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Hyperconnected Urban Synchromodality: Synergies between Freight and People Mobility

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Abstract: *This paper investigates the opportunity to exploit an on-demand freight transshipment service in urban areas. This contribution attempts at first to focus on the feasibility to connect people and freight mobility with a joint usage of transportation options. It builds on the hyperconnectivity principles enabled by the Physical Internet (PI) manifesto for city logistics. To this end, this paper proposes an effective solution approach for optimizing multimodal on-demand transshipment. The approach considers multiple mobility options such as on-demand delivery services, cargo bikes, tramways, and buses to transship goods from an urban logistic hub to another. The hyperconnected synchromodal mobility solution is proposed as an alternative option to classical pickup and delivery-based transportation. The proposal is first characterized in link with the interconnectivity needs and then its operability is modeled as a new transportation approach. The proposed solution aims to increase the sustainability of cities by reducing congestion levels, the impact of logistics moves, as well as carbon emissions in urban areas. An illustrative case is provided to demonstrate how the novel hyperconnected synchromodal transportation system could operate, and to provide an evaluation of the economic and sustainability benefits of such system in an urban context.*

Keywords: *Hyperconnected City Logistics, Synchromodality, Physical Internet, Parcel Distribution, Sustainable Mobility*

Conference Topics: *Distributed intelligence, last mile & city logistics.*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper: ☐ PI Nodes, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

Urban population is steadily growing, as demonstrated by the World Business Council for Sustainable Development predicting that by 2025 more than 4.4 billion of people will be living in urban areas. New mega cities are appearing in many countries, especially in Latin America and Asia, which will rise to over 85% the world population living in cities by 2050. The raise of e-commerce proportion in deliveries and the mass customization trend in retailing are responsible for lower volumes per shipment and higher number of shipments. These urban shipments are continuously confronted to an increased service level now expressed in hours to deliver rather than in days. Transportation of goods in urban areas represents an important proportion of the total moves on a daily basis within cities.

From the residents' perspective, the main moves consist of transporting goods supplied from groceries or retail stores, and on moving out to nearby pickup points to collect online ordered products. From the private logistics companies' perspective, the main moves are the well-known last-mile deliveries that are nowadays more and more under pressure induced by the higher requirements of the online retailing system. With the surge in small-package delivery services, these actors represent a vital link between the globally dispersed suppliers and the city residents with a challenge for their efficiency, service level, ecological footprint, and social impact on the city.

The concept of Physical Internet (PI), (Montreuil, 2011), was proposed as a novel and open framework in order to connect within the same system humans, objects, networks, and the main stakeholders (cities, logistics operators, couriers, postal services, retailers). A more distributed and sustainable logistic system could be reached enabling the easy access of goods. Within the PI vision, goods are moved, handled, and stored via a logistic web that corresponds to an open network of logistic networks. The implementation of the PI framework enables to move toward a more interconnected and decentralized transportation service where goods are encapsulated in smart easy-to-handle and modular PI-containers. Within urban areas, interconnectivity is to be strongly enhanced thanks to the usage of a large multi-tier set of logistic hubs and the usage of several transportation options to ensure safe, efficient, and fast transshipment moves between all the origin-destination pairs. Based on all these features, the introduction of the Hyperconnected City Logistics (HCL), (Crainic and Montreuil, 2016), enables a more efficient and sustainable way to handle and transport goods. HCL presents an approach to shift from disconnected dedicated transportation systems to a connected decentralized and highly collaborative transportation and logistics system emphasizing the use of the available spaces and existing infrastructure.

At the city level, the urban infrastructures that provide and operate interconnected sustainable modes rely on public transport resources dedicated to people mobility (buses, tramways, rapid transit systems). With the objective of reducing the impact of freight transport and logistics on the urban fabric, many recent papers stressed the interest in interconnecting people and freight mobility. In the existent literature on city logistics, the solutions presented focus on the integration of freight into a single passenger network. Many of these innovative logistic practices mixing freight and passengers are implemented in the form of pilots and are focused on a single public transportation mode, but few concrete solutions remain. According to a multimodal approach, synergies between freight and passengers based on the sharing of vehicles and public transport infrastructures requires consideration of the notions of hyperconnectivity and synchromodality.

This research paper first focuses on the feasibility of goods transshipment with a joint usage of public mobility and freight urban vehicles. Within an urban area, interconnectivity would be strongly enhanced thanks to the usage of a high number of multimodal transit hubs, which are locations where several transportation modes crossover. Interconnectivity would also be leveraged by the usage of several transportation options to ensure efficient and fast transshipment moves, synchromodality, between all the origin-destination pairs of the multimodal transit hubs network. Accordingly, this paper proposes a model-based decision support system to transship goods in an urban area based on the joint use of public transport mode (tramways and buses) and on-demand mode (cargo bikes and taxis). The paper uses a case to illustrate a mobility solution based on modular containerization (PI-containers). This case is built within an urban area where a set of predefined itineraries are designed to run different type of vehicles and multiple transportation modes. Finally, this paper demonstrates the benefits from creating synergies between freight and people mobility in urban areas from economic, ecologic, and societal perspectives.

2 Literature review

The literature dedicated to city logistics has proposed several innovative practices with the aim to improve the unsustainable situation currently operated by freight mobility at road traffic level. City logistics emphasizes the need for an optimized consolidation of loads from different shippers and carriers based on the coordination of freight transportation activities (Crainic 2008; Toh et al., 2009; Anand et al., 2012; Cleophas et al., 2019). Tactical planning models (Crainic et al., 2009) and operational transportation models (Crainic et al., 2004; Hemmelmayr et al., 2012; Crainic et al., 2015; Nguyen et al., 2017) have been proposed to cope with a number of real urban contexts. In these latter works, the two-tier modeling framework proposed for city logistics underlines the important role of peri-urban structural resources to connect distribution operations to urban areas. The expansion to multi-tier distribution systems is rapidly facing limitations when companies act solely, due to the heavy investment costs in durable facilities. Faced with a highly competitive context, urban deliveries must be redesigned to find the appropriate level of economic efficiency while integrating environmental and societal perspectives. In parallel, city logistics activities are subject to the regulations implemented by local authorities to minimize negative impacts (Savelsbergh and Van Woensel, 2016). The systemic view of city operations points out the crucial need for collaborative and sharing-based practices. City Logistics research and practice have shown that enhancing only traffic and parking regulations is no longer efficient to deal with all urban issues (de Jong et al., 2015) and that a more global vision on people mobility and goods delivery is desired in terms of sharing transportation networks, vehicles and routes.

The Physical Internet initiative enabled the emergence of the Hyperconnected City Logistics (HCL) for designing urban logistics and transportation systems that are significantly more efficient and sustainable (Crainic and Montreuil, 2016). In the PI framework, goods are encapsulated in standard, modular, smart, and reusable PI-containers, routed across open distribution networks. HCL is based on the key concept of interconnectivity, in order to shift to an open system engaging a multitude of diverse actors and emphasizing the interconnected utilization of existing urban logistics facilities and usable spaces. It enables leveraging on-demand paired transportation requests including transshipment, cross docking logistic operations as well as multiple transportation tools and options.

Several facts underlined the failure of current transportation companies to provide efficient distribution networks at the urban level (Crainic, 2008; Montreuil, 2011). Many researchers and practitioners have investigated innovative solutions with the consideration of shared vehicles between persons and goods as well as shared cargo bikes (Gruber et al., 2014) or freight rapid transit system (Fatnassi et al., 2015). Innovative mobility business models materialized in the last years finding a way to use alternative energy vehicles during slow periods outside rush hours (Hildermeier and Villareal, 2014). Several studies and literature reviews were published in order to present the potential benefits of the use of multimodal transportation system in urban areas (Kumar et al., 2016 ; Cochrane et al., 2017; Cleophas et al., 2019; Mourad et al., 2019; Cavallaro and Nocera, 2022).

Reducing the environmental impact of freight transport activities in urban areas is one of the primary concerns for more virtuous mobility, often approached through encouraging modal shift from road to other more environmentally friendly modes of transport. The concept of synchromodality, whose various foundations are discussed in many recent publications such as (Dong et al., 2018), (Ambra et al., 2019) and (Lemmens et al., 2019), allows standardized containers to switch between different modes of transport, dynamically adapting the routes according to planning approaches particularly based on real-time information. Faced with this search for flexibility, the number of transport modes directly available in a city impacts the possibilities for modal shift. Many research works propose approaches based on the design of interconnected networks, but there is no approach to evaluate the economic, environmental and societal performance of urban distribution based on multimodal mobility using several public transport modes. In order to characterize the concept of urban synchromodality the following section is devoted to defining its underlying assumptions.

3 Multimodal on-demand transshipment problem

The modeling approach relies on multiple transportation options, time windows and distance constraints. These features give rise to a multimodal on-demand transshipment problem. However, only a few studies expressed these opportunities and attempted to model this specific on-demand transportation problem. Here, different types of vehicles with their own characteristics are being used for specific time windows at a daily basis. Each itinerary is dedicated to a specific transportation mode between different pairs of multimodal transit hub locations. Then, the proposed decision support system uses jointly several mobility options to serve a set of goods delivery requests. Several insights are derived from this illustrative case on the benefits of hyperconnectivity in ensuring an adequate delivery service, alternatively to dedicated on-demand vehicles. Also, the role of synchromodality is underlined in reducing the waiting time and parcels footprint at the urban level.

The model considers each PI-container as an independent traveler over the network aiming to reach its destination node before a deadline, by means of choosing several pairs of vehicles and multimodal transit nodes. Depending on the selected vehicle option and the arrival time to a node, a PI-container might need to spend some time in that multimodal transit node to get the next selected trip. Although the PI-containers are travelling independently from each other, they share capacity on the same selected trips and in the same visiting nodes. As the ultimate goal is to arrive with the least possible delay, the model tracks the timing of each PI-container's moves in the network. If the available urban mobility options or the operating couriers do not reach the expected service level (no late delivery), the use of on-demand vehicles which might speed up the moves is allowed yet penalized due to their unfavorable impacts. In the model is considered a single-size PI-container.

The problem is defined for a planning horizon broken into time intervals (large periods) to capture the deviations arising from the congestion and demand levels. The planning horizon is also broken into decision periods (small periods) to capture the problem dynamics, to update the parameters and to re-optimize the problem. In addition, there are scheduled moves on the public network over the whole horizon. For example, the defined time settings for a 6am-6pm horizon with 4 large periods, 12 small periods and several scheduled moves are shown in Figure 1.

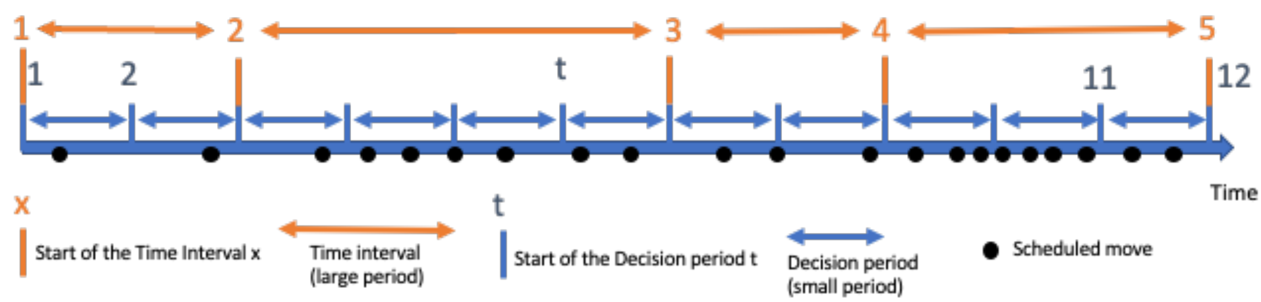


Figure 1: Time settings

There is one local hub, acting as the origin of arriving PI-containers and accessible for all transport modes. There are several access hubs dispersed in different zones of the city that can receive and dispatch PI-containers. This network design approach is based on the concepts of multi-plane meshed networks interconnecting hubs introduced in Montreuil et al., 2018. Access hubs are connected to one/several other access hubs by one/several transportation modes depending on the zone and accessibility of each arc by each transport mode. Each access hub can be the destination of an arriving of PI-container expressed by a capacity for reception and dispatching activities during each period that can be defined the same as either the traffic-level time intervals or the decision periods. The capacity limit should be defined relative to the length of each period, otherwise it can impose unnecessary inflexibility in routing optionality. Depending on the length of each period, this capacity parameter implies the maximum availability of operational resources (workforce or chargeable equipment for unloading and loading operations) and space in the load/unload and holding area.

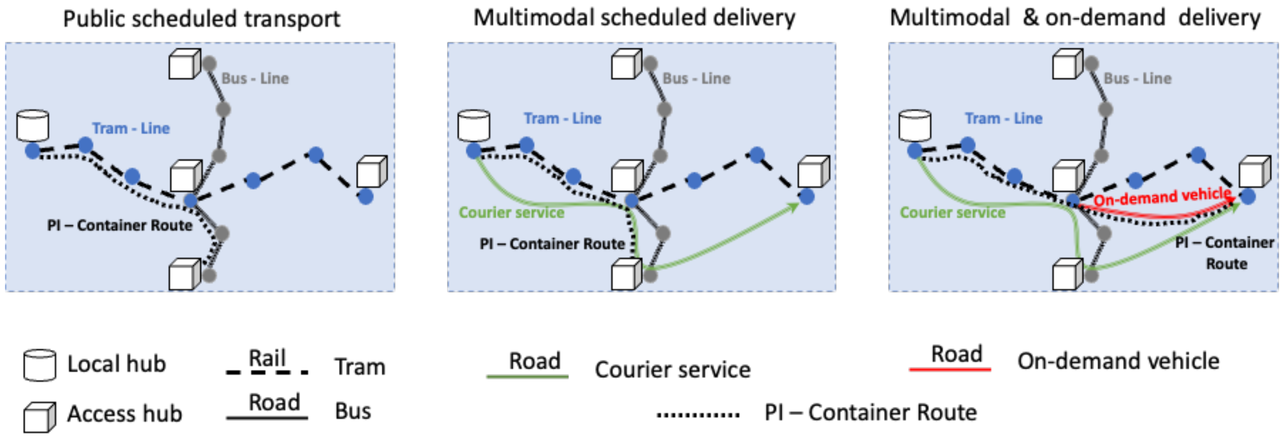


Figure 2: Multimodal good transportation system within Physical Internet context

The travel time on each arc depends on the transportation mode speed and the period' congestion factor, specified at the beginning of the large periods. Each of the public transportation modes has scheduled departures from the respective access hubs to respective destinations over the planning horizon. The courier service is another scheduled transport option with fixed and known itineraries (with scheduled departure from respective access hub). Each vehicle in the scheduled transport option (public or private) has a remaining capacity parameter which should be considered while assigning the PI-containers. On-demand vehicles can travel on some of the arcs depending on the zone of the arc's ends, the decision period and the on-demand transport option. As public transport and courier options have a fixed reachable network, their accessibility matrix is large-period independent and is defined separately.

Unlike the previous modes, there are no scheduled moves for on-demand vehicles. But assigning a PI-container to an on-demand vehicle to move on an arc on the network incorporates an uncertainty in the arrival of the on-demand vehicle. This arrival uncertainty may differ for each on-demand vehicle option (such as cargo bike versus taxi) in each access hub for each large period of the day. In a one-size PI-container setting and assuming that each request corresponds to a single PI-container, the arriving on-demand vehicle always has sufficient capacity. Calling an on-demand vehicle enforces an empty move for that vehicle to reach the respective access hub. Therefore, a fixed cost for each utilization of an on-demand vehicle is considered.

PI-containers start at the local hub and need to be delivered to an access hub destination. It is possible to choose a mixture of transportation nodes and intermediate access hubs to connect the arriving PI-containers to their destinations. Each PI-container has a soft deadline for its delivery to the destination access hub. Violation of this deadline incorporates a penalty cost, which might differ from one PI-container to another depending on the length of the delay. The following components should be considered in the objective function to minimize the impact of PI-containers' journey in the time and space of urban transport network space:

- Penalty cost for deviating from delivery deadlines;
- Fixed cost for calling on-demand vehicles (for their empty moves);
- Total arc-dependent travel costs incurred by choosing on-demand vehicles (includes the cost of undesired environmental consequences, like a CO_2 tax).

4 Illustrative example

To illustrate the solution approach proposed based on PI-container mobility, this section considers a typical urban context related to Bordeaux, a mid-size city in France. Different types of mobility options with their own characteristics are being used for specific time windows on a daily basis. The use case is built within an urban area where a set of predefined itineraries are designed to run vehicles of different types and multiple transportation modes. Each itinerary is dedicated to a specific transportation mode between different pairs of access hubs. The distance matrix for the illustrative example was generated based on the hypercentre of the city of Bordeaux. The network is composed of two types of nodes serving as PI-container transshipment and temporary storage locations. A local hub is located at the Bordeaux train station, it represents the starting point of the PI-containers and is characterized by a large capacity in terms of storage, speed of transshipment and connectivity with the public transport modes. In addition, the network is made up of 12 loading/unloading points which are access hubs corresponding, in terms of public transport, to stops on the routes and in some cases to interconnection points between the different modes. One of the characteristics of the access hubs is that they provide transshipment spaces with relatively small storage capacity corresponding to temporary waiting areas.

At the level of the selected urban area, Figure 3 presents the location of the transshipment nodes, the lines of the two public transport modes considered (bus and tram) as well as the spatial location of demand points that come from the survey on urban freight transport in the city of Bordeaux (French Mobility, 2015). The connections between the nodes of the network correspond to the routes taken by the different public transport modes using two types of infrastructure: rail for the tram and road for the bus.

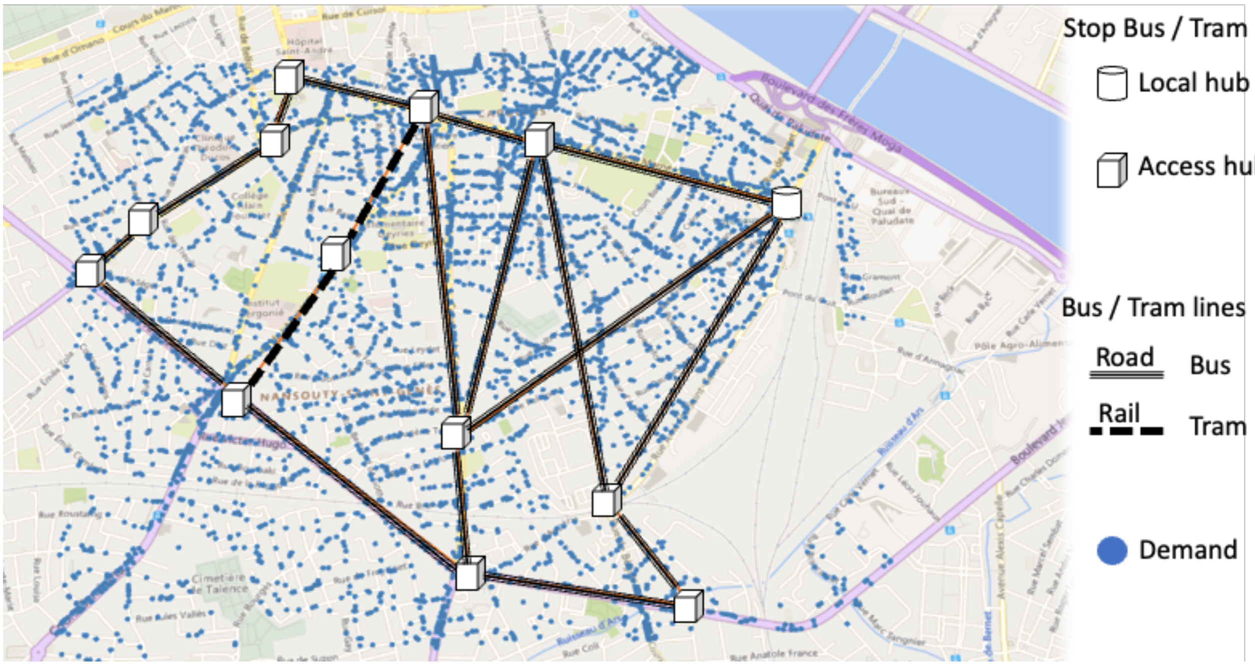


Figure 3: Spatial pattern of freight movements in Bordeaux hypercentre (one week)

The illustrative case is hereafter used to demonstrate how a multi-modes transportation system could operate, and to provide an assessment of the economic and sustainability benefits of such system in an urban context. The following section presents the results for different levels of demand, different time settings and different PI-container mobility options.

5 Preliminary results

This section investigates the performance of alternative configurations of multimodal on-demand delivery service exploiting several mobility options in satisfying a set of PI-container delivery demands. The performance assessment procedure considers the different characteristics of the problem in order to conciliate economic, ecological, and societal objectives. To this end, the following two subsections present different mobility network configurations over different time horizons and demand levels.

5.1 Scheduled multimodal delivery service

In this first investigated mobility network configuration, eight nodes are considered: 7 access hubs and 1 local hub. For the transport options, only scheduled public and private routes are exploited to connect the nodes. For public transport there are tram and bus lines and a courier service to the private sector, as shown in Figure 4. On a time-window of 3 hours divided into three periods of 1 hour, 14 scheduled departures are planned, as illustrated with the table in Figure 4.

	Period		
	1	2	3
1	6:00		
2	6:12		
3	6:30		
4	6:42		
5	7:00		
6		7:12	
7		7:30	
8		7:42	
9		7:48	
10		7:54	
11			8:12
12			8:30
13			8:42
14			8:54

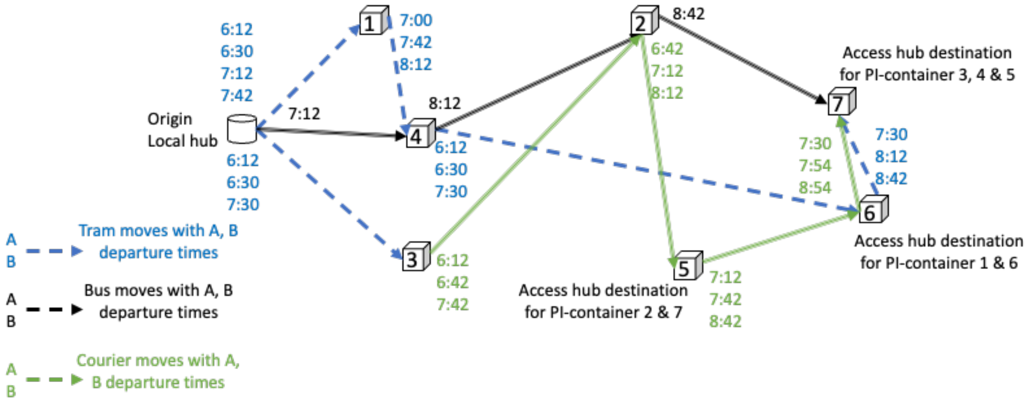
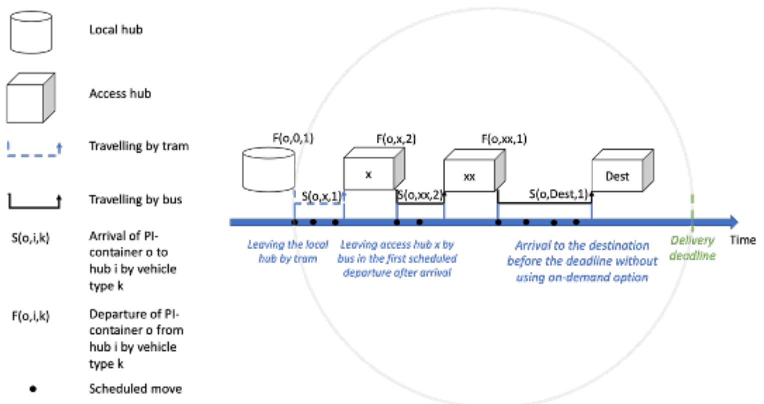


Figure 4: Timetables and multimodal network

The first results obtained are based on the delivery of 7 PI-containers considering the following assumptions: i) at each period the routes, the timetables and the travel times are known, ii) capacities are available on each route, iii) no constraints on congestion levels, transfer, and storage capacities in the access hubs, and iv) all containers are at the local hub at time zero. As presented at the table level in Figure 5, this first step made it possible to validate the solution approach by obtaining for each PI-container a route allowing to reduce unnecessary moves and the total waiting time from the PI-containers to the destination access hub. In the example, PI-containers 1 and 7 arrive at their final destination with a delay of 24 minutes and 36 minutes.



PI -Container	Access hub destination	Delivery due time	Arrival time to the destination node
1	6	7:00	7:24
2	5	9:00	7:36
3	7	8:00	7:48
4	7	8:00	7:48
5	7	9:00	7:54
6	6	8:00	7:24
7	5	7:00	7.36

Figure 5: Example of delivery plan

5.2 Multimodal on-demand delivery service versus routing

In this second configuration of the mobility network, thirteen nodes are considered: 12 access hubs and 1 local hub. For the transport options, public scheduled lines and on-demand modes are exploited to interconnect the access hubs. The selected public transport network consists of one tram line and six bus lines. Over a 2-hour time window between 7 PM and 9 PM, 113 departures on public transport lines are planned. In terms of on-demand transport, two options are retained: taxi and cargo bike. Each of these options incorporates additional characteristics to measure the impact of the on-demand transport in the urban space (number of added vehicles to the city traffic flow, occupied city parking space per unit of time, etc.). For taxis, some parameters are added to consider the ecological impact (fuel consumption and CO_2 emission rate). Due to the different parameters for the multiple transportation options, the proposed problem involves finding a route for each PI-container, composed by a set of travel moves and transits. To this end, an analysis based on the delivery times of 30 PI-containers is proposed in Figure 6. The aim is to compare a modelling and optimization-based approach for the multimodal on-demand transshipment problem (Multimodal & on-demand) with an exact approach with CPLEX for solving Vehicle Routing Problem (VRP).

The two tested delivery modes incorporate the following assumptions: i) at each period the routes, the timetables, and the travel times are known; ii) the capacities are available on each route; iii) no constraints on congestion levels, transfer and storage capacities in the access hubs; iv) all containers are at the local hub at time zero; v) the loading/unloading time for one PI-container is 180 seconds; and vi) unlimited availability of on-demand resources. The results presented in Figure 6 make it possible to specify for each PI-container the local hub of departure (Origin), the access hub of arrival (Destination), the expected delivery time taking as start time 7PM (Delivery time expressed in minutes and seconds), and the arrival time taking as start time 7PM (Arrival time expressed in minutes and seconds) according to the two delivery modes. The VRP approach proposes a solution with a distribution of the 30 PI-containers in two trucks. Truck 1 will handle the delivery of 17 PI-containers and truck 2 will deliver 13 PI-containers, for a total distance traveled of 13.04 km.

Truck n°1

			Due date		Actual delivery time			
					Multimodal & on-demand		VRP	
Nb Order	Origin	Destination	min	sec	min	sec	min	sec
1	1	2	119	7140	102,20	6 132	3,28	197
7	1	2	119	7140	102,20	6 132	3,28	197
8	1	2	92	5520	87,20	5 232	3,28	197
16	1	2	75	4500	73,20	4 392	3,28	197
3	1	3	66	3960	62,00	3 720	11,82	709
4	1	4	77	4620	77,00	4 620	21,07	1 264
9	1	4	118	7080	105,80	6 348	21,07	1 264
27	1	4	110	6600	103,00	6 180	21,07	1 264
12	1	5	74	4440	73,20	4 392	29,80	1 788
13	1	5	48	2880	45,20	2 712	29,80	1 788
26	1	5	100	6000	99,50	5 970	29,80	1 788
5	1	9	42	2520	40,20	2 412	71,00	4 260
6	1	9	71	4260	70,50	4 230	71,00	4 260
11	1	9	56	3360	54,20	3 252	71,00	4 260
19	1	8	80	4800	76,50	4 590	80,02	4 801
20	1	8	76	4560	67,50	4 050	80,02	4 801
30	1	8	105	6300	86,50	5 190	80,02	4 801

Truck n°2

			Due date		Actual delivery time			
					Multimodal & on-demand		VRP	
Nb Order	Origin	Destination	min	sec	min	sec	min	sec
17	1	12	83	4980	69,80	4 188	4,58	275
21	1	12	92	5520	89,00	5 340	4,58	275
23	1	12	55	3300	43,20	2 592	4,58	275
14	1	10	64	3840	62,80	3 768	41,80	2 508
28	1	11	97	5820	96,00	5 760	50,05	3 003
15	1	13	87	5220	83,00	4 980	59,83	3 590
18	1	13	71	4260	69,00	4 140	59,83	3 590
25	1	13	88	5280	83,00	4 980	59,83	3 590
29	1	13	105	6300	98,00	5 880	59,83	3 590
2	1	7	54	3240	52,20	3 132	69,37	4 162
24	1	7	86	5160	80,80	4 848	69,37	4 162
10	1	6	78	4680	77,20	4 632	78,00	4 680
22	1	6	76	4560	63,50	3 810	78,00	4 680

Figure 6: Deliveries plans of 30 PI-containers (Multimodal & on-demand versus VRP)

The VRP approach proposes a solution in which the vehicle utilization rate decreases after each visit to the access hubs. As mentioned previously, all PI-containers are available at 7PM, regardless of the expected due dates. This constraint can lead to very long waiting times for the PI-containers once they reach their destination, as is the case for the orders 1 and 7 assigned to Truck 1. Lastly, the travel and unloading operations represent an occupation of urban space, either in terms of traffic or in terms of parking spaces.

In terms of the multimodal and on-demand solution, the results presented in Figure 6 show that each PI-container will have its own route defined according to the actual delivery times. This reduces the waiting time at the access hubs and ensures that the actual delivery time is close to the due date. This removes the constraint associated with the presence of all PI-containers at 7 PM, thus allowing greater flexibility in terms of arrival at the local hub. Of the 30 PI-containers delivered, 29 used only public transport by combining bus and tram lines, and only one PI-container used on-demand transport by cargo bike. The main resulting impacts are based on the reduction of the use of urban space and on the reduction of CO_2 emissions for goods delivery activities.

6 Conclusion

In this paper, a new approach is proposed for freight transshipment in an urban area based on the joint use of on-demand mode and public transport. The modeling approach is based on multiple transportation options, time windows and distance constraints. The solution approach is based on a forward-looking periodic approach that periodically solves the related on-demand multimodal transshipment problem with CPLEX. Based on the case of an urban mobility network in France, we proposed results that confirmed the effectiveness of our proposal in terms of service and sustainability. Several insights are derived from this showcase on the benefit of hyperconnectivity in ensuring an adequate delivery service, alternatively to dedicated on-demand vehicles. Also, the role of synchromodality is underlined in reducing the waiting time and parcels footprint at the urban level. Finally, this work demonstrates the benefits from creating synergies between freight and people mobility in urban areas from the economic, ecologic, and societal perspectives. These results show the feasibility of our proposal, and the performance levers it could bring in the future.

Avenues for further research include extending the model to consider several local hubs, more vehicle types/services in an on-demand mode. Extending the set transport options in the mobility network could also be an interesting avenue: leveraging options for goods transport that currently mainly dedicated to move people, such as automated vehicles (AVs) for on-demand transport requests.

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