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Research paper

Feasibility and optimization of freight-on-transit schemes for the sustainable operation of passengers and logistics

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ABSTRACT

The integration of passengers and cargo flows is a promising strategy to reduce negative externalities and improve the operational and environmental performances of first-last mile transport and logistics. This is supported by the recent increase in just-in-time and fragmented deliveries, as well as technological advancements in transport and logistics. In this study, we investigate the financial and operational conditions under which an integrated system can be used instead of performing conventional independent passenger transport and freight deliveries to achieve the goal of reducing freight vehicle-km and -consequently-the associated environmental impact. We propose the generalization of a multi-commodity network design problem model to address customer and policymaker preferences simultaneously for the implementation of a freight-on-transit (FOT) system. We test the model in a cross-border area between Italy and Slovenia and propose a sensitivity analysis based on several scenarios that can simulate the preferences of stakeholders under different conditions. The results show that FOT can yield considerable benefits in terms of meeting freight transport demand if it is supported by adequate policies and technologies. Furthermore, political and stakeholder engagement plays a relevant role in the success of FOT initiatives, which are aimed at utilizing transportation services and include the reduction of transport-related externalities and, more generally, the environmental and social impacts of mobility.

1. Introduction

Recent trends such as growing urbanization, globalization, and the increasing diffusion of e-commerce have led to an increased number of deliveries as well as increased activity and fragmentation of logistics. These trends present additional challenges to transport and logistics operators as well as authorities and policymakers, which results in significant negative impacts on the environment, communities, and society, thereby affecting people's quality of life (Lu et al., 2022; Nocera et al., 2020). Short-haul passenger and freight transport, particularly the first and last legs of longer transport movements (henceforth referred to as the first-last mile or FLM), is considered to be one of the most critical aspects of transport operations as it generates high costs and leads to disutility and extensive negative impacts in proportion to the entire trip; furthermore, it can exacerbate conflicts between overlapping needs and different components of the mobility system (Buldeo Rai et al., 2017; Macioszek, 2019; Taniguchi & Thompson, 2018). Authorities and policymakers try to tackle congestion and conflicts for road space, noise, and other transport-related impacts in inorganic, uncoordinated ways, which yield limited outcomes. Counterproductive effects, such as a further loss of competitiveness of transport operations and a more articulated, unsmooth structure of the mobility system, are also observed (Dablanc, 2007; Schröder & Liedtke, 2017). In 2007, the Green Paper on Urban Mobility (European Commission, 2007) explicitly mentioned the potential of the integration between passenger and freight transport, with the goal of increasing the environmental, social, and financial sustainability of the FLM. Scholars and practitioners followed this suggestion and developed a substantial body of literature on possible forms of short-haul passenger -freight combined transport (henceforth, freight-on-transit or FOT) in both cities and rural areas (Cavallaro & Nocera, 2021, 2023). In urban environments, the main goals include tackling congestion, noise, and environmental issues and promoting a more efficient use of urban space. In rural environments, FOT primarily aims to increase the financial sustainability of transport and logistics operations, retain the attractiveness and competitiveness of remote areas and businesses, and increase the number of opportunities and quality of life for local

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residents (Azcuy et al., 2021). FOT contributions for the FLM can be classified based on two aspects. One includes the investigation of the performances of simulated or real-life integrated systems, mostly by means of ad-hoc performance indicators (Mazzarino & Rubini, 2019), whereas the other includes the development of mathematical models aimed at the optimization of integrated systems and introduction of numerous variants of the routing, dial-a-ride, ride-sharing, and pickup-and-delivery problems using specific constraints (Ghilas et al., 2018). More precisely, performance indicators have been used to discuss the convenience of integrated systems and their suitability for achieving sustainability targets and reducing transport negative externalities. The EU-funded project NOVELOG (2016) proposed a transferable universal toolkit for the key performance indicators for FOT. The topic was further studied by Bruzzone (2019), Bruzzone et al. (2021) and Mazzarino and Rubini (2019). The goal of these contributions is to explore the potential benefits of FOT operations in comparison to conventional transport and logistics management, focusing on the environmental, socioeconomic, and financial/operational performances of FOT. Although the results obtained in these studies are interesting, they do not answer the question of when to adopt FOT and when to perform independent delivery/transport movement, according to stakeholders' needs and preferences. Moreover, the focus of the evaluation based on performance indicators does often not comprise the operational aspect but rather only the environmental and social impacts (and benefits) of FOT. Unlike performance evaluation, the mathematical modeling approach has been adopted by several authors. Metaheuristic and heuristic models have been used in most studies on this topic. Li et al. (2014) proposed a mixed integer linear programming model to solve the share-a-ride problem for people and parcel-sharing taxis. Ghilas et al. (2018, 2016a, 2016b, 2013, 2016c) presented a series of heuristic algorithms to solve different variants of the pickup-and-delivery problem, including time windows, scheduled lines (to simulate the public transport component), and the stochastic demand. Dong et al. (2018) and Pimentel and Alvelos (2018) proposed mixed integer linear programming for shared transport by subways and buses, respectively. Meanwhile, Ozturk and Patrick (2018) proposed FOT by trams and presented an approximation algorithm and a pseudo-polynomial dynamic programming algorithm, supplemented by a heuristic method and two mixed integer models. Molenbruch et al. (2021) also proposed a metaheuristic routing algorithm for an on-demand FOT, and Li et al. (2022) presented a mixed integer linear programming model to determine the optimal allocation of freight on public transit (capacity matching) to avoid passenger disutility. To the best of our knowledge, existing studies on FOT have focused on optimal routing and scheduling models. In this study, we develop a model designed to determine the conditions under which it is convenient to adopt an FOT approach or operate passenger and freight transport separately (conventional approach), according to the perspectives of multiple stakeholders. For this purpose, we present the case study of the area between Trieste (Italy) and Koper (Slovenia). Our model considers a generalization of the problem of designing a network for a multi-commodity flow, see e.g., Ahuja (1993). Indeed, freight can be seen as a set of multiple commodities (flow demands) between different origins and destinations and we are interested in designing a network of bus trips and other transportation/transshipment services used for both passengers and freight that can satisfy at least some of these demands.

The ultimate goal is to determine the conditions and constraints (intrinsic characteristics of the mobility systems; policies and regulations by authorities; or stakeholders' needs, requests, and preferences) that favor the adoption of a FOT (i.e., FOT is financially and operationally preferable, allowing for a sustainable reduction of freight vehicle-km and of the consequent impacts) and which, on the contrary, play for the retainment of existing independent operations. In contrast to previous operational research on FOT, our model acts on the strategic level and demonstrates the ability of FOT to serve freight transport demand in relation to external and operational conditions as well as current freight and passenger volumes, vehicle-km, and subsidies.

The contribution of this study is thus twofold, as it presents a simulation tool with practical implications in real-life FOT decision-making and explores an open research gap with an innovative method that is an alternative to performance evaluation by means of indicators. The remainder of this paper is structured as follows: Section 2 introduces the problem and discusses the structure, variables, objectives, and constraints of the proposed model; Section 3 describes the case study area and the model application, and Section 4 discusses the results. Finally, Section 5 concludes the paper.

2. Problem description and modeling framework

In this paper, we discuss the convenience of a FOT system according to various conditions and de facto propose a feasibility study that could be useful to authorities and decision makers as well as to scholars studying the topic. This study will help understand the constraints and conditions because of which FOT becomes feasible and how different decisions made by decision-makers can affect the overall validity of the concept. We consider the problem of opting for the transportation of freight on public transportation to satisfy the demand of customers distributed in a set $\mathcal{N}$ of different non-overlapping areas that constitute the region of interest. We consider different types of decision makers that participate in the system to satisfy the demand. Specifically, we have:

- the main decision maker (DM_0), who addresses the feasibility study;
- the decision makers that provide transportation services. Specifically, S denotes the set of transportation service providers,
- the decision makers that manage intermediate hubs. Specifically, H denotes the set of intermediate hub managers.

The main decision maker DM_0 is typically a public or government authority, but can also be a private company, interested in determining whether a FOT system is worth implementing, possibly with public funding. DM_0 defines the "political" constraints and goals of a FOT system. They may include the CO2 emissions, the number of potential customers, the amount of freight shipped, the amount of financial support to be provided.

The transportation service providers $DM_i, i \in S$, are the managers of the transportation companies who decide which sets of bus trips or other transportation services can be considered for integrated passenger and freight transportation. In addition, they define constraints on the maximum amount of freight that can be loaded on their vehicles and on the minimum return they require to provide their services.

The intermediate hub managers $DM_i, i \in H$ are the managers of the companies responsible for transferring cargo from one vehicle to another, and possibly storing it temporarily. They decide where these operations can take place. In addition, they define constraints on the maximum amount of freight that can be handled and minimum return they require to provide their service.

It is important to note that the above decision makers may overlap and be of different types. For example, some transportation service providers and intermediate hub managers may belong to the same company or even be the same person. Differently, in areas with low demand for transportation, some hub manager can simply be the owners of proximity stores, such as newsstands, close to bus stops that provide their services to supplement their incomes.

Hereinafter, we will also use the following terminology. An amount of freight is:

- *shipped* if it is moved from its origin to its destination;
- *transported* if it is moved on a vehicle along a transportation service leg, e.g., it is moved between two consecutive stops of a bus trip;
- *transshipped* if it is moved from one vehicle to another;
- *served* if it is either transported or transshipped.

In addition, we will use the term *service* to refer to both a transportation service and a transshipment service provided by DMs other than DM_0.

We aim to develop and solve a model that allows the DM_0 to address the following problem:

Problem 1. Determine which decisions should be implemented by the DM_0 and which responses the other DMs should give to realize a FOT system.

For the solution of the presented Problem 1, we propose a generalization of a multi-commodity network design problem where the decisions on which arcs of the network to activate must also guarantee some returns to the different DMs. Specifically, we have to design a network for a multi-commodity flow, so we are subject to standard flow balancing and capacity constraints, but we must also consider at least some additional financial constraints to guarantee the DMs' returns.

In the formulation of our model, We assume that:

Assumption 1. DM_0 is evaluating the feasibility of a FOT system that includes a set of transportation services that have a constant daily schedule.

Under the above assumption, DM_0 can focus its decisions on the services of a single day and consider the average daily demand available at the beginning of the day as the potential demand for freight service. This assumption also implies that the un-served demand is considered lost and not rescheduled to be served later. In addition, we hold that DM_0 and the other decision maker have already reached the following agreement in a preliminary phase.

Assumption 2. Any decision maker other than DM_0 is obligated to provide the services requested by DM_0, who in turn guarantees the desired minimum return on those services.

Under this second assumption, DM_0 must decide the amount of freight served by the various services provided by the other decision makers and, coherently, the amount of financial support that it is willing to provide to these services.

2.1. Network and main notation

We model the region to serve as an oriented network $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ where the nodeset $\mathcal{N}$ includes the nodes that represent the region areas, and arcset $\mathcal{A}$ includes an oriented arc $k = (b, e) \in \mathcal{N}^2$ if at least a service with a leg k may be activated.

We distinguish the different types of freight/commodities to be shipped c by the couple of their origin nodes o and destination nodes d, that is, $c = (o, d)$.

We assume that there exists a demand $\bar{v}^c$, for shipping each freight $c = (o, d) \in \mathcal{N}^2$. In addition, we assume that each freight c would travel a distance λ^c if not shipped through the FOT system.

Let D be the set union of the sets of transportation service providers and of the intermediate hub managers, i.e., $D = H \cup S$. In addition, the following notations are included:

- Γ denotes a set of services; specifically
  - Γ_i is the set of services that a $DM_i, i \in D$, can provide
  - $\Gamma_S = \bigcup_{s\in S} \Gamma_s$ is the set of all the services that can be provided by the transportation service providers,
  - $\Gamma_H = \bigcup_{h\in H} \Gamma_h$ is the set of all the transshipment services that can be provided by the intermediate hub manages,
  - $\Gamma = \Gamma_S \cup \Gamma_H$ is the set of all the possible services that can be provided.
- Λ denotes the maximum amount of serviceable demand; we define Λ_j as the maximum amount of serviceable demand by $DM_i \in D$, as a consequence of the implementation of its service $j \in \Gamma_i$.
- $i(j)$ denotes that $DM_i \in D$, with $i = i(j)$, is the DM that provides the service $j \in \Gamma_i$.

We remark that we assume without loss of generality that each service $j \in \Gamma$ is unique to a specific $DM_{i(j)} \in D$. Indeed, this assumption does not prevent the possibility that two or more equivalent services provided by different competing service providers exist, e.g., two buses connecting the same origin–destination pair in the same time window. On the other hand, this assumption is necessary to allow DM_0 to uniquely identify which DM must be financially supported for the activation of a service.

2.2. Variables

We introduce the following sets of continuous non-negative variables to model the decisions to be made by DM_0.

For all the commodities $c \in \mathcal{N}^2$,

$$v_j^c = \text{amount of freight } c \text{ that must be } \textit{served} \text{ by service } j, \quad \forall j \in \Gamma,$$

$$w_{jl}^c = \text{amount of freight } c \textit{ transshipped} \text{ from service } j \text{ to service } l, \quad \forall j \in \Gamma^c, l \in \Gamma_j^c$$

where $\Gamma^c \subseteq \Gamma_S$ is the set of transportation services that may transport some of the freight c and $\Gamma_j^c \subset \Gamma^c$ is the set of services in Γ^c that may receive freight c from service j because their schedules allow sufficient time for a transshipment.

For all services $j \in \Gamma$:

$$Q_j = \text{amount of the financial support provided by } DM_0 \text{ to } DM_{i(j)} \text{ for its service } j.$$

We also introduce the following set of binary variables to model which service must be implemented as a result of the DM_0 decisions:

$$x_j = \begin{cases} 1 & \text{if the } DM_{i(j)} \text{ must implement service } j, \\ 0 & \text{otherwise} \end{cases} \quad \forall j \in \Gamma.$$

Finally, we introduce the following sets of continuous non-negative variables to simplify the writing of constraints and objectives. For all the commodities $c \in \mathcal{N}^2$,

$$v^c = \text{overall amount of freight } c \textit{ shipped},$$

$$v_{jk}^c = \text{amount of freight } c \textit{ transported} \text{ along leg } k \text{ of service } j. \quad \forall j \in \Gamma^c, \forall k \in j.$$

2.3. Objectives

We assume that the main decision maker DM_0 is a public authority interested in reducing the environmental impact of freight transportation and minimizing both the financial support provided to other DMs for their services and the number of transshipment operations.

Accordingly, we consider as possible objective functions:

$$\max z_0 = \sum_{c\in\mathcal{N}^2} \lambda^c v^c \tag{1a}$$

$$\max z_1 = \sum_{c\in\mathcal{N}^2} v^c \tag{1b}$$

$$\min z_2 = \sum_{j\in\Gamma} Q_j \tag{1c}$$

Objective (1a) states that DM_0 maximizes the amount of freight shipped within the FOT weighted by the distance it must travel as it is strictly correlated to the emissions induced by shipment operations that can be avoided.

Objective (1b) states that DM_0 maximizes the amount of freight shipped within the FOT, as it is strictly correlated with the number of served customers and, hence, customer satisfaction.

Objective (1c) states that DM_0 maximizes its provided financial support.

2.4. Constraints

The number and type of services provided a DM_i (for $i \in D$) can be subject to some constraints. These are discussed in Sections 2.4.1 to 2.4.3.

2.4.1. Flow-balancing constraints

The flow-balancing constraints, i.e. mass conservation constraints, guarantee that freight cannot be lost or created within the FOT system.

For each freight $c = (o,d) \in \mathcal{N}^2$, let $\Gamma^c(o)$ be the subset of transportation services in Γ^c that have a leg that starts in o and $\Gamma^c(d)$ be the subset of transportation services in Γ^c that have a leg that ends in d. Additionally, let $k(j,o)$, respectively $k(j,d)$, be the leg that starts in o, respectively ends in d, of a service $j \in \Gamma^c$.

The following conditions must hold.

$$\bar{v}^c \geq v^c = \sum_{j \in \Gamma^c(o)} v^c_{jk(j,o)} = \sum_{j \in \Gamma^c(d)} v^c_{jk(j,d)}, \quad \forall c = (o,d) \in \mathcal{N}^2 \tag{2}$$

Condition (2) imposes that the total amount of freight v^c shipped from o to d must not exceed the demand $\bar{v}^c$ and must be equal to the amount loaded on services belonging to $\Gamma^c(o)$ at the beginning of their legs $k(j,o)$, and unloaded from services belonging to $\Gamma^c(d)$ at the end of their legs $k(j,d)$.

For each $c = (o,d) \in \mathcal{N}^2$, let j^c be the ordered set of legs of a service $j \in \Gamma^c$ along the path from origin o to destination d. The following conditions must also hold:

$$v^c_{jk+1} = v^c_{jk} + \sum_{l: j \in \Gamma^c_l(e)} w^c_{lj} - \sum_{l \in \Gamma^c_j(e)} w^c_{jl} \quad \forall c = (o,d) \in \mathcal{N}^2,\ j \in \Gamma^c,\ k = (b,e) \in j^c \tag{3a}$$

$$v^c_{jk} = \sum_{l: j \in \Gamma^c_l(b)} w^c_{lj} \quad \forall c = (o,d) \in \mathcal{N}^2,\ j \in \Gamma^c,\ k = (b,e) \text{ first leg of } j^c \text{ if } b \neq o \tag{3b}$$

$$v^c_{jk+1} = 0 \quad \forall c = (o,d) \in \mathcal{N}^2,\ j \in \Gamma^c,\ k = (b,e) \text{ last leg of } j^c \tag{3c}$$

where $k+1$ is the leg that follows leg k, $\Gamma^c_j(e)$ is the subset of services in Γ^c that connects with j at the node e, and $\Gamma^c_j(b)$ is the subset of services in Γ^c that connects with j at node b of leg $k = (b,e)$.

Condition (3) imposes that the amount of freight c transported by service j at the beginning of each of its legs must be equal to the amount of c transported by j in the previous legs k plus the amount of c transshipped from other services to j minus the amount of c transshipped from j to other services.

Condition (3) allows that the transshipment from a transportation service j to a transportation service l to occur at a different node for each pair of services. However, it assumes that the transshipment can only occur in one of the possible multiple nodes in $\mathcal{N}$ where the routes of the two transportation services intersect. However, these assumption can be trivially relaxed to situations where transshipments between the same pair of services can occur at different nodes. In these cases, the transshipments should be described by a larger set of variables. Instead of variables w^c_{jl}, we should introduce w^c_{jlk} whose values represent amount of freight c transshipped from service j to service l at node k.

2.4.2. Capacity constraints

The capacity constraints express the limits on the amount of freight that can be served by DMs.

With regard to the transportation service providers, the capacity constraints can be expressed as follows:

$$\sum_{c \in \mathcal{N}^2 : j \in \Gamma^c} v^c_{jk} \leq \Lambda_j x_j, \quad \forall j \in \Gamma_S,\ k = (b,e) \in j \tag{4}$$

Condition (4) imposes that the total amount of freight to be transported by service j at the beginning of each of its legs must not exceed the service transportation capacity if the service is implemented, and no freight can be transported otherwise.

With regard to the intermediate hub managers, the capacity constraints can be expressed as follows:

$$\sum_{c \in \mathcal{N}^2} \sum_{j \in \Gamma^c} \sum_{l \in \Gamma^c_j(r)} 2w^c_{jl} + \sum_{c=(r,d), d \in \mathcal{N}^2} v^c + \sum_{c=(o,r), o \in \mathcal{N}^2} v^c = \sum_{j \in \Gamma_H(r)} v_j, \quad \forall r \in \mathcal{N} \tag{5a}$$

$$v_j \leq \Lambda_j x_j, \quad \forall r \in \mathcal{N}, j \in \Gamma_H(r) \tag{5b}$$

$$\sum_{j \in \Gamma_H(r)} x_j \leq 1, \quad \forall r \in \mathcal{N} \tag{5c}$$

where $\Gamma_H(r)$ is the subset of services in Γ_H that corresponds to the opening of an intermediate hub at node $r \in \mathcal{N}$ to provide transshipment services.

Condition (5) imposes that the total amount of freight that can be transshipped, loaded and unloaded in each node of the network cannot exceed the freight movement capacity of the intermediate hub that operates in the node, if any. Variable v_j in the condition (5b) denotes the total amount of freight served by service j of an intermediate hub manager.

Here, we remark again that, possibly, transshipment services can be provided by the owners of proximity shops. In this situation, the intermediate hub may consist of a small storage room or simply of a dedicated space on the shelves of the stores.

2.4.3. Financial constraints

Financial constraints guarantee the economic sustainability of the DMs' services. Before placing these constraints, we need to introduce the conditions that define the values of the variables v^c_j for transportation services.

$$v^c_j = v^c_{jk(j,o)} + \sum_{l \in \Gamma^c_j} w^c_{jl}, \quad \forall c = (o,d) \in \mathcal{N}^2, j \in \Gamma_S \tag{6}$$

Condition (6) states that the total amount of freight $c = (o,d)$ served by transportation service j is equal to the amount of freight c loaded at the freight origin o, if o is part of a leg of j, plus the amount of freight c transshipped on j from other services.

The first set of financial constraints includes the budget constraints that form the upper bound of the expenses that a DM can afford:

$$\sum_{j \in \Gamma_i} \left(f_j x_j + \sum_{c \in \mathcal{N}^2 : j \in \Gamma^c} g^c_j v^c_j \right) \leq B^i + \sum_{j \in \Gamma_i} Q_j, \quad \forall i \in D \tag{7a}$$

$$\sum_{j \in \Gamma} Q_j \leq B^0 \tag{7b}$$

where f_j and g^c_j are respectively the fixed and the variable costs paid by DM_i to implement service j; B^i is the budget allocated by DM_i to implement its services $j \in \Gamma_i$; B^0 is the budget allocated by DM_o to possibly support services $j \in \Gamma$.

Condition (7a) imposes that DM_i's expenses must not exceed the allocated budget plus the financial support provided by DM_0.

Condition (7b) imposes that the financial support provided by DM_0 to the services cannot exceed budget B^0.

Note that the above conditions (7a) and the following equation (8) are written from the transportation service providers' perspective. The same conditions when expressed from the intermediate hub managers' perspective include $d_j v_j$ instead of $\sum_{c \in \mathcal{N}^2 : j \in \Gamma^c} g^c_j v^c_j$ because the costs of the operations do not depend on the origin and the destination of the freight. The costs d_j and g^c_j should also include the inventory costs when the cargo are supposed to remain at the intermediate hub for some time during its transshipment from one vehicle to another vehicle.

The second set of financial constraints includes the economic sustainability constraints that form the lower bound of the earnings that a DM should expect:

$$Q_j - f_j x_j + \sum_{c \in \mathcal{N}^2 : j \in \Gamma^c} (p^c_j - g^c_j) v^c_j \geq E_j x_j, \quad \forall i \in D, j \in \Gamma_i \tag{8}$$

where p^c_j is the payment received by $DM_{i(j)}$ per unit of service j for freight c and E_j is the minimum earning expected by $DM_{i(j)}$ for implementing service j.

Condition (8) imposes that a minimum earning must be guaranteed to a DM_i that implements a service j.

The constraints presented in the previous subsections can be easily generalized, and others can be introduced if they are required to better specify the request under examination. These could consider, for example, that some services are in some way interdependent because they either are mutually exclusive or must all be implemented together, or that more than one intermediate hub must be present in some of the network nodes. Other constraints could be introduced to deal with start-up costs. Indeed, the implementation of a FOT system may require the restructuring and re-certification of the used vehicles. The associated costs can only be justified if sufficient services are provided. Finally, other constraints may include special legal costs, e.g. related to liability, both in the start-up phase and in the operating phase.

In Section 3.1, following the introduction of the case study, we present a scenario analysis to model the FOT under different conditions of the presented constraints. In Section 4, we discuss the role of possible variations in the overall setting and constraints affecting our model and FOT itself.

3. Case study

We conducted a case study to determine the feasibility of FOT in the area between the towns of Trieste (in North-Eastern Italy), Koper, and Piran (in Slovenia), including the three cities themselves (see Fig. 1). Koper has 25,753 residents and features an interurban and international station for both buses and trains. It has the most important container port in the Adriatic Sea (Xin, 2021). Along the Adriatic coastline, one major road crosses Izola, Belvedere, Strunjan, and Portoroz and reaches the town of Piran at the outskirts of Koper's administrative division and terminus of most bus services. Piran has 3733 residents. Along with other coastal settlements in Istria, it has several tourists during the summer season: as of 2010, Piran had already offered 14,015 beds for tourist exploitation, compared to only 4654 beds available in Koper (Gosar, 2014). Compared to Istrian towns, Trieste is a larger city (about 230,000 inhabitants) and is a competitor of Koper for port activities. As it is a watershed between the Western and Eastern blocks, its post-war economic and social development trends have mainly tended towards central Europe and the Mediterranean (Benazzo, 2021; Gaiser, 2018). Therefore, its systematic passenger and freight movements towards Slovenia are still very limited. Few commuters cross the border on a regular basis, and the goods delivery and management systems of Italy and Slovenia are largely separated, each relying on their respective national infrastructures. From the perspective of the volumes of movements towards Istria, Trieste can easily be included in the corridor towards Koper, which was included in this study. The smallest mobility figures, at least for passenger transport, are observed.

Bus services in the area are operated by a local subsidiary of Arriva, a company part of the Deutsche Bahn (German Railways) group. Local buses operate around Koper, whereas interurban buses serve the stretch between Trieste, Koper and Piran, approximately from 5:00 to 22:30 daily. For the application of the model in the baseline scenario, as presented in Section 2, we analyzed and considered specific characteristics of the case study area:

- According to the location of the termini and main stops of buses along the Trieste-Koper-Piran corridor, we determined the placement of 16 "intermodal hubs" r (Fig. 1), where goods can be consolidated and loaded/unloaded onto buses. Of these, 10 are located outside the urban area of Koper and serve an equal number of locations on the corridor, in accordance with existing transit routes and stops. Six, instead, are within the municipality of Koper and serve some of its main points of interest, already served by the existing bus network: the historic center, the hospital, the main commercial/industrial area, and the intermodal bus and railway station.
- Consistent with other studies (Bruzzone et al., 2021; Jansen, 2014), we limited FOT to off-peak hours and excluded departures between 6:00 and 9:00 and between 16:00 and 18:00. This allows to safeguard the capacity of buses to transport passengers during demand peaks as well as to ensure at least three FOT services per day to each intermodal hub from a policy and operative perspective. This also allows for the management of "return logistics", dealing with empty rolls and containers.
- In accordance with previous research (Ghilas et al., 2013), we considered that each bus can be adapted to transport (inside the cabin, if the bus is low-floor, or in the baggage compartments, otherwise) two standard rolls, for a total of 1.84 cubic meters of palletized goods. Because the density of the load cannot be determined, we hypothesized a loading capacity of 100 kg per bus conservatively. This could be easily increased in the case of heavier loads (e.g., liquids) without occupying an additional volume. Regarding intermodal hubs, we assigned a storage capacity of 3000 kg each, with two exceptions: the hub at the bus and train station in Koper, where we have allocated a total capacity of 25,000 kg; the hub at the Trieste bus and train station, for which we considered that either the 3000 kg or the 25,000 kg storage capacity could be realized; (Tables 1 and 2).
- In this case study, we referred to the official timetable of buses between Trieste, Koper, and Piran, which is based on a bi-hourly cross-border service plus a twice-hourly local service in Istria. This schedule, however, varies consistently, and services do not always follow a regular pattern. In general, 12 buses per direction operate between Trieste and Koper daily, whereas 38 serve the Koper to Piran stretch, and 36 daily return trips are offered within Piran on the urban service.
- Following the indications of previous research (Bruzzone et al., 2021; NOVELOG, 2016) we selected the categories of goods to be included in the FOT system through Slovenia Statistics (SiStat, 2017) non-perishable palletized and pre-slung goods transported by vehicles with a capacity $\leqslant 9{,}999$ kg. Thus, we limited our case study to the freight of the selected categories headed to or leaving the area of interest and exclude goods carried on trucks with a capacity exceeding 9999 kg. Finally, we considered empty trips and return logistics. Data of freight volumes were obtained by merging official statistical data available on SiStat and traffic count data provided by the Koper Regional Development Centre. Considering the freight volumes, traffic counts, and distances between the various stops and intermediate hubs, the model can determine the amount of goods moved along the main itineraries (from Trieste towards Koper and Piran or vice-versa, and between different intermodal hubs in Slovenia) in our area of study, each assigned in the model to a corresponding bus line.

The model developed according to the presented conditions is thus able to estimate the number of freight vehicle trips that can be avoided by FOT in the case study area according to the specifications illustrated above, thus overcoming datasets uncertainty regarding freight transport. Moreover, we analyzed multiple scenarios,determined by different conditions of the constraints presented above and/or by the maximization of different objectives. Our scenario analysis was aimed at understanding the conditions under which FOT is financially and operationally viable as an alternative to conventional non-integrated passenger and freight transport. Section 3.1 presents the 15 scenarios examined and specifies their characteristics.

3.1. Scenarios

We considered 15 different scenarios (Scenarios A_0 - E_2) with the aim of showing how our model allows DM_0 to determine its financial support and how the different objectives may influence the services that will be provided. We assumed that, given the main hypotheses

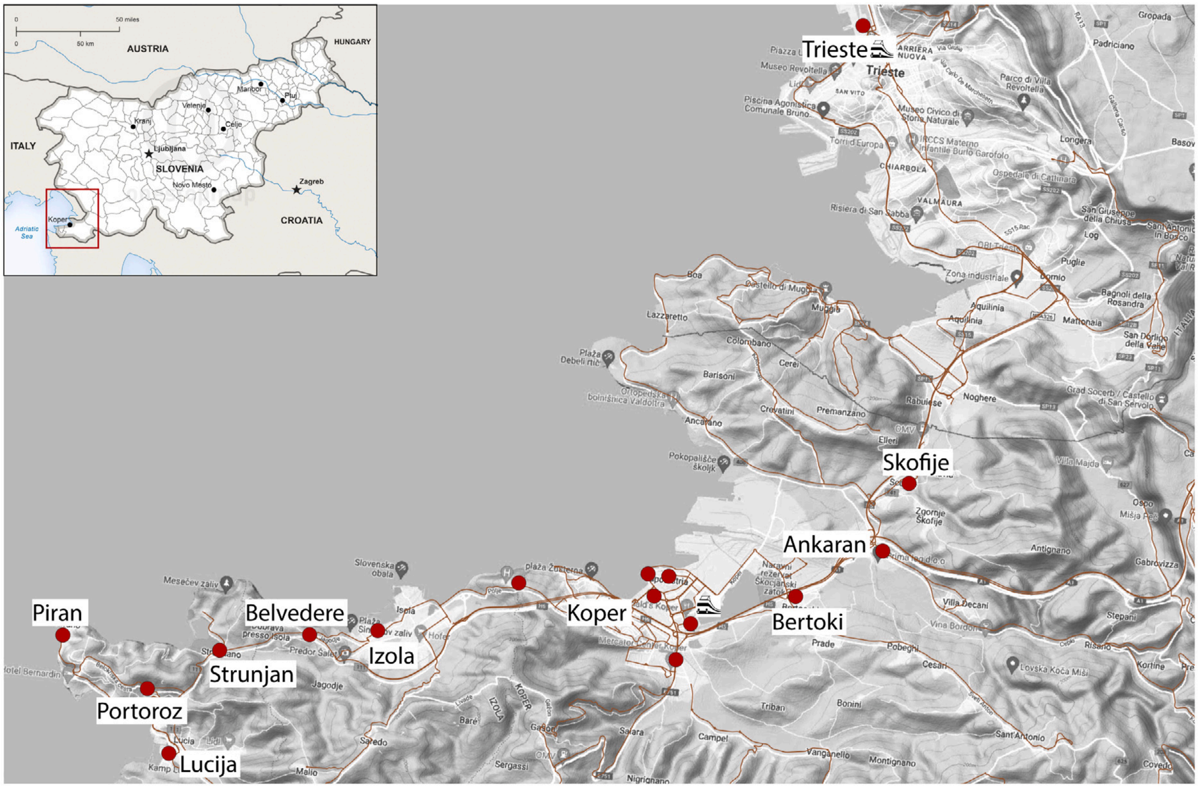

Fig. 1. Case study area: geographic location, bus routes, consolidation and intermodal hubs.

Table 1
Hub characteristics.

Hub type	Num. of hubs	Fixed cost [€]	Variable cost [€/kg]	Price [€/kg]	Minimum earning [€]	Capacity [kg]
TS, KP	2	400.00	0.01	0.30	300.00	25,000
Others	14	40.00	0.01	0.30	50.00	3000

on the values of the selected parameters (see Tables 1 and 2), the objectives (1a), (1b), and (1c) introduced in Section 2.3 are optimized following a lexicographical approach. Specifically,

- In scenarios characterized by subscript 0, DM_0 first optimizes the objective (1a) and then the objective (1c).
- In scenarios characterized by subscript 1, DM_0 first optimizes objective (1a), then objective (1b), and finally objective (1c)
- In scenarios characterized by subscript 2, DM_0 first optimizes objective (1b) and then objective (1c)

For example, in scenarios characterized by subscript 0, as a first step, DM_0 solves the model defined by constraints (2)–(8) and objective function (1a) to determine the optimal value z_0^* of z_0.

As a second step, DM_0 solves the same model again, with the additional constraint

$$z_0^* = \sum_{c \in \mathcal{N}^2} \lambda^c v^c$$

and considering the objective function (1c) instead of (1a). Hence, at the end of the first step, DM_0 can assess the maximum amount of freight-km that the FOT system can manage and decide whether it is worth pursuing the realization of the system. At the end of the second step, DM_0 can assess the cost of the FOT system and determine whether it is worth the emissions saved.

We applied the objective optimizations described above to different policy and operational conditions. The baseline is the current setting where passengers and goods are treated independently; thus, the freight system receives no subsidies from DM_0, whereas the bus system does not serve any freight (served demand, involved services, number of hubs are all equal to 0). The 15 alternative scenarios are all based on this condition, and different uptake and constraints by all DM_i are simulated.

In Scenarios A_0–A_2, we assume that the operators have unbounded budgets, and no financial support is provided by DM_0. The opposite case is considered for Scenarios B_0–B_2. In Scenarios C_0–C_2, we consider the same assumptions as those in B_0–B_2. Furthermore, we assume that the financial support by DM_0 cannot exceed 1,000.00 € per day. In Scenarios D_0–D_2, we consider the same assumptions as in B_0–B_2; furthermore we assume that the services provided by cross-border buses have a freight loading capacity of 500 kg (see Table 2). In Scenarios E_0–E_2, we consider the same assumptions as in D_0–D_2; furthermore we assume that the financial support by DM_0 cannot exceed 5,000.00 € per day. Table 4 summarizes the results.

Table 3 reports the main characteristics that differentiate the various scenarios. For example, Scenario C_1 assumes that operators are not willing to invest their budgets but may receive up to 1000.00 €/day from DM_0; buses can carry at most 100 kg of freight for each run; objectives(1a), (1b), and (1c) are optimized lexicographically.

The problem considered in this study is NP-hard because it generalizes a multi-commodity network design problem. However, all instances reported in Table 4 were solved using FICO Xpress 8.2, a commercial optimization solver for mixed integer linear programming, in a few seconds on a laptop equipped with an Intel Core i7-9750H CPU @ 2.60 GHz and 32 GB RAM.

4. Discussion

The results presented in Table 4 offer insights into the potential of an FOT in general and in the study area. To provide the reader with a reference to understand the results of the scenario analysis, we recall that in the baseline scenario, where goods are carried by dedicated vehicles, we estimated that approximately 851,000 kg×km of the daily freight of the categories of interest is moved in the case study area

Table 2
Bus characteristics.

Bus type	Num. of lines	Num. of services	Num. of stops	Fixed cost [€]	Variable cost [€/kg × km]	Price [€/kg]	Minimum earning [€]	Capacity [kg]
Cross-border	3	17	5–10	10.00	0.01	0.40	10.00	100 or 500
Local	3	104	6–7	10.00	0.01	0.30	10.00	100

Table 3
Scenario characteristics.

	Scenario subscript		
Scenarios letter	0	1	2
A	Operators' budgets unbounded DM_0 financial support = 0 Objectives: (1a) (1c), Capacities = 100 kg	Operators' budgets unbounded DM_0 financial support = 0 Objectives: (1a) (1b) (1c), Capacities = 100 kg	Operators' budgets unbounded DM_0 financial support = 0 Objectives: (1b) (1c), Capacities = 100 kg
B	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1a) (1c), Capacities = 100 kg	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1a) (1b) (1c), Capacities = 100 kg	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1b) (1c), Capacities = 100 kg
C	Operators' budgets = 0 DM_0 financial support = 1000.00 €/day Objectives: (1a) (1c), Capacities = 100 kg	Operators' budgets = 0 DM_0 financial support = 1000.00 €/day Objectives: (1a) (1b) (1c), Capacities = 100 kg	Operators' budgets = 0 DM_0 financial support = 1000.00 €/day Objectives: (1b) (1c), Capacities = 100 kg
D	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1a) (1c), Capacities = 100–500 kg	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1a) (1b) (1c), Capacities = 100–500 kg	Operators' budgets = 0 DM_0 financial support unbounded Objectives: (1b) (1c), Capacities = 100–500 kg
E	Operators' budgets = 0 DM_0 financial support = 5000.00 €/day Objectives: (1a) (1c), Capacities = 100–500 kg	Operators' budgets = 0 DM_0 financial support = 5000.00 €/day Objectives: (1a) (1b) (1c), Capacities = 100–500 kg	Operators' budgets = 0 DM_0 financial support = 5000.00 €/day Objectives: (1b) (1c), Capacities = 100–500 kg

Table 4
Results for Scenarios A - E.

Scenario Scenario	DM_0 daily budget	Served demand WDT in kg × km	Served demand in kg	Num. of trasp services	Num. of hubs	Served demand percentage
Scenario A_0	0.00	122,340	12,994	111	16	17.9%
Scenario A_1	0.00	122,340	13,303	113	16	18.3%
Scenario A_2	0.00	101,612	15,083	120	16	20.8%
Scenario B_0	3,742.00	122,340	12,470	117	16	17.2%
Scenario B_1	3,771.66	122,340	13,173	118	16	18.1%
Scenario B_2	3,607.07	98,511	15,083	118	16	20.8%
Scenario C_0	1,000.00	46,500	3000	29	5	4.1%
Scenario C_1	1,000.00	46,500	3000	29	5	4.1%
Scenario C_2	989.00	7300	3800	28	5	5.2%
Scenario D_0	6,021.70	303,790	17,570	121	16	24.2%
Scenario D_1	6,078.56	303,790	20,413	121	16	28.1%
Scenario D_2	5,863.97	272,273	23,260	120	16	32.0%
Scenario E_0	4,736.70	281,250	12,870	69	7	17.7%
Scenario E_1	4,990.67	281,250	17,100	76	9	23.5%
Scenario E_2	4,845.48	226,965	20,188	84	15	27.8%

owing to traffic counts and freight transport statistics, as discussed in Section 3.

Hereinafter, in commenting the application of our model to the case study, we use the term *served demand* when we consider the served demand only in terms of its weight in kg, and *served demand WDT* when we consider the served demand weighted by the distance to be traveled in kg × km.

Consider scenarios A_0–A_2, B_0–B_2, and D_0–D_2 that assume no budget constraints. Under this hypothesis, all 16 hubs are always used, that is, it is convenient to have a hub in each town/village served by public transport. In particular, Scenarios A_0–A_2 show that the payment that hubs receive for their freight transshipment services are sufficient to guarantee minimum earnings, even in absence of financial support from DM_0. Differently, not all 121 transportation services made available by buses are exploited in Scenarios A_0–A_2 and B_0–B_2.

A comparison between Scenarios A_0–A_2 (no financial support from DM_0) with Scenarios B_0–B_2 (no bound on the financial support from DM_0) shows that some transportation services cannot guarantee minimum earnings if there is no financial support from DM_0. In addition, a comparison between Scenarios B_0–B_2 (capacity of cross-border buses: 100 kg/*bus*) with Scenarios D_0–D_2 (capacity of cross-border buses: 500 kg/*bus*) shows that the potential of cross-border FOT can be exploited only if the buses have a capacity greater than 100 kg each. If we assume that a worker can move freight only up to 100 kg without any assistance, then a 500 kg/*bus* capacity would require the presence of a forklift or other mechanical aid at the hubs served by cross-border buses. In addition, a greater capacity may raise some passenger comfort concerns, both regarding the spare capacity and timeliness of operations (Ghilas et al., 2013). Meanwhile, we remark that the improved capacity setting of 500 kg/*bus* is still a conservative value, with limited impact on vehicle surface availability especially in the presence of a luggage compartment, which is the case for the vast majority of interurban trips.

The considered scenarios also prove that, given the available bus service, at most 20% (32% in case of greater bus capacities, scenario D_2) of the demand can be served by integrating passengers and freight transportation. This can lead to consistent reductions in the traveled distances and -likely-related negative externalities compared to the existing situation, particularly since our FOT application moves freight on existing bus services only.

The comparisons between scenarios B_0–B_2 with scenarios C_0–C_2, and scenarios D_0–D_2 with scenarios E_0–E_2 show how the service provided depends on the financial support provided by the DM_0 in an extreme situation where the operators are assumed to be unwilling to budget any money in advance. In particular, if financial support is limited, the FOT system is only capable of marginal benefits; furthermore, conventional independent passenger and freight transport become convenient for most trips, and only 4.1%–5.2% of the total freight transport demand is served by buses in the FOT.

The differences between the results of scenarios indexed by 0, for example, B_0, and the results of the corresponding scenarios indexed by 1, for example, B_1, prove that, in general, multiple solutions that provide the same results in terms of served demand WDT are possible. Hence, second-level optimization that maximizes the number of customers served at the cost of a relatively small increase in the financial support required from DM_0 is worth considering.

The differences between the results of scenarios indexed by 2, e.g., B_2, and those of the corresponding scenarios indexed by 1, e.g., B_1, show one of the main consequences of the limited availability of bus capacities. The optimization of the amount of served demand contrasts with that of the served demand WDT. In the first case, bus capacity is mostly exploited to serve parcels that must travel short distances. In the second case, parcels that travel longer distances are preferred.

The diagram in Fig. 2 shows how the amount of served demand WDT varies as a function of the financial support of the DM_0, under the assumption that cross-border buses have a capacity of 500 kg. With a little abuse, we can say that Fig. 2 shows the served demand WDT in Scenario E_0 when the DM_0 daily budget varies instead of being fixed equal to 5000.00 €/day.

In Fig. 2, we can observe that the marginal increase of the served demand WDT decreases when the financial support of DM_0 is greater than 4,000.00 €/day, since the bus capacities tend to be fully utilized. In fact, 4,000.00 €/day of financial support can make the system still guarantee the 80% of the service that could be achieved with the maximum subsidy. Differently, the shape of the diagram for low values of financial support is, at least in part, due to the fact that a hub in Trieste with 25,000 kg storage capacity is not economically viable when the DM_0 financial support drops below 3,000.00 €/day, and thus only a hub with 3000 kg storage capacity is considered. In this situation, most of the served demand WDT has either its origin or destination in the main hub of Koper, which is more central in the transport network. However, we note that, if the financial support of DM_0 falls below 2,000.00 €/day, the results of our model suggest to reopen the hub in Trieste with a storage capacity of 25,000 kg in order to serve very few other hubs while giving up the more numerous services from the main hub in Koper. In fact, Trieste is the largest city considered and it is the only one that can guarantee the existence of a sufficient amount of demand towards or from very few other hubs.

The possibility that the larger hub in Trieste could go from operational to non-operational to operational again, depending on the available financial support, can be confusing for the DM_0. However, it is worth nothing that a maximum loss of 13% of the demand that can be served can occur if the DM_0 decides to always support the larger hub in Trieste, possibly sacrificing the financial support for the hub in Koper.

Table 5 allows you to compare the results of four other scenarios: Scenario F_0, respectively F_2, equivalent to Scenario E_0, respectively Scenario E_2, but with a financial support of DM_0 equal to 4,000.00 €/day; Scenario G_0, respectively G_2, equivalent to Scenario F_0, respectively Scenario F_2, but where deliveries between the three main cities – Trieste, Koper and Izola – are not permitted. These scenarios were considered for the following reasons. As already pointed out commenting Fig. 2, in Scenario F_0 the system is still able to serve 80% of the demand WDT. In this situation only 5 hubs are operative: the two large hubs in Trieste and Koper and the hubs in Izola, Portoroz and Piran. Note that, differently, when the financial support of DM_0 is not limited (see Scenario D_0) all the 16 hobs are kept operational. In particular, in Scenario F_0, the service concentrates on the 13,3% of the total volume of demand that requires longer journeys between origins and destinations where the demand form transportation is high. This type of service certainly has an economic justification, but it penalizes small communities. Furthermore, an efficient freight-only service serving the main cities would probably be a tough competitor to beat.

In Scenario F_2, the service maximizes the served demand in kg. In this case, 16 hubs are open, all the small communities are at least partially served. Note, however, that these results are obtained by serving a much smaller fraction of demand WDT than the one served in Scenario F_0. Only the hub with 3000 kg storage capacity is considered for Trieste.

In addition, comparing Scenario F_2 with Scenario D_2, we can observe that the system serves about the 74% of the volume of the demand in kg that it can serve when the DM_0 financial support is not bounded.

Scenarios G_0 and G_2 show the results that can be achieved with the same amount of financial support from DM_0 as for Scenarios F_0 and F_2, if the delivery of freight between the three main cities is not allowed, either because DM_0 wants to force a service oriented towards the small communities, or because competitors make this kind of service economically unviable. In Scenario G_0 the two large hubs in Trieste and Koper remain open, as in F_0, and serve the 6 largest municipalities other than themselves and Izola. In Scenario G_2, as in F_2, the smaller hub is considered for Trieste. We note that the comparison between G_0 and G_2 shows again how the maximization of the served demand WDT may conflict with the maximization of the volume of served demand in kg or, better, with the number of serviced communities.

Finally, we remark that the services considered in Scenarios D_2 and F_2 saturate either the capacity of the buses or the capacity of the smaller hub in Trieste (in Scenario F_2). As a consequence the volume of the served demand with at least origin or destination in small communities would not increase further even if the fixed costs of their hub decrease.

From a more general perspective, our results highlight the potential of servicing passenger and freight demand shares through the same vehicle: the model shows promising performance even with several budget and operational constraints considered. Policy drivers for the implementation of FOT are numerous, and the improvement of operational performances is not their only concern. Reducing the total number of circulating vehicles (passengers plus freight transport) may help transportation service providers in reducing the operational costs while matching the preferences of passengers and freight operators. Although a discussion of the quantification of the reduction in external costs is not within the scope of our study, the topic is a central feature in FOT promotion, both at academic and policy levels (Cavallaro & Nocera, 2021). Its inclusion in the discourse may highlight the potential of FOT from environmental and social perspectives alongside the operational theme. This will help enhance acceptance from key stakeholders and customers and increase the feasibility of FOT. In the wider picture, stakeholders could be persuaded to ease some constraints and/or provide political support and structural funding to the system; this could ultimately allow for more accurate and effective management as well as extended operations. From a social and policy-oriented perspective, the FOT is not aimed at reducing the traveled distances tout-court; however, in the widest sense, it is aimed at a reduction of negative externalities. The emphasis should hence be on lowering the reliance on polluting vehicles for purposes of passenger and freight mobility and on redeveloping non-sustainable distribution models. The use of public transport and/or alternatively powered vehicles, including bicycles and e-bikes, for logistics operations might substantially contribute to reducing environmental pollution and its impact on climate change. Further incentives in this direction by policymakers and key actors can play a substantial role in the development of greener modes and transport models. These considerations related to fleet and operations and to last-mile management could be included in our model in a future stage, with some small adjustments to some parameters. Finally, the

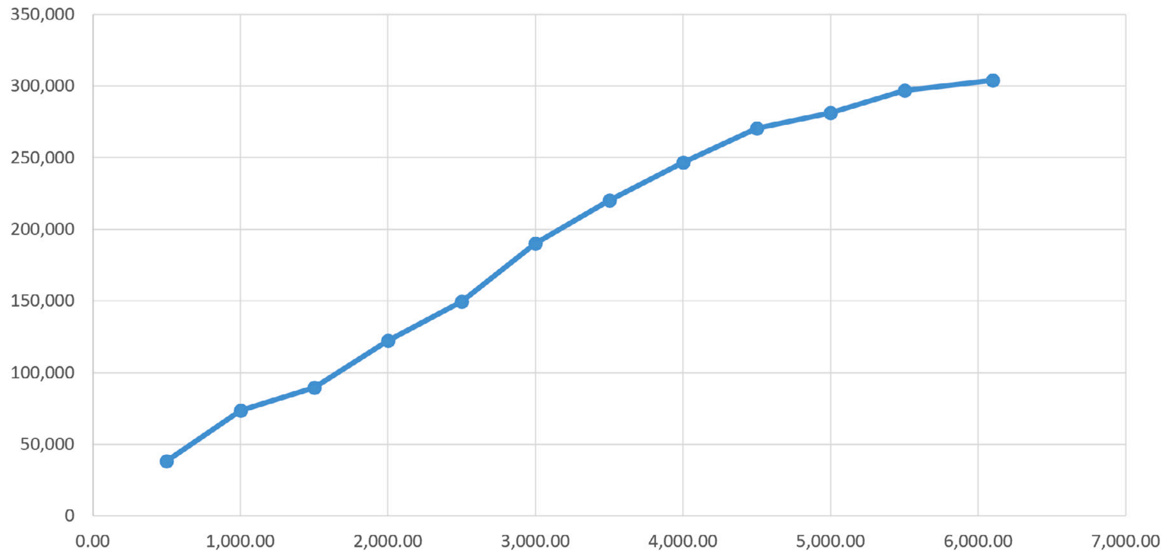

Fig. 2. Amount of served demand WDT as a function of the DM_0 financial support.

Table 5
Results for Scenarios F - G.

Scenario Scenario	DM_0 daily budget	Served demand WDT in $\text{kg} \times \text{km}$	Served demand in kg	Num. of trasp services	Num. of hubs	Served demand percentage
Scenario F_0	3,950.64	246,698	9633	42	5	13.3%
Scenario F_2	3,833.60	133,626	17,222	110	16	23.7%
Scenario G_0	3,909.73	219,086	10,093	50	8	13.9%
Scenario G_2	3,949.34	140,584	16,772	116	16	23.1%

purpose of this study is to confirm the potential of FOT services in a wider sense. In some areas, the impact may be higher than that in our case study, depending on the use of transit, the uptake of ICT to favor real-time operation adaptation, and the policy framework. Previous studies have shown that the local boundary conditions have a weight, similar to the presence of a political class sensitive to the theme. The reduction of external costs is an important objective but not the sole objective. With slight changes in the objective functions, our model can potentially consider any parameter combination to find the best match between customers, passengers, and stakeholders and it contributes to previous literature focused on routing issues. Finally, the results may also be useful for policymakers to determine possible developments of the service and to focus on those investments leading to effective results and promising benefits.

5. Conclusions

Operation problems involving routing or scheduling optimization have been intensively studied in the last few decades with several goals, including the integration of passengers and cargo flows. In most instances, the balance of customer satisfaction and time-sensitiveness is generally found to conflict with the aims of policymakers, which is not feasible from an operative and managerial point of view. Moreover, the additional costs to be borne by the public authority or policymakers are often found to be the main braking drivers for both academic and real-life applications of Freight on Transit (FOT). Hence, the volumes and fragmentation of First-Last Mile (FLM) logistics are rapidly expanding, particularly in developed countries, in response to the growing demand driven by global trends, including the consequences of the Covid-19 pandemic. While the number of available vehicles is limited and many clients may require fixed-time deliveries, an improvement in routing and scheduling can increase customer satisfaction while saving operational costs. In this regard, the integration of passengers and cargo flows for FLM operations is of interest not only for scholars but also for European and national institutions. In this study, we developed a model to support strategic decisions concerning the implementation of an FOT system. The proposed model aims to help a public authority, referred to as DM_0 in this paper, to understand the conditions under which an FOT may maximize the amount of freight shipped on public transport while simultaneously retaining the performance of public services and minimizing the financial support provided by the public authority. The model is highly generalizable, can solve for a wide number of instances, and is capable of solving regardless of the size of the dataset. This was validated through numerical experiments. The results are promising as they highlight the potential of our method for solving the problem with different and potentially conflicting objectives. The success of a public transport agency largely depends on the number of satisfied passengers who use the system and will continue to use it in the future (de Oña et al., 2013). Estimation of the impacts of the deterioration of public transport quality is not considered in this study; however, the conservative values that we applied for freight loads on transit help us ensure that passengers' perceptions remain unchanged with regard to both comfort (related to spare capacity onboard) and travel time. The goal of the optimization in this study is to meet the largest possible share of freight delivery demand under different funding conditions and objectives. These could come in tandem with a contextual reduction of generated external costs if overall mileage is reduced. The results of the optimization can be proactively used by policymakers to choose the most appropriate investments. The case study discussed herein refers to a real-life cross-border instance between Italy and Slovenia. For possible future local implementation, our results will help authorities to weigh the potential of the FOT. Finally, all experiments in this study were conducted according to a deterministic schedule; however, stochastic factors, such as last-minute deviations, roadworks, or accidents, may cause delays during travel and delivery at the destination. This should be adequately considered during scheduling, for instance, by introducing a maximum tolerance in the interval between departures. Further research may also involve the study of different loading conditions, changing or alleviating both space and weight constraints, and the consideration of the consequences of adopting zero-emission fleets, a theme that is attracting increasing attention. In particular, future studies could consider the features of an EV fleet specifically to solve the charging coordination problem and discuss the role, potential, and acceptability of small electric vehicles in covering FLM duties for complementing an FOT system in urban areas and smaller locations. The introduction of new types of vehicles, possibly specially designed, could also open up the possibility of transporting goods that are perishable or require special protective services such as refrigeration or heating. In this situation, time constraints stricter than the 24-hour delivery window implied by Assumption 1 might be worth considering together with the introduction of on-demand transport services.

CRediT authorship contribution statement

Francesco Bruzzone: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Revision. **Silvio Nocera:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Revision. **Raffaele Pesenti:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahuja, T. L. O. J. B. (1993). Network Flows. Theory, Algorithms, and Applications. Prentice Hall.

Azcuy, I., Agatz, N., & Giesen, R. (2021). Designing integrated urban delivery systems using public transport. *Transportation Research Part E: Logistics and Transportation Review*, *156*, Article 102525.

Benazzo, S. (2021). Una strategia per Trieste, prima edizione. Ricollocare una periferia centrale sullo scacchiere globale. *Limes*.

Bruzzone, F. (2019). Cargo Hitching as a tool to transform the urban mobility system. Integrating passengers and goods transportation towards a more sustainable, desirable and efficient mobility. In *AESOP 2019 book of papers*.

Bruzzone, F., Cavallaro, F., & Nocera, S. (2021). The integration of passenger and freight transport for first-last mile operations. *Transport Policy*, *100*, 31–48.

Buldeo Rai, H., van Lier, T., Meers, D., & Macharis, C. (2017). Improving urban freight transport sustainability: Policy assessment framework and case study. *Research in Transportation Economics*, *64*, 26–35.

Cavallaro, F., & Nocera, S. (2021). Integration of passenger and freight transport: A concept-centric literature review. *Research in Transportation Business & Management*, 100:718.

Cavallaro, F., & Nocera, S. (2023). Flexible-route integrated passenger–freight transport in rural areas. *Transportation Research Part A: Policy and Practice*, *169*, 103604.

Dablanc, L. (2007). Goods transport in large European cities: Difficult to organize, difficult to modernize. *Transportation Research Part A: Policy and Practice*, *41*(3), 280–285.

de Oña, J., de Oña, R., Eboli, L., & Mazzulla, G. (2013). Perceived service quality in bus transit service: A structural equation approach. *Transport Policy*, *29*, 219–226.

Dong, J., Hu, W., Yan, S., Ren, R., & Zhao, X. (2018). Network planning method for capacitated metro-based underground logistics system. *Advances in Civil Engineering*.

European Commission (2007). Green Paper - Towards a new culture for urban mobility.

Gaiser, L. (2018). L'europa di mezzo punta su Trieste e sul Nord-Est, Roma non conta nulla. *Limes*.

Ghilas, V., Cordeau, J.-F., Demir, E., & Van Woensel, T. (2018). Branch-and-price for the pickup and delivery problem with time windows and scheduled lines. *Transportation Science*, *52*, 1191–1210.

Ghilas, V., Demir, E., & Van Woensel, T. (2016a). An adaptive large neighborhood search heuristic for the pickup and delivery problem with time windows and scheduled lines. *Computers & Operations Research*, *72*, 12–30.

Ghilas, V., Demir, E., & Van Woensel, T. (2016b). The pickup and delivery problem with time windows and scheduled lines. *INFOR: Information Systems and Operational Research*, *54*(2), 147–167.

Ghilas, V., Demir, E., & Woensel, T. V. (2013). *Integrating passenger and freight transportation: Model formulation and insights*: *Working paper*, (p. 38). Technische Universiteit Eindhoven.

Ghilas, V., Demir, E., & Woensel, T. V. (2016c). A scenario-based planning for the pickup and delivery problem with time windows, scheduled lines and stochastic demands. *Transportation Research, Part B (Methodological)*, *91*, 34–51.

Gosar, A. (2014). The development of tourism in Istria. *International Journal of Euro-Mediterranean Studies*, *7*, 155–174.

Jansen, T. (2014). *Development of a design model for integrated passenger and freight transportation systems* (Ph.D. thesis), Eindhoven: Technische Universiteit Eindhoven.

Li, F., Guo, X., Zhou, L., Wu, J., & Li, T. (2022). A capacity matching model in a collaborative urban public transport system: Integrating passenger and freight transportation. *International Journal of Production Research*, *60*(20), 6303–6328.

Li, B., Krushinsky, D., Reijers, H., & Van Woensel, T. (2014). The share-a-ride problem: People and parcels sharing taxis. *European Journal of Operational Research*, *238*(1), 31–40.

Lu, C.-C., Diabat, A., Li, Y.-T., & Y., Y.-M. (2022). Combined passenger and parcel transportation using a mixed fleet of electric and gasoline vehicles. *Transportation Research Part E: Logistics and Transportation Review*, *157*, 102:546.

Macioszek, E. (2019). Freight transport planners as information elements in the last mile logistics. In G. Sierpiński (Ed.), *Integration As Solution for Advanced Smart Urban Transport Systems, vol. 844* (pp. 242–251). Cham: Springer International Publishing, Series Title, Advances in Intelligent Systems and Computing.

Mazzarino, M., & Rubini, L. (2019). Smart urban planning: Evaluating urban logistics performance of innovative solutions and sustainable policies in the Venice Lagoon—the results of a case study. *Sustainability*, *11*(17), 4580.

Molenbruch, Y., Braekers, K., Hirsch, P., & Oberscheider, M. (2021). Analyzing the benefits of an integrated mobility system using a matheuristic routing algorithm. *European Journal of Operational Research*, *290*(1), 81–98.

Nocera, S., Pungillo, G., & Bruzzone, F. (2020). How to evaluate and plan the freight-passengers first-last mile. *Transport Policy*, *36*, 56–66.

NOVELOG (2016). Deliverable d.3.1 "Evaluation Framework".

Ozturk, O., & Patrick, J. (2018). An optimization model for freight transport using urban rail transit. *European Journal of Operational Research*, *267*(3), 1110–1121.

Pimentel, C., & Alvelos, F. (2018). Integrated urban freight logistics combining passenger and freight flows – mathematical model proposal. *Transportation Research Procedia*, *30*, 80–89.

Schröder, S., & Liedtke, G. T. (2017). Towards an integrated multi-agent urban transport model of passenger and freight. *Research in Transportation Economics*, *64*, 3–12.

SiStat (2017). *Road goods transport by type of goods, Slovenia, Annually*: *Technical report*, Republic of Slovenia Statistical Office, (Online; Accessed 28 October 2022).

Taniguchi, E., & Thompson, R. G. (2018). *City logistics 3: towards sustainable and liveable cities*. John Wiley & Sons.

Xin, C. (2021). *The role of north adriatic ports*. China-CEE Institute.