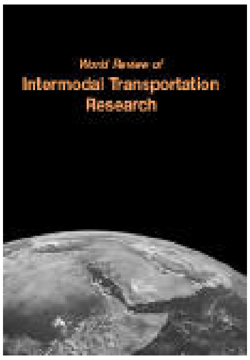


World Review of Intermodal Transportation Research

ISSN online: 1749-4737 - ISSN print: 1749-4729
https://www.inderscience.com/writr

Analysis of last-mile operations for mobility and logistics in rural areas

Nara Quintela Begnini, Hiroshi Morita

DOI: 10.1504/WRITR.2022.10052632

Article History:

Received:	06 July 2022
Accepted:	15 November 2022
Published online:	24 July 2023

Analysis of last-mile operations for mobility and logistics in rural areas

Nara Quintela Begnini* and
Hiroshi Morita

Graduate School of Information Science and Technology,
Osaka University,
Suita, 1-5 Yamadaoka 565-0871, Osaka, Japan
Email: nara.begnini@ist.osaka-u.ac.jp
Email: morita@ist.osaka-u.ac.jp
*Corresponding author

Abstract: This research investigated the integration of bus lines with on-demand passenger transportation mixed with parcel delivery services for last-mile transportation. A mixed integer programming formulation is proposed for the optimisation problem of finding routes for the delivery vehicles, synchronising them with the bus lines, so that passengers and parcels use both modes in their trips. To validate the model, we used randomly generated instances based on a rural community and solved them using a commercial solver. We compare the performance of such a system against non and partially integrated scenarios and show that significant savings in drive time can be achieved, even when prioritising the passengers' perspectives. We also present a method to aid a decision-maker in visualising the trade-off of this prioritisation for the service operator. These findings suggest that the proposed approach might be particularly effective in rural areas, but these conclusions are highly dependent on the instances.

Keywords: rural mobility; vehicle routing; integration to bus lines; public transit; mixed passenger and freight; hybrid transportation; last mile delivery; optimisation model.

Reference to this paper should be made as follows: Begnini, N.Q. and Morita, H. (2023) 'Analysis of last-mile operations for mobility and logistics in rural areas', *World Review of Intermodal Transportation Research*, Vol. 11, No. 3, pp.235–257.

Biographical notes: Nara Quintela Begnini holds a BSc in Industrial Engineering and a MSc in Information and Physical Sciences. Currently, as a PhD student at the University of Osaka, she specialises in the development of models, and their solution methods, for transportation problems, such as logistics and mobility, within the operations research framework.

Hiroshi Morita is a Professor at the Department of Information and Physical Sciences, Graduate School of Information Science and Technology, Osaka University. He received his PhD in Engineering from Kyoto University in 1992. His research interests are related to system modelling and optimisation, operations research, data science and energy management. He has published research papers at *European Journal of Operational Research*, *Transportation Research*, *Applied Energy* and so on.

1 Introduction

Rural residents face different mobility challenges than their urban counterparts. According to Ritchie and Roser (2018), rural populations will see a decrease in their numbers, and at the same time, as pointed out by the International Transport Forum (ITF, 2021), an increased share of elderly people, especially in developed countries. These two factors build upon each other to lower the demand for mobility services and reduce the supply of drivers and support staff. This situation is already visible in some countries, and the World Economic Forum (WEF, 2020) identifies Japan as a prominent example, expecting it to intensify each year. On the supply side, a smaller staff makes flexibility against disruptions challenging to achieve, and the consequences are severe. For example, one late bus might impact the schedule of the whole day of one of its users, leaving them without options. Not only seniors but also users who have reduced mobility or cannot drive, among others, heavily rely on public transit, taxis, and special on-demand transport. For this reason, their quality of life is directly impacted by the quality of transportation services.

In areas without railways, public transit is practically synonymous with bus lines, so the quality of bus service is a significant component of the above-mentioned quality. However, most bus routes are not profitable (low demand being a primary reason), so connecting more distant areas is left to the public sector, which suffers the financial burden of subsidising those routes, often leaving these areas with a reduced frequency of such services, thereby impacting the users.

A partial solution to reduce the burden of subsidies on bus lines is to extend their services to include freight transportation, allowing logistic operators to load the buses with boxes, which would be unloaded at bus stops later on the bus route. Delivery companies in Japan have attempted such a scheme. Moreover, the academic community has been making it clear that changes are necessary to overcome mobility challenges, especially outside urban environments. Arvidsson et al. (2016) concluded that a promising approach for alleviating last-mile challenges is to treat passenger and freight flows as a single entity. Bruzzone et al. (2021) highlight that the last mile is considered one of the main bottlenecks of transportation, imposing high costs, and it is often perceived as inefficient. At the operational level, several studies focusing on solutions to allow sharing of resources, mixing flows, and integrating modals have been reported, as surveyed by Mourad et al. (2019) and Cleophas et al. (2019), developing models and solution approaches that demonstrated the potential of such a change in the transportation paradigm. Many applications and services would also benefit from improvements in delivery services (Boysen et al., 2021), especially those that operate under high time pressure, such as online food shopping (Trott et al., 2021). Additionally, using public transit might be a viable way to reduce emissions impact.

Regarding optimisation approaches, there is a lack of studies that tackle the challenge of mixing passengers and freight while synchronising public transit to last-mile vehicles. The research gap is noticeable when investigating methods considering the passenger experience in such a transportation solution and showing its possible benefits. Observing the claims from these studies, the motivation for the present research was to improve rural transit by proposing a transportation service for people and freight that integrates bus lines and last-mile on-demand transport. Our main assumption is that the users are initially in a main town, which is a local service hub, and the users are heading towards a small village in the same region; this is a typical movement pattern in rural areas. The main goals were to model such a service and show its benefits relative to services with other levels of cargo mixing and integration. The proposed model is expected to be helpful for both analysing feasibility in pre-implementation studies and for solving synchronisation and routing problems after implementation.

Three main questions guided this research:

1 What problems arise at the operational level of mixed and integrated transportation systems, and how can they be modelled and optimised?

2 How can we model a transportation service that integrates fixed bus lines and last-mile on-demand transport for people and freight in rural areas?

3 What benefits can such a service bring at the operational level?

We proposed a mixed-integer programming (MIP) formulation for optimising the routes of last-mile delivery vehicles such that they are synchronised with buses while also considering passenger convenience, and we generated instances based on a real bus line in the Japanese countryside to validate our model. The service's performance was compared to other alternative formats, such as non-mixed and non-integrated ones. We also present a method to aid a decision-maker in visualising the tradeoff between the perspectives of the passengers and the service operator. In a specific scenario, we demonstrated that the savings in drive time decrease as the number of parcels grows. These findings suggest that the proposed approach might be particularly effective in rural settings.

In Section 2, we review a selection of the relevant studies focusing on modelling and solving integrated services, essentially tackling the first research question. A description of our problem and the alternative scenarios used to compare our approach are presented in Section 3. This is followed by the mathematical formulation in Section 4, answering the second research question. The third question is considered in Section 5, where we validate the model using instances based on real locations and present a case study. Section 6 concludes the paper by summarising the present study and ideas about future research.

2 Literature review

The problem of combining the flows of people and parcels spans several fields, including policy-making and operational decisions. This review focuses on the latter, summarising contributions to modelling and determining the routing, assignment, scheduling, and synchronisation of vehicles to meet transportation requests. This problem has similarities with the Pickup and Delivery Problem (PDP) and its special case, the Dial-a-Ride Problem (DARP).

In the PDP, the challenge is to generate optimal routes for vehicles to pick up loads from their origins and transport them to their destinations. This problem has many variants, which differ according to the requirements, such as customers requiring both pickup and delivery or only one service, and a particular time window. Parragh et al. (2008) conducted an extensive survey on PDP models for many of its variants, including the solution methods. The DARP is a special case of the PDP concerned with the transportation of passengers and usually has a constraint on or optimises the level of service. This problem is often used to model on-demand door-to-door transportation services, particularly for people who are elderly and have a disability. A survey by Cordeau and Laporte (2007) became a classic paper on the relevant models and algorithms, and recently Ho et al. (2018) surveyed the later research developments related to the DARP.

2.1 Parcel pick-up and delivery

Ghilas et al. (2013) proposed an arc-based mixed-integer programming formulation for the problem of routing and scheduling pickup and delivery vehicles to transport two types of requests (parcels and passengers) when there was also the opportunity to transfer them to scheduled lines (such as bus or train) used by the general public. To the best of our knowledge, they were the first to propose an integrated system mixing parcels and passengers where private vehicles are responsible for the initial and last miles, and scheduled lines can optionally be used for the intermediate miles. To analyse the benefits of the proposed system relative to a non-integrated one, they used a commercial solver on small instances and concluded that it is possible to achieve significant savings, both in terms of monetary cost and CO2 emissions, as well as fleet size. From a modelling perspective, the passengers are differentiated from the parcels by adding constraints that impose a maximum travel time for passenger-type requests. In subsequent work, Ghilas et al. (2016b) formulated a similar problem, considering only parcels, called the Pickup and Delivery Problem with Time Windows and Scheduled Lines (PDPTW-SL) and introduced some families of valid inequalities for this problem. Additionally, they compared the operational costs of the proposed system to the PDPTW and its performance under different network design choices, such as the frequency and the number of scheduled lines and tighter or wider time windows. In Ghilas et al. (2016a), the authors compiled a set of instances for the PDPTW-SL of up to 100 requests and three scheduled lines and developed an adaptive large neighbourhood search (ALNS) heuristic to solve them, unlike in the previous work, which used a commercial solver and only up to 11 requests could be scheduled. In Ghilas et al. (2018), an exact method was proposed for the PDPTW-SL, and the authors presented a set-partitioning formulation and a branch-and-price algorithm, solving instances of up to 50 requests.

Unlike other studies presented in this review, Pimentel and Alvelos (2018) did not consider vehicle routing, instead modelling the assignment of parcels to bus stops and last-mile operations. They assumed assignments to be valid when the customer location is reachable within an agreed service time and proposed a MIP model to balance freight loads and synchronise the distribution and minimise service time.

In Mourad et al. (2021), the challenge was to route a fleet of autonomous pickup and delivery robots that could use public transit. The available capacity for the robots depends on how crowded the public line is; information revealed upon arrival at the station. The proposed model was based on the one proposed by Ghilas et al. (2016b), with extensions to consider the stochastic nature of passenger demand on public lines. Their solution method is sample average approximation combined with an ALNS.

2.2 Goods distribution

Goods distribution is a special case of a PDP where no pickup is necessary because the goods are assumed to start in a distribution centre. The challenge is related only to delivery to final customers.

In the context of distributing goods from a warehouse to a congested city centre, Masson et al. (2017) proposed a two-tier system where in the first tier, a public bus line connects the distribution centre to bus stops, and in the second tier, city freighters carry out the last-mile transport. Their proposed MIP and a metaheuristic algorithm produce a delivery plan. In a case study, they evaluated the impact of the two-tier system on the number of city freighters required and their utilisation, compared to a single-tier approach where trucks deliver directly from the distribution centre.

Azcuy et al. (2021) focused on the tactical problem of deciding where to place transfer stations in a two-tier system while considering operational decisions in the last-mile tier. Also, they proposed a MIP model for minimising the expected travel distance across different demand scenarios and solved it using ALNS metaheuristics. They also presented a sensitivity analysis on the instance parameters, such as the capacity of last-mile vehicles and depot location.

The last-mile does not necessarily have to be performed by vehicles. As the driver handles parcels to the final consumer, an interesting approach is combining vans and porters. Allen et al. (2021) designed and reported the results of a trial of such an approach, indicating a significant reduction in vehicle parking time at kerbside, driving time, and distance travelled.

2.3 Passengers transportation

Aldaihani and Dessouky (2003) was one of the early studies on integrating curb-to-curb services and fixed-route bus lines. They referred to the problem as a hybrid routing problem, routing paratransit vehicles such that total distance travelled and passengers' total travel time are minimised. They focused on implementing a solution framework with tabu search heuristics to generate and improve feasible routes.

Häll et al. (2009) introduced the Integrated DARP (IDARP), defined as the problem of obtaining optimal routes and schedules for vehicles in a dial-a-ride service where the passengers can transfer to fixed-route service, if necessary. They assumed that the fixed-route service had a high frequency, so they did not include constraints to model timetables. Incorporating such realistic constraints, Posada et al. (2017) extended the IDARP to add features such as heterogeneous fleet and flexible start and end points for the requests, yielding the IDARP with timetables (IDARP-TT). They developed two models for the IDARP-TT. Thereafter, seeking to evaluate the performance of an IDARP in a real case study of a rural area in Sweden, Posada and Häll (2020) developed an ALNS metaheuristic with an operator specific to the IDARP. Their results demonstrated the potential of integrated passenger transportation.

Molenbruch et al. (2021) also provided an evaluation method for integrated mobility systems in the context of dial-a-ride services and regular public transport. Their problem assumes a heterogeneous set of passengers with different mobility constraints as well as a heterogeneous fleet of paratransit vehicles. The total drive distance must be minimised, and public transit need not be used in the passengers' trips. They developed a metaheuristic procedure based on a large neighbourhood search (LNS) method. Their extensive analysis covered the effects of different operational characteristics and demand-related parameters.

2.4 Research gap

Based on this literature review, we identified two growing research fields with relatively recent contributions. Those fields are integrated transportation services, where passengers or cargo are allowed to transfer from public transit to on-demand vehicles, and mixed transportation services, passengers and cargo travelling together in the two modes mentioned. However, the overlap of both types of service is mentioned in only one work, by Ghilas et al. (2013), and the authors did not pursue the same problem in subsequent works. Moreover, in their study, passengers are distinguished from packages by adding constraints imposing a maximum travel time for them. We believe there is more to explore and suggest in this matter, such as how passengers would be affected and methods to make the shared ride as convenient as possible for all stakeholders (passengers, delivery customers, and transport companies). In our study, our method to make rides as convenient as possible for passengers is by giving them priority over parcels and offering a method to analyse the tradeoff from the transport company's perspective.

3 Problem statement

On a given day, a transportation service provider receives a number of requests that must be fulfilled. There are two types of requests: parcel and passenger. A passenger request means a person demands transportation to a destination in the rural village. A parcel request means that a location (household, company) requested a parcel delivery in a rural village. Passengers need to declare their desired destination and departure time; for parcels, only a destination is declared. For both types, a common origin is assumed. In the case of parcels, that is a fixed warehouse or distribution centre, whereas, in the case of passengers, it is a public bus terminal or the hub of the points of interest. We assume the considered transportation provider operates in a rural area with a low population density, whereas there is an urban centre that serves as the main hub of essential services for the population and public transit is available, but at a low frequency. The goal is to transport every request to its destination by generating routes and schedules for the delivery vehicles available to the transportation provider. Therefore, the problem considered in this research is of an operational nature. We consider a static and deterministic environment, so all required information, such as the requests, travel times, and destinations for the day (the planning horizon), is known beforehand.

The main idea proposed in this research is to use last-mile delivery vehicles in coordination with public buses in an integrated, or hybrid, transportation service to fulfil all requests. Such a service would cover personal mobility and parcel logistics demand originating at a local urban hub directed at a remote village or town. Moreover, the proposed service is also considered a mixed transportation system since people and parcels share resources at the fixed bus route level, the "middle mile", and the last-mile level.

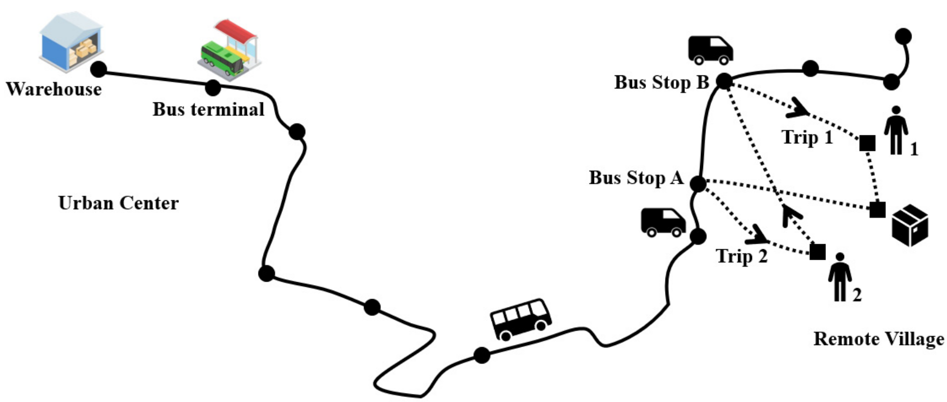
In our proposed approach, at the declared departure time, the passenger will board the bus and then disembark at a bus stop determined by our model, where a delivery vehicle will be waiting to pick them up and transport them to the desired destination. We assume that the passenger has the freedom to decide their departure time, which depends on their schedule in the city, and we only consider transporting them back to the village.

However, the departure time must also coincide with a time in the bus timetable. We also assume that passengers can move to the bus stop where they will board the bus but do not desire or cannot walk or go by themselves to their destination (it might be far, or they might be carrying groceries). Parcel requests are made to start their journeys at the warehouse, where different delivery companies will have brought the parcels, and the warehouse is assumed to be one stop on the bus route. There are no other storage facilities along the bus route, so parcels must be transferred to delivery vehicles upon arrival at their designated bus stops.

The last mile for the passenger and parcel transportation is handled by a delivery vehicle waiting at the bus stop to pick them up. The fleet is homogeneous and adapted to safely transport both people and freight, as are the buses. Transferring parcels and passengers from the bus to the delivery vehicle must be considered because it affects the delivery vehicle schedule, compromising future deliveries. Likewise, the time to drop off the passengers and finish a parcel delivery is calculated for every destination node.

As an illustration of the proposed approach, Figure 1 shows a bus line starting in an urban centre and heading to a remote village. Assume that passengers 1 and 2 take different buses. A feasible solution would be that passenger 1 and the parcel are picked up by a delivery vehicle at Bus Stop B. This vehicle takes them to their destinations and then heads to Bus Stop A to pick up passenger 2. After delivering the second passenger, the vehicle returns to a bus stop. The other vehicle is not used.

Figure 1 Example of the proposed mixed and integrated transportation service. The dotted lines represent the routes of last-mile vehicles. The solid line is the fixed bus route



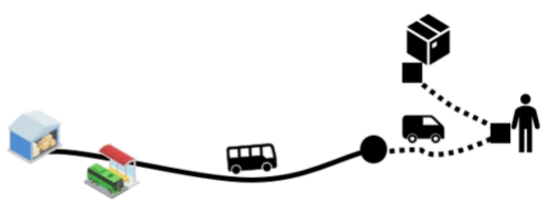
When solving this problem, the following questions must be answered:

- How do we find minimal routes such that the delivery vehicles are synchronised with the buses?
- Which parcels should be loaded onto which buses?
- At which bus stop should which passenger disembark, and which parcels should be taken from the bus there?

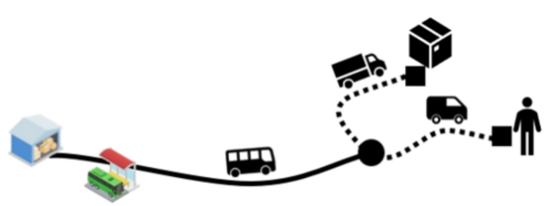
The questions above must be addressed keeping in mind the transportation provider and the passenger perspectives. The transportation provider wishes to minimise its operational costs, that is, the costs incurred from vehicle usage, while guaranteeing the fulfilment of all requests within the planning time horizon. The passengers wish to arrive conveniently at their destinations as soon as possible. In a mixed system, these become conflicting objectives because a longer route that first visits a passenger's destination and then proceeds to deliver a parcel is more desirable (for the passenger) than a shorter route that does these in the opposite order. Also, considering the integrated nature of this system, prioritising the passengers generates routes where the delivery vehicle has to go to bus stops that, usually, are more convenient for the former. For this reason, we consider objective functions that reflect the perspectives above in the following priority order: i) minimise the total travelling time of the passengers and ii) minimise the total drive time of the delivery vehicles.

To show the benefits of our mixed and integrated approach, we compare it to traditional services. Figure 2 illustrates the four scenarios listed in the order of decreasing levels of integration and mixing. Scenario A corresponds to the proposed approach. In Scenario B, we remove the aspect "mixed" from the last mile but keep it at the public transit level. That is, different fleets of last-mile delivery vehicles will serve passengers and parcels. In Scenario C, passengers use public transit followed by last-mile vehicles, and parcels do not use public transit but instead are transported directly from the urban centre by trucks. We consider trucks a different type of vehicle than delivery vehicles due to their larger capacity from only needing to carry parcels. Therefore, here the aspect "mixed" is removed: parcels and passengers are entirely separated. However, solutions are still "integrated" for the passengers. Finally, Scenario D represents a situation without bus lines, where exclusive services serve each type of request from their origin.

Figure 2 Illustrations of the four scenarios

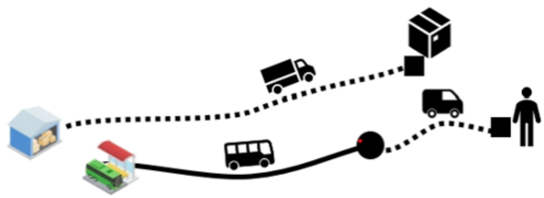


(a) Scenario A. Mixed: Yes. Integrated: Yes.

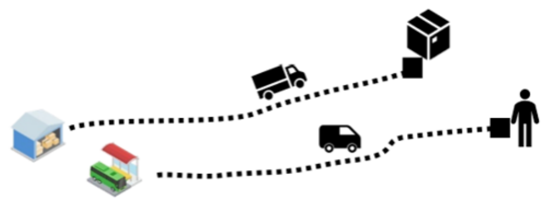


(b) Scenario B. Mixed: Partially (in bus line). Integrated: Yes

Figure 2 Illustrations of the four scenarios (continued)



(c) Scenario C. Mixed: No. Integrated: Partially (for passengers)



(d) Scenario D. Mixed: No. Integrated: No

The solution to a transportation problem is highly dependent on the underlying design of the network considered. Decisions regarding the design are, for example, bus timetable frequency, bus stop locations, delivery vehicle quantity and capacity, and depot location. Our proposed approach does not intend to optimise these decisions, as they are outside our scope.

4 Mathematical formulation

In this section, we present a mixed integer programming formulation for the four scenarios described in the previous section. It is important to note that Scenario A can be modelled as a generalisation of the other scenarios. For this reason, we first introduce notation and description particularly focused on it. Where appropriate, we will highlight how to modify these to model Scenarios B, C, and D.

We denote by $R = R^c \cup R^p$ the set of all customer requests, where R^c are parcel requests and R_p are passenger requests. Our problem does not consider requests to pick up a passenger or parcel, so we let each node $i \in R$ represent the destination of a request.

To model bus movement, we let B be the set of buses and S be the set of physical bus stops along the considered bus line. To model the bus timetable, we use set $T = B \times S$, where each node $i \in T$ is visited by a bus at time h_i. An interpretation of this set is that each node represents a point in time and space where passengers and parcels can transfer from a bus to a delivery vehicle. Observe that we did not consider bus capacity for parcels or passengers because, since this study is focused on rural areas, we assume low demand, below any level that would affect operations and the feasibility of solutions. Since passengers decide which bus they will ride, the transfer nodes available for them are those on their bus timetable. For this reason, set $T^p(r) \subset T, \forall r \in R^p$ contains the transfer nodes that passenger *r* may use.

The last-mile vehicles vary according to the scenario, but the fleet of last-mile vehicles is homogeneous, with a capacity of q_c units of parcels and a capacity of q_p people. Set *O* contains the location of the initial depot of each vehicle in the fleet and set O^f contains their final depot. Initial and final depots can be the same location but do not need to be. The parameter l_i is the loading or unloading time of node *i*. If $i \in T$, it can be interpreted as the time required to transfer passengers from the bus to the last-mile vehicle, and if $i \in R$, it is the time it takes to drop off passengers or finish a parcel delivery.

The model is defined on a graph network $G = (V, A)$. The nodes in set $V = R \cup T \cup O \cup O^f$ are respectively the requested destinations, the bus visits to each bus stop, and the two vehicle depots. The set of arcs *A* contains all the feasible arcs connecting the nodes in set

$$V : A = (O \times T) \cup (T \times R) \cup (R \times R) \cup (R \times T) \cup (R \times O^f) \cup (T \times T)(O \times O^f).$$

Each arc $(i, j) \in A$ has a known travel time t_{ij}. Last-mile vehicles not used in a solution will use the arcs (i, j), where $i \in O$ and $j \in O^f$, between their initial and final depots. The subset $A^r \subset A$ contains arcs that parcels and passengers are allowed to use, i.e., arcs between transfer nodes and destinations, and it is defined by $A^r = (T \times R) \cup (R \times R)$.

The first set of decision variables used is x_{ij}, which is binary and indicates whether a last-mile vehicle uses arc $(i, j) \in A$. Another set of binary decision variables is y_{ij}^r, which indicates whether a request $r \in R$ traverses arc $(i, j) \in A^r$. Lastly, for nodes $i \in R \cup O \cup O^f$, a continuous decision variable h_i indicates the departure time of a last-mile vehicle from *i*. When $i \in T$, h_i is a parameter defined by the bus timetable plus the loading and unloading service time l_i. h_i ensures synchronisation between the last-mile vehicles and the buses.

Our model is based on the one proposed by Masson et al. (2017), whose formulation includes capacity constraints for the transfer nodes. Here, we do not consider that, but we need more control over the movement of parcels and passengers, primarily due to the different level of service that passengers require. Therefore, we extended their model by adding the decision variable y_{ij}^r, which are used to check the requests' trips and calculate their travel time. Moreover, we distinguish between the two types of cargo through the objective function, as explained in Section 3, where we prioritise the level of service for passengers, $r \in R^p$, by minimising their travel time. Another difference is that, since we have two types of cargo, last-mile vehicles must have capacities specific to each type. Following, we present the mathematical model used for Scenario A.

$$\min z_1 = \sum_{r \in R^p} \sum_{(i,j) \in A^r} (t_{ij} + l_i) y_{ij}^r \tag{1}$$

$$z_2 = \sum_{(i,j) \in A} t_{ij} x_{ij} \tag{2}$$

$$s.t. \sum_{j \in T \cup O^f} x_{oj} = 1 \quad \forall o \in O \tag{3}$$

$$\sum_{i \in R \cup O} x_{io} = 1 \quad \forall o \in O^f \tag{4}$$

$$\sum_{(i,j) \in A} x_{ij} = \sum_{(j,i) \in A} x_{ji} \quad \forall i \in R \cup T, i \neq j \tag{5}$$

$$\sum_{i \in T \cup R} x_{ij} = 1 \quad \forall j \in R \tag{6}$$

$$\sum_{(i,j) \in (T \times R)} y_{ij}^r = 1 \quad \forall r \in R^c \tag{7}$$

$$\sum_{i \in T^p(r)} y_{ij}^r = 1 \quad \forall r, j \in R^p, j \neq i \tag{8}$$

$$\sum_{i \in T \cup R} y_{ij}^r = 1 \quad \forall r \in R \tag{9}$$

$$\sum_{j \in R} y_{ij}^r = \sum_{j \in T \cup R} y_{ij}^r \quad \forall r, i \in R, i \neq r \tag{10}$$

$$\sum_{r \in R^c} y_{ij}^r \leq q_c x_{ij} \quad \forall (i,j) \in A^r \tag{11}$$

$$\sum_{r \in R^p} y_{ij}^r \leq q_p x_{ij} \quad \forall (i,j) \in A^r \tag{12}$$

$$h_j \geq h_i + t_{ij} + l_j - M\left(1 - x_{ij}\right) \quad \forall (i,j) \in A \tag{13}$$

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in A \tag{14}$$

$$y_{ij}^r \in \{0,1\} \quad \forall r \in R, \forall (i,j) \in A^r \tag{15}$$

$$h_i \geq \mathbb{R}^+ \quad \forall i \in V \tag{16}$$

The objective function has two components: z_1, given in equation (1), which minimises the passengers' routes in the sense of making their rides as short as possible; and z_2, given in equation (2), which minimises the delivery vehicles' routes, meaning minimising total drive time. Therefore, the two components z_1 and z_2 express the passengers' convenience and the transportation provider's objective, respectively. These two objectives are optimised lexicographically, with z_1 being optimised first.

In constraints (3) and (4), we assure that all vehicles will leave and return to a depot. Remember that, since variables x_{ij} do not specify which vehicle traversed an arc, it is not possible to guarantee that a vehicle will come back to the depot from which it departed. Constraint (5) assures vehicle flow conservation for a node. Constraint (6) assures that all request destination nodes are visited by a vehicle.

In constraint (7), we have that parcel requests may depart from any transfer node. Meanwhile, passengers have a preferred bus, so constraint (8) limits their departures to transfer nodes visited by their preferred bus. Constraint (9) indicates that all requests must arrive at the requested destination. Constraint (10) assures request flow conservation.

Constraints (11) and (12) ensure that a vehicle will not carry more parcels or passengers than its capacity. Constraint (13) assures that a delivery vehicle will, at least, meet the bus as it arrives at a bus stop, or, at most, make sure a vehicle is waiting for the bus at the bus stop. Remember that h_i is a constant when $i \in T$. Finally, constraints (14)–(16) state the domains of our decision variables.

Next, to model Scenario B, we separate the problem into two parts, one being transporting the passengers and the other being delivering the parcels. Since we do not consider bus capacity, this task is straightforward. Essentially, to obtain the solutions for this scenario, we need to solve two problems separately. First, we reduce Scenario A's formulation to the problem of transporting only the passengers. This is achievable by making $R = R^p$ and removing constraints (7) and (11) since these are exclusive to parcels. Next, to reduce Scenario A's formulation to the problem of delivering only parcels, make $R = R^c$, and remove equation (1) and constraints (8) and (12) since these are exclusive to passengers.

Regarding Scenario C, it is also necessary to separate the problem into two parts, as in the previous scenario. Since the approach is still the same for the passengers, reducing Scenario A's model follows the same steps for Scenario B. For parcels, however, the model should be reduced to the vehicle routing problem (VRP) with multiple vehicles. The modifications are as follows: make $R = R^c$; make $A = (O \times R) \cup (R \times R) \cup (R \times O^f) \cup (O \times O^f)$, removing set T; modify constraints (3), (5), and (6) to remove set T; remove equation (1); remove constraints (8) and (12); remove constraints (7), (9), and (10) since it is not necessary to control the flow of requests anymore; and remove constraint (13) since it is not necessary to synchronise with buses anymore.

Lastly, Scenario D is considered a "shared" transportation problem since passengers share the same last-mile vehicle. For parcels, the model used is the same as in Scenario C. For passengers, however, it becomes the VRP-TW where time constraints are applicable only to departure. Since there are no buses, passengers do not specify the preferred time to ride a bus; instead, we assume they have a preferred time to depart for their destination. When solving the instances, the preferred time to ride a bus becomes the desired departure time. To model departure time, we use the parameter $H^r, \forall r \in R$, to set the time that a last-mile vehicle departs to transport passenger r. The necessary modifications are as follows: make $R = R^p$; make $A = (O \times R) \bigcup (R \times R) \bigcup (R \times O^f) \bigcup (O \times O^f)$, removing set T; modify constraints (3), (5), (6), (9), and (10) to remove set T; modify constraint (7), originally used to start the flow of parcels, to start the flow of passengers instead; remove equation (1); remove constraint (8) because these constraints require passengers to leave from transfer nodes; and add the following constraints, which assure that passengers will leave the urban centre at their preferred times:

$$h_j \geq H^r - M\left(1 - y_{ij}^r\right) \quad \forall r \in R, \forall (i,j) \in O \times R \tag{17}$$

$$h_j \geq H^r y_{ij}^r + M\left(1 - y_{ij}^r\right) \quad \forall r \in R, \forall (i,j) \in O \times R \tag{18}$$

5 Experimental analysis

This section evaluates the operational performance of the proposed integrated approach (Scenario A) in comparison to non-integrated approaches (Scenarios B to D). First, we show how we prepared the instances used, which are based on real locations. Then, we show the results obtained from the implementations of the proposed models when solved using a commercial solver. Next, we present a case study derived from the generated instances, starting with a comparison of total drive time between scenarios and then showing the tradeoffs between passenger convenience and shorter vehicle routes and lastly focusing on parcel delivery to show the benefits of integrating it to include bus lines.

5.1 Instance generation

The sets of requested destinations were generated based on real locations in rural Japan, specifically in the city of Akaiwa, Okayama Prefecture. This region has characteristics consistent with what we wanted to test our proposed approach: an urban hub to which the population from the surrounding villages and communities frequently commute. We did not obtain data regarding real demand for personal transportation and parcel delivery in the area, so we generated these data under our best assumptions. Data about the bus lines running in the region were obtained from an online repository (GTFS-JP, 2019) hosting public data in the form of General Transit Feed Specification (GTFS) files from services operating in Japan. GTFS is a data format used by transit agencies to share time and geographical data about their services. For more details about GTFS, we refer the interested reader to Google Developers (2022).

The data from Akaiwa city includes many bus routes, but for our instances, we choose one route that runs 3 buses per day, leaving the bus stop that we considered the bus terminal; the buses depart at 10:20, 13:50, and 15:30. We wrote code to generate random locations only in areas having low population density along, or nearby, the bus route. These locations are considered possible destinations in the villages and communities. To identify locations having low population density, we downloaded datasets containing geographical and demographical data from the Statistics Bureau of Japan (2020). The random locations are separated into 26 sets and randomly assigned to be either a parcel or a passenger request. Each set, labelled from a to z, contains varying numbers of passengers (5 or 10) and parcels (5, 10, 15, or 20), sampled from the pool of locations assigned to that set, totalling 208 instances. Finally, driving distances and drive times between the locations and the bus stops were obtained from Openrouteservice (n.d.). Due to limitations regarding the size of the distance matrix retrieved from the routing service, it was necessary to select a maximum of 18 bus stops, including the assumed bus terminal and the warehouse. As described, we assumed that passengers chose the time they desired to ride the bus, so we randomly assigned passengers to one of the three buses. The fleet size was set to 5 delivery vehicles, with a capacity for 3 passengers and 7 (in Scenario A and B) or 20 parcels (in Scenario C and D). As for the loading time l_i, it was set to 4 minutes.

5.2 Model implementation and verification

All models were implemented in Python 3.8 and solved using the commercial MIP solver Gurobi Optimizer version 9.0 and the relevant libraries for Python. We used a computer with an Intel Core i7 3.2 GHz and 32 GB of memory to solve all instances, setting the time limit for optimisation to two hours. In Table 1, we summarise the minimum, maximum, and average runtimes, grouped by scenario, and numbers of passengers and parcels in the set of instances. Until 15 parcels and either 5 or 10 passengers, all instances were solved to optimality. However, increasing to 20 parcels resulted in some instances not being solved to optimality, and for these instances, we show the solution quality, given by the gap between the lower and upper bounds obtained by the solver. The optimality gaps for these instances are shown in Tables 2a and 2b.

Table 1 Average, minimum, and maximum runtime in seconds to solve instances, separated by number of parcels and passengers

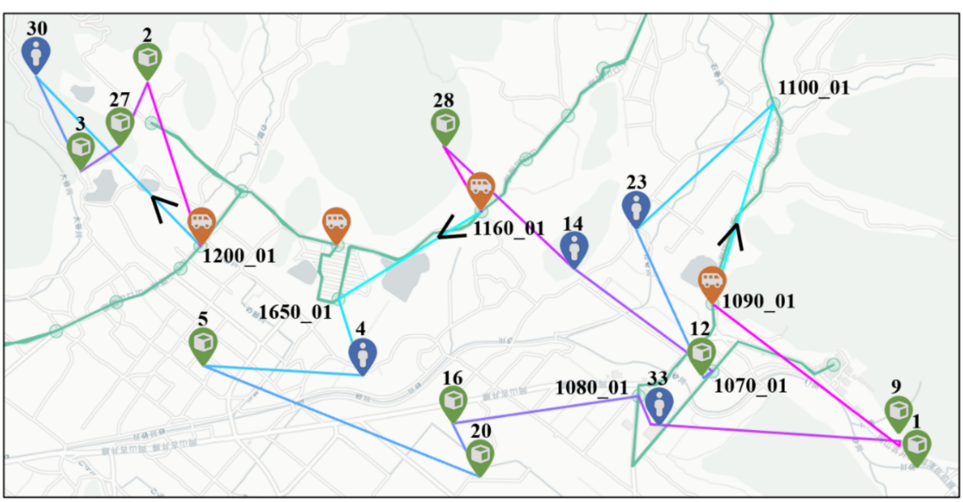
Passengers	*Parcels*	*Average*	*Min*	*Max*
		Scenario A		
5	5	0.5	0.3	1.0
	10	3.3	0.7	14.5
	15	73.0	3.4	1257.2
	20	629.9	20.9	7211.8
10	5	0.7	0.5	1.6
	10	8.7	1.5	100.7
	15	170.4	5.0	1696.4
	20	2420.8	14.9	7233.9
		Scenario B, solving for parcels		
	5	0.2	0.1	0.5
	10	3.1	0.7	13.0
	15	136.5	6.7	1965.4
	20	1154.6	19.2	7200.4
		Scenarios C and D, solving for parcels		
	5	0.03	0.01	0.05
	10	0.34	0.12	0.7
	15	2.6	0.8	11.1
	20	14.1	5.4	38.1
		Scenarios B and C, solving for passengers		
5		0.07	0.06	0.08
10		0.14	0.13	0.15
		Scenario D, solving for passengers		
5		0.20	0.04	0.39
10		55.1	12.2	166.8

Table 2 Optimality gaps after solver runs for 2 hours

(a) Gaps in Scenario A			
Passengers	*Parcels*	*Instance*	*Gap (%)*
5	20	n	3.68
10	20	c	2.80
		g	3.53
		k	3.43
		n	2.38
		q	1.74
		w	5.86
(b) Gaps in Scenario B, solving for parcels			
	Parcels	*Instance*	*Gap (%)*
	20	e	0.12
		n	0.55
		w	0.40

To visualise the solutions obtained from the solver and verify their correctness, i.e., outputting satisfactory routes and schedules for the vehicles, we also implemented a visualisation tool to draw the routes on a map. An illustrated example of an instance and its solution are shown in Figure 3. The lines connect locations to be visited by a vehicle along its route; they do not represent the actual roads.

Figure 3 Visualisation of Instance F, 5 passengers and 10 parcels. Right: solution obtained by the solver. Locations with labels ending in "_01" are bus stops. The arrows indicate vehicle direction. One of the vehicles is parked outside the visible map



5.3 Case study

Our case study is divided into three parts and is useful to answer the third research question, "What benefits can such a service bring at the operational level?". Initially, we aim to evaluate the proposed service in terms of drive time. Then, we show how to see the tradeoff between the operational and passenger perspectives. Lastly, we again evaluate the service, this time focusing only on parcel delivery.

5.3.1 Comparison of total drive time between scenarios

Here we compare the operational perspective indicators, total drive time of last-mile delivery vehicles, between all four scenarios. This analysis allows us to visualise the savings obtained when implementing an integrated system using the non-mixed and non-integrated scenarios as the baseline, as indicated.

The distributions plotted in Figure 4 are the results in travel time for all 26 sets of instances for varying numbers of passengers and parcels. The results for Scenarios B to D are obtained by summing the results of the separated problems explained in Section 4. Table 3 lists the mean drive times shown in Figure 4, as well as the relative differences between each increasing level of integration, Scenario C, B, and A, in this order, taking Scenario D, no integration, as the baseline.

An intuitive result is the performance of Scenario D: the long distances and lack of integration naturally cause longer drive time since trucks go to the village and then return. Observe that Scenarios C and D use trucks with a bigger capacity (of 20 parcels) than the last-mile vehicles used in Scenarios A and B. If a smaller capacity were used, more trucks, or more trips, would be required, worsening the results.

Figure 4 Distributions of drive time obtained for all sets of instances for the indicated numbers of passengers and parcels. The green triangles indicate the mean value

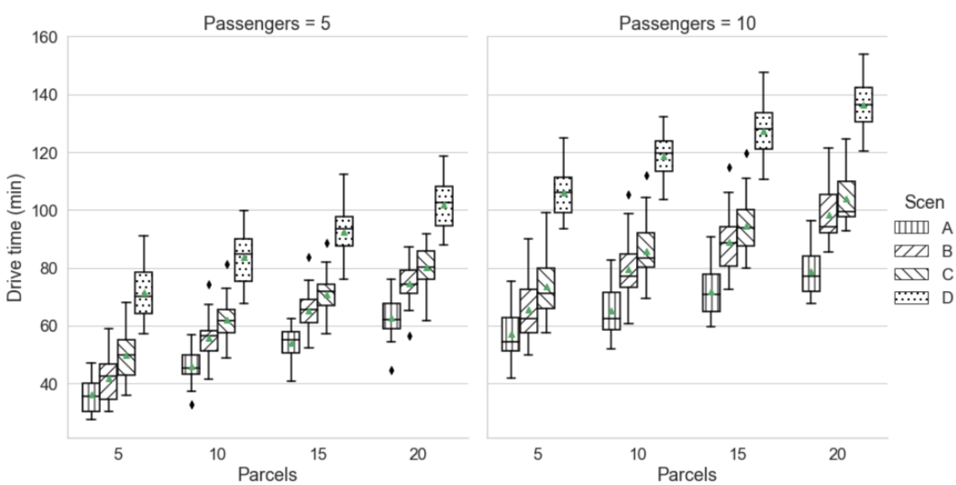


Table 3 Mean drive time for each scenario and relative differences

		Average drive time (min) in Scenario				*Relative difference*			
Passengers	*Parcels*	*A*	*B*	*C*	*D*	*D to C*	*C to B*	*B to A*	*D to A*
5	5	36.1	41.8	49.8	71.4	–30%	–11%	–8%	–49%
	10	46.1	55.7	62.2	83.8	–26%	–8%	–12%	–45%
	15	54.2	65.1	70.9	92.6	–23%	–6%	–12%	–41%
	20	62.7	74.8	80.2	101.8	–21%	–5%	–12%	–38%
10	5	57.1	65.5	73.5	106.2	–31%	–8%	–8%	–46%
	10	65.1	79.4	85.9	118.6	–28%	–5%	–12%	–45%
	15	72.0	88.9	94.7	127.3	–26%	–5%	–13%	–43%
	20	78.9	98.5	103.9	136.6	–24%	–4%	–14%	–42%

The gap between Scenarios D and C indicates the benefit of the first level of integration, assigning passengers to an integrated service. In Table 3, we see that this ranges from 21% to 31%. Significant savings are obtained because of the low capacity of last-mile vehicles for passengers assumed in all scenarios (of only 3 passengers, the same as a basic taxi). As we introduce a second level of integration, for parcels, from Scenario C to B, the savings in drive time end up not being as significant, ranging from 4% to 11%. This can be explained by two facts: the last-mile vehicles assigned to the bus stops in Scenario B have a much small capacity than the trucks in Scenario C; and the last-mile vehicles are scattered along the bus route. In our instances, with a low volume of parcels, the truck does not need to return to the depot in the main town many times, and this capacity advantage reduces the savings obtained by using the buses. However, the vehicles' capacity and which bus stop should be assigned to be depots of last-mile vehicles are design choices, and their optimisation is beyond the scope of this study. Nonetheless, our method demonstrates the benefits under a given choice.

The shortest travel time, as expected, is obtained by mixing the two types of cargo and integrating bus lines into their transport, the last level of integration and the proposed approach, Scenario A. The second-to-last column in Table 3 shows the average savings, ranging from 8% to 14%, when mixing passengers and parcels in the last mile and in the buses (B to A). Finally, the last column compares the two extremes considered, a non-integrated system to a mixed and integrated one (D to A), with savings ranging from 38% to 49%. These high values are expected since this shift eliminates the long trips performed by the trucks and divides them among buses and last-mile vehicles.

We recognise that a transportation service performance goes beyond driving time. However, within the scope of operational optimisation, the driving time is the most used indicator, used in many other works. So, here we discuss our results and whether they agree with other authors.

Posada and Häll (2020) compared the total driving distance between integrated and not integrated approaches. In their case study, they used instances with our assumed characteristics of rural instances, with destinations roughly clustered around bus stops, and also found a significant reduction, ranging from 6.32% to 20.69%. Note that this is driving distance and not driving time, which are different indicators, although correlated. Our results and theirs agree that integrated transportation has the potential to reduce driving time in passengers' transportation.

The work in Ghilas et al. (2016a) compared their proposed approach to a standard PDP with time windows, checking two indicators: total cost of the service; and total driving time by the last-mile vehicles. We note that, in their case, using the scheduled lines, or bus lines, was optional. So, there were solutions where the scheduled lines were not used, and therefore no benefits were observed. In our models, the use of bus lines is either mandatory (Scenarios A, B, and C for passengers) or not allowed (Scenarios C for parcels and D) since our goal is to evaluate the performance/benefits of full implementation of the service such as in Scenario A. Therefore, our results are not directly comparable to theirs, for the mentioned reason, and because we used different instances and they did not consider passengers. However, we both found benefits in integrated transportation, obtaining significant savings in total driving time, primarily when destinations are clustered around transfer locations (bus stops).

Concluding this discussion, we highlight that, in our results, since the passengers are prioritised, they are always delivered before parcels when mixed in the last mile. We demonstrated the advantage of such a system from an operational perspective, even when prioritising the passenger perspective. Our results agree with other studies and reinforce that it is feasible to mix passengers and parcels since the mixed aspect did not neutralise the benefits of integration.

5.3.2 Analysis of tradeoff between passenger ride time and vehicle drive time

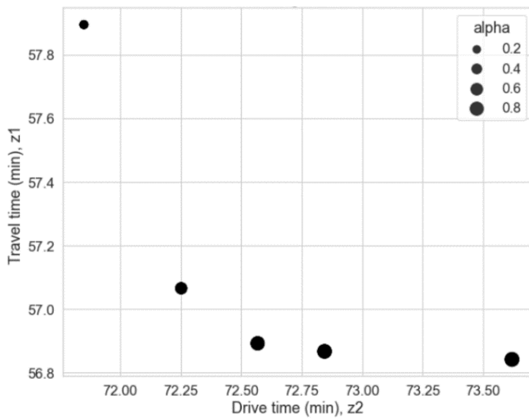
Our model prioritises the passenger perspective by optimising first the total ride time of the passengers. As explained in Section 3, the two objective functions z_1, passengers' total travel time, and z_2, vehicles' total driving time, are conflicting. In this section, we experiment with applying different weights to these objectives in a weighted objective function to visualise the tradeoff between them. The weighted multi-objective function is shown in equation (19):

$$\min \alpha z_1 + (1-\alpha) z_2 \tag{19}$$

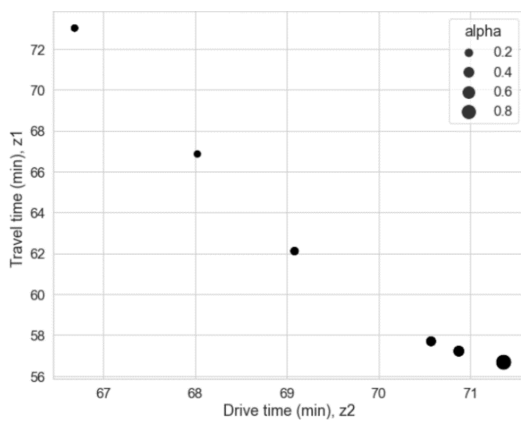
To look at the different degrees of priority of the two objectives, the Pareto efficient points were found for $\alpha \in [0.01, 0.02, \ldots, 0.99]$. Figure 5 shows the results of solving two instances (b_10_20 and i_10_20) with 10 passengers and 20 parcels for the indicated weights. The effect of reducing the priority of passengers' convenience is that solutions will contain trips where parcels are delivered before passengers if such trips are shorter. Therefore, visualising the efficient points allows a decision-maker to choose appropriate weights so that passenger convenience and vehicle usage are balanced.

In Figure 5a, travel time ranges from 56.8 min to around 57.8 min, while drive time ranges from around 72 min to 73.5 min, which is a small range, only one minute, and it might even be imperceptible for the passengers. In Figure 5b, however, the total travel time ranges from 56 to 72 min, which is more noticeable. The tradeoff is that improving the quality of service for the passengers comes at the cost of increasing total drive time from around 67 to 71 min.

Figure 5 Pareto efficient points of selected instances



(a) Instance b_10_20



(b) Instance i_10_20

In practice, reducing the priority of passengers' convenience, i.e., reducing α, is that solutions will contain trips where parcels are delivered before passengers if doing so yields shorter trips. The service might be negatively impacted if passengers feel that parcels take precedence over them in the priority line. Visualising the tradeoff allows a decision maker to choose solutions according to their interest: they might find it competitive to favour the passenger's experience at the expense of higher vehicle usage.

However, visualising the tradeoff means finding Pareto points for each instance by solving for all α values, and the computational time required to do so highly depends on the instance. It might be impractical in many cases. In the context of mixed and integrated transportation, developing an efficient approach to finding such Pareto points is out of the scope of the present work. However, we would like to emphasise that it might be a promising research direction since, to the best of our knowledge, algorithms developed for this context do not consider a tradeoff between operational goals and quality of service. In a related field, in the context of DARP, Paquette et al. (2013)

developed a multicriteria heuristic to deal with the challenge of generating Pareto points between service costs and user inconvenience. Thus, obtaining insights from this related and existing body of research might be possible.

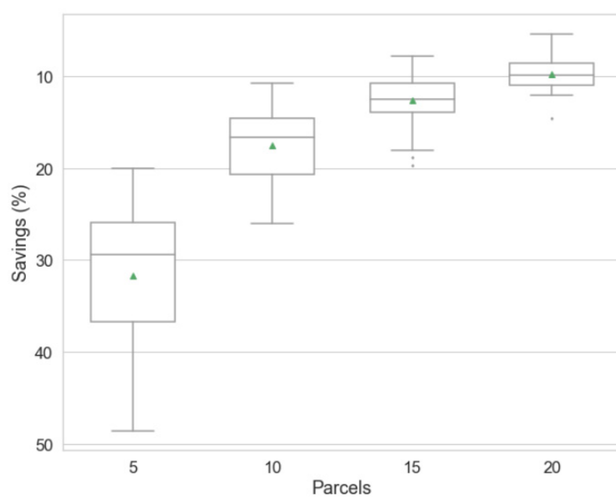
5.3.3 Analysis of direct delivery vs. integrated delivery of parcels

In this analysis, we disregard passenger transportation and focus only on benefits for delivery services, asking whether using buses jointly with delivery vehicles offers any advantage compared to only using delivery trucks, i.e., a traditional, direct, non-integrated approach. We compare Scenario D to Scenario B, both solved only for parcels, and calculate the average savings in drive time of D relative to B, shown in Table 4. Figure 6 shows the distributions from which those averages were calculated.

Table 4 Average savings in drive time caused by changing from a non-integrated (Scenario D) to an integrated (Scenario B) delivery scheme

	Drive time (min)		
Parcels	*B*	*D*	*Savings (%)*
5	17.4	25.4	31.7
10	31.4	37.9	17.5
15	40.8	46.6	12.7
20	50.4	55.8	9.8

Figure 6 Distributions of savings in drive time. Observe that the y axis is reversed. The green triangles indicate the mean value



As we increase the quantity of parcels, we get smaller savings in driving time. While those savings depend heavily on the instance, we observe a decreasing trend, with the most savings obtained when there are the fewest parcels. A related conclusion was reached by Masson et al. (2017) in their case study: as the amount of cargo increases until the trucks' capacity, the trucks will travel less because they need to return to the depot fewer times to reload, whereas city freighters need frequent trips back to the bus stops to reload. Therefore, this operational advantage explains why a transportation system integrated to include fixed lines such as bus routes is more suitable for rural areas: it exploits the low volume and long distances typical to that setting.

6 Conclusion

In this paper, we proposed a transportation service that both mixes parcels and passengers, and integrates last-mile delivery and bus routes in the context of rural areas. We described a MIP formulation to optimise the routes of the last-mile delivery vehicles such that they are synchronised to the buses while considering passenger convenience. To validate the model, we generated instances based on a real bus line in the Japanese countryside. Also, we evaluated the performance of the proposed service, using the generated instances, against other possible service formats, such as non-mixed and non-integrated ones. Regarding the drive times of the last-mile vehicles, our analysis concluded that the proposed approach yields the shortest total drive time across the set of instances. This result was expected, but our model allows the visualisation of such a benefit. We also showed that, by applying weights to the two objective functions, a decision maker can visualise the tradeoff between them and decide to increase the savings in drive time while still observing the passenger perspective. Focusing on the integrated delivery of parcels, we showed that the savings in drive time decrease as the number of parcels increases. These results indicate the advantage of our proposal when considering operational aspects in rural areas. The results obtained are valid for the generated instances under a list of assumptions that are reasonable but not representative of all rural regions which exhibit a wide array of characteristics. When considering another area, the analysis carried out in this paper should be repeated based on instances that reflect the characteristics of that region.

Future work might focus on incorporating realistic aspects into the model, such as a heterogeneous fleet and heterogeneous requests (passengers in wheelchairs or refrigerated parcels). We can also mention the use of autonomous vehicles to alleviate the critical issue of driver supply. Additionally, we can also think of algorithm development. As explored in our literature review, the vehicle routing research community has extensively used (meta)heuristic approaches. Developing approaches to obtain reasonable solutions to bigger instances might allow the implementation of a more complex and integrated last-mile service.

References

Aldaihani, M. and Dessouky, M.M. (2003) ‘Hybrid scheduling methods for paratransit operations’, *Computers & Industrial Engineering*, Vol. 45, No. 1, pp.75–96.

Allen, J., Piecyk, M., Piotrowska, M., Cherrett, T., McLeod, F., Oakey, A. et al. (2021) ‘Combining on-foot porters with vans for last-mile parcel deliveries: results of a study in central London’, *World Review of Intermodal Transportation Research*, Vol. 10, No. 1, pp.65–85.

Arvidsson, N., Givoni, M. and Woxenius, J. (2016) ‘Exploring last mile synergies in passenger and freight transport’, *Built Environment*, Vol. 42, No. 4, pp.523–538.

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

Boysen, N., Fedtke, S. and Schwerdfeger, S. (2021) 'Last-mile delivery concepts: a survey from an operational research perspective', *OR Spectrum*, Vol. 43, No. 1, pp.1–58.

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

Cleophas, C., Cottrill, C., Ehmke, J.F. and Tierney, K. (2019) 'Collaborative urban transportation: recent advances in theory and practice', *European Journal of Operational Research*, Vol. 273, No. 3, pp.801–816.

Cordeau, J.-F. and Laporte, G. (2007) 'The dial-a-ride problem: models and algorithms', *Annals of Operations Research*, Vol. 153, No. 1, pp.29–46.

Ghilas, V., Demir, E. and Van Woensel, T. (2013) *Integrating passenger and freight transportation: model formulation and insights*, BETA publicatie: Working papers 441.

Ghilas, V., Demir, E. and 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*, Vol. 72, pp.12–30.

Ghilas, V., Demir, E. and Van Woensel, T. (2016b) 'The pickup and delivery problem with time windows and scheduled lines', *INFOR: Information Systems and Operational Research*, Vol. 54, No. 2, pp.147–167.

Ghilas, V., Cordeau, J.-F., Demir, E. and Woensel, T.V. (2018) 'Branch-and-price for the pickup and delivery problem with time windows and scheduled lines', *Transportation Science*, Vol. 52, No. 5, pp.1191–1210.

Google Developers (2022) *GTFS Static Overview*. Available online at: https://developers.google.com/transit/gtfs/ (accessed on 20 October 2021).

GTFS-JP (2019) *Gtfs-jp*. Available online at: https://www.gtfs.jp/ (accessed on 27 October 2021).

Häll, C.H., Andersson, H., Lundgren, J.T. and Värbrand, P. (2009) 'The integrated dial-a-ride problem', *Public Transport*, Vol. 1, No. 1, pp.39–54.

Ho, S.C., Szeto, W.Y., Kuo, Y.-H., Leung, J.M., Petering, M. and Tou, T.W. (2018) 'A survey of dial-a-ride problems: literature review and recent developments', *Transportation Research Part B: Methodological*, Vol. 111, pp.395–421.

ITF (2021) *Innovations for better rural mobility*, ITF research reports, OECD Publishing, Paris.

Masson, R., Trentini, A., Lehuédé, F., Malhéné, N., Péton, O. and Tlahig, H. (2017) 'Optimization of a city logistics transportation system with mixed passengers and goods', *EURO Journal on Transportation and Logistics*, Vol. 6, No. 1, pp.81–109.

Molenbruch, Y., Braekers, K., Hirsch, P. and Oberscheider, M. (2021) 'Analyzing the benefits of an integrated mobility system using a matheuristic routing algorithm', *European Journal of Operational Research*, Vol. 290, No. 1, pp.81–98.

Mourad, A., Puchinger, J. and Chu, C. (2019) 'A survey of models and algorithms for optimizing shared mobility', *Transportation Research Part B: Methodological*, Vol. 123, pp.323–346.

Mourad, A., Puchinger, J. and Van Woensel, T. (2021) 'Integrating autonomous delivery service into a passenger transportation system', *International Journal of Production Research*, Vol. 59, No. 7, pp.2116–2139.

Openrouteservice (n.d.) Available online at: https://openrouteservice.org (accessed on 10 October 2021).

Paquette, J., Cordeau, J.-F., Laporte, G. and Pascoal, M.M. (2013) 'Combining multicriteria analysis and tabu search for dial-a-ride problems', *Transportation Research Part B: Methodological*, Vol. 52, pp.1–16.

Parragh, S.N., Doerner, K.F. and Hartl, R.F. (2008) 'A survey on pickup and delivery problems', *Journal für Betriebswirtschaft*, Vol. 58, No. 1, pp.21–51.

Pimentel, C. and Alvelos, F. (2018) 'Integrated urban freight logistics combining passenger and freight flows – mathematical model proposal', *Transportation Research Procedia*, Vol. 30, pp.80–89. EURO Mini Conference on "Advances in Freight Transportation and Logistics".

Posada, M., Andersson, H. and Häll, C.H. (2017) 'The integrated dial-a-ride problem with timetabled fixed route service', *Public Transport*, Vol. 9, No. 1, pp.217–241.

Posada, M. and Häll, C.H. (2020) 'A metaheuristic for evaluation of an integrated special transport service', *International Journal of Urban Sciences*, Vol. 24, No. 3, pp.316–338.

Ritchie, H. and Roser, M. (2018) *Urbanization. Our World in Data*. Available online at: https://ourworldindata.org/urbanization (accessed on 17 January 2022).

Statistics Bureau of Japan (2020) *Statistical maps of Japan*. Available online at: https://www.stat.go.jp/english/data/chiri/map/index.html (accessed on 10 October 2021).

Trott, M., Landwehr, M.A.D. and Viebahn, C.V. (2021) 'E-grocery of tomorrow: home delivery of food between profitability, customer acceptance and ecological footprint', *World Review of Intermodal Transportation Research*, Vol. 10, No. 1, pp.46–64.

WEF (2020) *Transforming rural mobility in Japan and the world*, Technical report, World Economic Forum.