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Combining people and freight flows using a scheduled transportation line with stochastic passenger demands

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1 Introduction

The increasing demand for goods, especially in urban areas, together with the emerging information and technological advances are creating both opportunities and challenges for planning urban freight systems and improving their services. One of these promising opportunities is to use the underused assets in people transport systems (e.g. urban rail, buses or private-car trips) to transport goods [1]. As both people and goods move in the urban environment, a successful integration of their streams has the potential of enhancing the quality of their existing transportation services as well as reducing congestion and pollution levels [2]. For example, spare capacity in public transport systems can be used for retail store replenishment or a taxi can deliver freight when transporting a paseenger or during idle time. As this combination can lead to minimizing vehicle-miles traveled, it can also yield some transportation cost reductions for both passengers and freight.

This paper considers an integrated system in which a set of freight requests need to be delivered using a fleet of grounded robots where a public transportation service (referred to as *scheduled line (SL)*) can be used as part of a robot's journey[1]. This SL service is mainly used for transporting passengers and the idea of our model is to use this service for some freight deliveries when passengers demand is low. In other words, the model ensures that the potential transportation of freight does not distrub the transportation of passengers through the scheduled line. We thus consider that passengers and robots (carrying small parcels) share the same SL capacity where passenger demands are stochastic. Thus, depending on passenger demand realization, a robot might not be able to use the SL service and some recourse actions need to be applied. Thus, we develop a stochastic approach for operating this system and we perform an extensive computational study to analyze its performance and evaluate the impact of stochastic passengers demand on the overall cost of transporting freight through SL.

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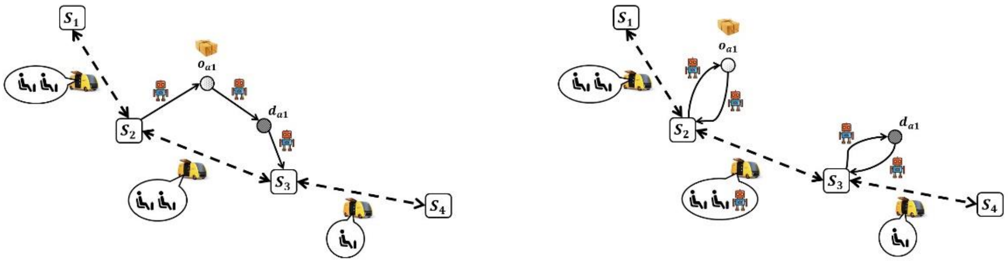
[1] This integrated system was inspired from Toyota new e-Palette concept.

2 Problem description

In this problem, a set of autonomous shuttles operate through a fixed-route scheduled line (SL) service for transporting passengers in both directions. This service consists of a set of transfer nodes (i.e. stations) and a set of scheduled lines linking them. Every SL has a capacity and a timetable. In addition, a fleet of grounded, pickup and delivery (PD) robots are located at transfer nodes to serve freight requests. Each PD robot has a capacity and a maximum service distance indicating the maximum distance it can go from a transfer node. Moreover, SLs and PD robots are associated with a shipping cost per one time unit.



(a) Direct delivery – PD robot

(b) Indirect delivery – PD robot and scheduled line

Figure 1: Request service modes: direct & indirect delivery

Furthermore, a set of freight requests need to be delivered using the fleet of PD robots. Each request is associated with an origin, a destination, pickup and delivery time windows, and a demand quantity. Thus, each request has to be served within its corresponding time windows. Depending on the availability of vacant places, PD robots carrying freight may travel with passengers through SLs. Therefore, delivering a request can be done in either direct or indirect way. In a **direct delivery**, a request is delivered directly to its final destination by a PD robot without the use of SL (**Figure 1 (a)**; request a_1 is picked up at its origin o_{a_1} by a PD robot coming from transfer node s_2, and delivered to its final destination d_{a_1} before the PD robot returns to transfer node s_3). This direct delivery is only feasible if the distance between request origin and destination locations is less than the maximum distance the PD robot can travel. On the other hand, in an **indirect delivery**, a request is collected by a PD robot, transfered through SL, and delivered afterwards to its final destination by the same PD robot (**Figure 1 (b)**; request a_1 is picked up at its origin o_{a_1} by a PD robot, transported through SL from s_2 to s_3 and finally delivered to its final destination d_{a_1} by the PD robot). We assume that a passenger or a PD robot take over one place in a shuttle and that passengers are prioritized. For the sake of simplifying the problem, we assume that each PD robot can serve only one request at a time and that freight quantities are known in advance. We also assume that the maximum number of PD robots that can be transported in a shuttle is bounded by a certain limit. On the other hand, passenger demand is only learned upon shuttles' arrivals to SL stations. Thus, the number of available places for PD robots at each SL departure is stochastic which might yield two capacity violation outcomes: **(i)** PD robot not being able to take the next SL departure due to the high passenger demand at the corresponding station, and **(ii)** PD robot having to get off the shuttle at an intermediate station in order to give its place to a passenger.

In both situations, the same capacity violation outcome, which is not having enough capacity for transporting passengers and PD robots within shuttles, will be obtained. When such route failures occur, recourse actions are needed in order to recover feasibility where applying these actions might lead to extra transportation costs compared to original routes. In this study, we consider the following recourse actions (respectively): **(i)** if PD robot cannot take the current departure due to high passenger demand, it will wait for the next SL departure which yields no extra costs as long as waiting the next departure does not violate request delivery time window. Second, **(ii)** if waiting the next departure also leads to violating SL capacity or request delivery time window, the PD robot will deliver the request directly to its final destination if this delivery is within the maximum distance it can travel. This recourse action implies additional costs as the PD robot will perform a longer trip than planned. Finally, **(iii)** if none of the first two actions leads to recovering route feasibility, the request will be transported to its final destination using an outsourced service (i.e. a dedicated vehicle) which induces extra transportation costs.

3 Solution approach

Similar to [3], we model this problem as a two-stage stochastic problem, where the first-stage aims at defining routes for PD robots carrying freight, and the second-stage involves evaluating these routes over a set of scenarios and computing their recourse costs. A scenario indicates the realized passenger demand at each departure from transfer nodes, and thus, the number of vailable places for transporting PD robots. As such, we provide a MIP formulation for the proposed pickup and delivery problem where the overall objective is to minimize the sum of the routing and recourse costs. Then, we propose a *sample average approximation (SAA)* method along with an *Adaptive Large Neighborhood Search (ALNS)* algorithm to solve the stochastic optimization problem. By iteratively solving the problem with different sets of scenarios, the proposed SAA algorithm aims at approximating the expected objective function of the stochastic problem and returning candidate solutions for it.

4 Expermintal study

We test the proposed approach over a set of instances with different network topologies (triangle and line networks) and freight request distributions (clustered, randomly-clustered and uniform-randomly distributed). In addition, we evaluate the posposed ALNS method by comparing its returned solutions with those obtained by solving the MIP using a CPLEX solver. We also analyze the performance of the removal and insertion operators that are used iteratively within the ALNS method to enhance an initial solution. We then quantify the impact of passenger demand realization on such delivery service by comparing the stochastic solutions with the deterministic ones and we highlight the potential gains that can be achieved from this combined delivery compared to classical freight delivery systems.

Results of testing instance with up to 60 freight requests showed that the proposed heuristic approach can return solutions that are within 0.6% of the optimal solutions. Results also revealed that an average of 3.3% extra costs can be observed when stochastic passengers demand is realized which reflect the effect of uncertainty of the total transportation costs. This increase is due to the recourse actions that are used to correct the interrupted robot routes. Analyzing the impact of different SL frequencies and capacities, the results demonstrated the positive effect of increasing the frequency of SL departures and the maximum capacity for PD robots on the system.

5 Conclusions

To conclude, our key contributions can be seen in the problem setting we consider, the modeling and solution approach we propose to handle it, and the experimental study we provide to assess its different stochastic aspects as well as the potential benefits of such combined systems.

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