 | 2 | 36 | 6416 | 4660 | 158.06 | 2143 | 1251 | 235.56 |
| \( s_{1.3} \) | 2 | 2 | 5 | 2 | 2 | 36 | 9433 | 6963 | 175.28 | 3471 | 2021 | 255.66 |
| \( s_{1.4} \) | 2 | 2 | 6 | 2 | 2 | 36 | 13390 | 9928 | 178.08 | 4419 | 2753 | 233.94 |
| \( s_{1.5} \) | 2 | 2 | 7 | 2 | 2 | 36 | 18285 | 13639 | 192.89 | 4333 | 2549 | 270.01 |
| \( s_{1.6} \) | 2 | 2 | 8 | 2 | 2 | 36 | 24208 | 18180 | 231.87 | 6401 | 4003 | 300.77 |
| \( s_{2.1} \) | 2 | 2 | 2 | 3 | 2 | 36 | 4047 | 2932 | 117.75 | 1587 | 913 | 182.49 |
| \( s_{2.2} \) | 2 | 2 | 3 | 3 | 2 | 36 | 6416 | 4660 | 121.62 | 2153 | 1250 | 202.53 |
| \( s_{2.3} \) | 2 | 2 | 3 | 3 | 2 | 36 | 9433 | 6963 | 149.70 | 3648 | 2304 | 218.40 |
| \( s_{2.4} \) | 2 | 2 | 4 | 4 | 2 | 36 | 13390 | 9928 | 165.16 | 4419 | 2753 | 233.94 |
| \( s_{2.5} \) | 2 | 2 | 4 | 5 | 2 | 36 | 18285 | 13639 | 172.09 | 5764 | 3741 | 210.33 |
| \( s_{2.6} \) | 2 | 2 | 5 | 5 | 2 | 36 | 24208 | 18180 | 193.27 | 6904 | 4531 | 273.52 |
| \( s_{3.1} \) | 2 | 2 | 1 | 4 | 2 | 36 | 4047 | 2932 | 108.53 | 1636 | 974 | 127.41 |
| \( s_{3.2} \) | 2 | 2 | 1 | 5 | 2 | 36 | 6416 | 4660 | 112.92 | 2383 | 1502 | 142.84 |
| \( s_{3.3} \) | 2 | 2 | 2 | 6 | 2 | 36 | 9433 | 6963 | 126.11 | 3592 | 2212 | 160.44 |
| \( s_{3.4} \) | 2 | 2 | 1 | 7 | 2 | 36 | 13390 | 9928 | 142.96 | 4427 | 2991 | 209.70 |
| \( s_{3.5} \) | 2 | 2 | 2 | 7 | 2 | 36 | 18285 | 13639 | 149.55 | 6488 | 4317 | 227.89 |

Average | 154.48 | 205.52
A driving minute of a PD vehicle is assumed to be 0.5 €. It seems reasonable considering operational costs such as fuel consumption, driver wage, insurance, tax, etc. Each bundle of package requests shipped on a fixed line is set to 0.5 €. At first glance, these numbers may not be seen as being very accurate. To shed light on this question, we have conducted an extensive study to verify these numbers and we believe that the numbers actually should be the same, for both operational costs and number of bundles. Finally, $\sigma$ is assumed to be 1.15, meaning that each passenger accepts to spend 15% more travel time than its possible direct trip duration. The test instances are available at SmartLogisticLab (2013).

6.2. CPLEX versus CPLEX with user cuts

In Table 8, we indicate lower bounds obtained at a root node (after applying preprocessing). Column $LP$ shows bounds obtained without applying any kind of cut generation. $CPX$ shows the bounds obtained by activating automatic cut generation of CPLEX (without user defined cuts). Finally, $Full$ column shows bounds obtained by applying both CPLEX and user defined cuts $^7$. The last column indicates the improvement in the lower bound when using user cuts, instead of applying only CPLEX cuts.

<table>
<thead>
<tr>
<th>Instance</th>
<th>LP</th>
<th>CPX</th>
<th>Full</th>
<th>Improvement %</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1.1</td>
<td>171.30</td>
<td>179.59</td>
<td>179.59</td>
<td>0.00</td>
</tr>
<tr>
<td>s1.2</td>
<td>185.34</td>
<td>190.50</td>
<td>190.75</td>
<td>0.13</td>
</tr>
<tr>
<td>s1.3</td>
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Average 205.52 219.17 221.43 1.08

Table 9 reports the results obtained by using CPLEX with and without proposed cuts. In both cases, a time limit of 10800 seconds (3 hours) is imposed to the solver. We indicate the objective function value, obtained GAP from the best bound, the best bound obtained, the CPU time (in seconds) and the number of explored nodes during the search process.

Computational results obtained in this section show that instances with up to 10 requests can be solved to optimality in a reasonable time by using proposed model with the additional constraints given in section 5. One can observe that by taking advantage of the proposed cuts $^7$We have also tested the performance of the model with some valid inequalities for DARP proposed by Cordeau (2006), namely subtour elimination constraints and precedence constraints for every pair of requests, but it proved slightly worse performance in terms of CPU time than what we obtained by using aforementioned cuts.

16
Table 9
Comparisons between CPLEX and CPLEX with user cuts

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significantly improves the performance of the CPLEX. For the 16 instances solved to optimality by both variants of the model within the time limit, on average CPU time was 1021.24 seconds for CPLEX alone compared with 337.58 seconds for CPLEX with additional cuts. The average number of explored nodes drops from 44690 to 6770. No feasible solutions were found for two instances by CPLEX alone whereas with user cuts, in both cases, optimal solutions were found within the time limit.

6.3. Fixed lines frequency and passenger travel time tolerance experiments

We have made some experiments on the fixed lines’ frequency and passenger’s travel time tolerance ($\sigma$). We consider four cases for the frequency of the public transportation, particularly every 30 minutes, 15 minutes, 5 minutes and finally 60 minutes. In addition, tested passenger trip time tolerance takes the following values: 1.15, 1.5 and finally 2.

We used three sets of instances described in Section 6 with corresponding modifications (fixed lines frequency and time windows). Note that considered instances are more relaxed than original ones. Therefore in order to limit the B&B search tree, the solutions obtained in previous section are used as initial incumbents. Three hours time limit is imposed.

For the sake of readability of the paper we did not include the detailed results in the paper, but these are available upon request from the authors. Overall based on the results obtained from solving considered instances, by having more frequent fixed line does not have any effect on total driving time whereas by having larger passenger trip time tolerance, savings of up to 25% may be reached (on average 3%, based on instances solved optimally). Therefore, longer passenger trip time tolerance makes a slightest impact to such transportation systems, considering the importance of the passenger service satisfaction.

7. Scenario comparisons

Since more stakeholders are involved in the considered transportation system, namely passenger door-to-door transportation, package transportation and public fixed line services,
different scenarios representing the cooperation and coordination are simulated. Figures 6b - 6f illustrate the considered scenarios with the legend shown in Figure 6a.

In scenario one (see Figure 6b), *integrated passenger and parcel transport networks with fixed lines (IFL)*, cooperation between taxi, courier and public transportation companies is considered. For instance, a taxi may pick-up a package and either deliver it to its destination, or transfer it to a fixed line. As courier vans are not designed to carry passengers, it is assumed that a package transportation company shares the information regarding the requests (origin, destination, time windows, demand, etc.). Therefore, the cooperation with courier companies means sharing the information regarding requests. From the modeling perspective, proposed model considers IFL as a base scenario.

In scenario two (see Figure 6c), *separated passenger and parcel transport networks with fixed lines (SFL)*, passenger and package transportation companies independently cooperate with public transport companies. Hence, a passenger can only be picked up by a taxi and it can be transferred to a fixed line. Similarly, a parcel can only be conveyed by courier vans, where use of fixed line is possible. In terms of modeling following scenarios, additional subsets of $\mathcal{V}$ are defined, as follows:

\begin{align*}
\mathcal{V}^1 &\text{ - set of vehicles belonging to a passenger transportation company} \\
\mathcal{V}^2 &\text{ - set of vehicles belonging to a courier company}
\end{align*}
The following constraints need to be added to the model in order to obtain scenario two. In words, constraints (40) and (41) make sure that no passenger request is serviced by courier vehicles and no parcel request is serviced by passenger service vehicles.

\[
\sum_{v \in V_1} \sum_{i \in N} \sum_{r \in P_2} (x_{vr}^v + x_{ir+r}^v) = 0 \quad (40)
\]

\[
\sum_{v \in V_2} \sum_{i \in N} \sum_{r \in P_1} (x_{ir}^v + x_{r+r}^v) = 0 \quad (41)
\]

In the third scenario (see Figure 6d), integrated passenger and parcel transport networks without fixed lines (INFL), passenger and parcel transport companies cooperate with each other and none of these cooperate with public transport provider. Hence, neither a parcel nor a passenger uses fixed lines. In terms of modeling, following constraints need to be added. Constraints (42) assure that no flow on fixed lines is allowed.

\[
\sum_{(i,j) \in F} \sum_{r \in P} y_{ij}^r = 0 \quad (42)
\]

In the fourth scenario (see Figure 6e), separated passenger and parcel transport networks without fixed lines (SNFL), none of the companies cooperate with each other. Therefore, e.g., requests from the taxi company can be carried out only by a taxi, similarly a parcel can be carried out only by courier vehicles and there is no transfer opportunity to public transportation lines. To model this environment, constraints (40), (41) and (42) are used. SNFL reflects the current real life situation.

In scenario five (see Figure 6f), separated passenger and parcel transport networks where only passengers can use fixed lines (SPFL), parcel and passenger transportation companies operate independently and only passengers have the opportunity to use public transportation. This scenario is somewhat similar to the reality as well, where a person uses a taxi from its origin to e.g., a train station, after traveling by train, it takes another taxi to its destination. To model such a transportation system, the following constraints are used.

\[
\sum_{(i,j) \in F} \sum_{r \in P_2} y_{ij}^r = 0 \quad (43)
\]

Thus, constraints (40), (41) and (43) are added to the model. We have modified three sets of instances described in Section 6.1 to test the mentioned scenarios. Hence, we added two depots with one vehicle each to every instance, such that both belong to the courier company. The scenarios are compared based on the total travel time of the PD vehicles and the amount of CO\textsubscript{2}e. The obtained results are normalized to the scenario proposed in the present paper (IFL). The findings are shown in Table 11.

As expected, integrated networks (IFL) where all actors cooperate and share the information regarding requests lead to most significant benefits. Compared to what happens in reality (SNFL), namely each service provider serves its own requests, proposed scenario proved 1.37 times less total travel time in the system (savings of 26.93%). Compared to scenarios 2 (SFL)
Table 11
Scenario comparison regarding driven time and $CO_2e$

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and 3 (INFL), our proposed system gives 1.33 and 1.03 less travel time, which is approximately 24.74% and 2.25% savings. The small difference in performance between proposed scenario and INFL, where use of the fixed lines is not allowed, is due to relatively short distances between considered station-hubs, as well as the pickup and delivery nodes. By considering shipments between more distant locations, the use of fixed lines would be more profitable. Regarding scenario 5 (SPFL), the proposed environment lead to 1.37 less travel time (26.93% savings). Based on the average results regarding $CO_2e$, the proposed system clearly outperforms any other scenario (except INFL) by approximately 70%. This is due to the fact that parcel requests are served by courier vans, which generate more $CO_2e$ emissions. Therefore, cooperation is clearly a profitable opportunity for the whole system. Note that the benefits slightly decrease along with the increase in number of requests to be served. Even so, the benefits remain substantial.

Scenarios where passenger and freight transport companies operate separately (SFL, SNFL, SPFL), proved to use at least the amount of vehicles used in IFL. For considered instances, in IFL on average two vehicles were used, whereas in SFL, SNFL, SPFL, 2.43 PD vehicles were needed to serve all requests.

8. Conclusions

This paper presented an extension to the PDP in the context of integrated passenger and package transportation with the opportunity to use public scheduled transportation. A mixed-integer linear formulation for PDP-FSL was proposed and additional valid inequalities are introduced. By using the proposed model, several scenarios were analyzed.

The proposed transportation system leads to significant operating cost reductions and $CO_2e$ savings, compared to the current situation. Furthermore, the opportunity to transship the requests to the scheduled public transportation leads to extra flexibility. In other words, more requests can be serviced by using fewer PD vehicles as capacity of the public transportation is used. Overall, our paper has demonstrated the following three important conclusions:
• Operational costs can be reduced by up to 27% by integrating passenger and freight flows, using fixed lines.

• $CO_2e$ emissions could be decreased by up to 70% by reducing the number of used vehicles and using available fixed lines.

• An idea of integrated transport systems is also promising to reduce dense traffic in urban areas.

Although the proposed transport system leads to important benefits, customer satisfaction level may be negatively affected due to slightly longer trip times. Thus, certain incentives (e.g., lower fares, etc.) for the passengers are needed to compensate this drawback in order to make such services more attractive. This integration is left out for future research. Another potential further research could be developing heuristic, exact algorithms that generate good quality solutions for reasonable-sized instances. In addition, as the considered transportation environment is subject to changes (e.g. traffic jams, new requests, etc.), algorithms for solving the dynamic version of the proposed problem could be investigated as well.

Acknowledgements

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framework for solving realistic VRPs

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