35th European Modeling & Simulation Symposium
20th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2023 The Authors.
doi: 10.46354/i3m.2023.emss.025

Mixed truck and robot delivery approach: a simulation study

Angelina Krendeleva[1], Giuliana Rotunno[1], Walter Ukovich[1] and Maria Pia Fanti[1,*]

[1]Polytechic University of Bari, Bari, 70125, Italy

[*]Corresponding author. Email address: mariapia.fanti@poliba.it

Abstract

Among the objects of scientific research in the field of logistics, one of the most important factors is the new technologies needed to simplify and speed up delivery systems compared to human labor. This paper proposes and test a last mile delivery strategy that combines trucks and robots. The city is divided in a set of zones and each zone is a hub where the trucks arrive to serve the final destinations belonging to the zone. Hence, the last mile delivery is performed in the narrow roads of the city by robots. The problem is formalized as an optimization problem that maximizes the number of deliveries per day. A case study implemented in the old town of Bari (Italy) is studied and the obtained solutions are analyzed considering different speeds of the robots and are simulated in PTV Vissim simulation software.

Keywords: The last mile delivery, optimization, simulation.

1. Introduction

In recent years, the last mile delivery process represents the biggest challenge faced by logistics companies. It is the weakest link in the supply chain as a source of significant congestion in cities and polluting externalities Rodrigue et al. (2009). At the same time, home deliveries increased significantly during the pandemic period (COVID-19) and this habit has become a constant in the lives of many people.

In particular, the delivery industry is undergoing many transformations to meet people's needs. Technological advances in automation offer the opportunity to develop newer, more sustainable, and more efficient delivery systems, creating the ground for the development of innovative delivery models that could transform the last mile delivery landscape. The advantages of autonomous transport in an urban area are evident and generate significant advantages, such as: reduction of traffic, containment of pollutants, possibility of operating in areas where there are limitations often imposed by municipalities, especially in historic centres.

In the literature there are several works in which many innovative concepts are presented to move people and goods. Regarding freight transport, the distribution of last mile goods can be carried out with electric vehicles, drones, delivery in the trunk of a parked car or deliveries in the last mile with autonomous robots based on trucks. The authors in Samouh et al. (2020) propose three options for last mile delivery: a robot delivery system, a drone delivery system, and a hybrid delivery system. The authors found that hybrid delivery can reduce delivery time.

In (Poeting et al. 2019; Srinivas et al. 2022), the authors propose using autonomous delivery robots to deliver small goods. The authors in (Boysen et al. 2018; Ostermeier et al. 2022; Simoni et al. 2020) propose to use the truck-robot system, proving the effectiveness of such a system in more congested areas of the city, especially when the robot will contain more than one parcel. Perboli et al. (2018) use the multimodal transportation to reduce emissions in the environment. At the same time, the authors do not set themselves the goal of reducing the delivery time.

In this context, simulation and optimization play an important role being one, a decision support tool and the other, widely used in various works that focus on urban distribution. Samouh et al. (2020) propose the combination of different last mile food delivery systems (robot delivery system, drone delivery system and a hybrid delivery system) to analyse the performances of the system with the support of an agent-based simulation in MATLAB.

To simulate the last mile of parcel delivery, Poeting et al. (2019) present a system featuring conventional trucks and parcel robots and uses an ABS freight transport simulation. The authors use ABS implemented with the simulation software AnyLogic and to support the decision processes a mathematical optimization (two extension of the Traveling Salesman Problem) are solved heuristically. Moreover, a new simulation and optimisation framework is applied in Perboli et al. (2018) with the integration of different deliveries modes (i.e., cargo bikes and lockers). A simulation based on the Monte Carlo method and optimization modules are defined directly in Python and the realism of case study is guaranteed by the introduction in the framework of different real data sources and stakeholder requirements. The research results highlighted that the switch to vehicles with a low environmental impact and to lockers, could lead an improvement in the economic efficiency of the business model of the traditional carrier and in the working conditions of the drivers.

Another similar problem is taken to account by Simoni et al. (2020) that exploit a very efficient and special dynamic programming solution the "Weighted Interval Scheduling Problem". Starting to an integrated truck-robot system for the last-mile delivery, the authors presented a heuristic that identifies solutions based on initial truck tours and corresponding joint robot operations. In addition, an efficient heuristic solution procedure is presented in Boysen et al. (2018) to minimize the weighted number of delayed deliveries of customers. A scheduling procedure which determines the truck route along robot depots and drop-off points.

The aim of this paper is to propose and test a last mile delivery strategy that combines trucks and robots starting from the ideas in (Boysen et al. 2018; Ostermeier et al. 2022). The city is divided in a set of zones and each zone is a hub where the trucks arrive to serve the final destinations belonging to the zone. The peculiarity is that the final destinations in the hubs can be reached by pedestrians, bicycles or light electric vehicles through reserved routes. Hence, the last mile delivery is performed in the narrow roads of the city by robots. The problem is formalized as an easy optimization problem that maximizes the number of deliveries per day. The problem is analyzed considering different speeds of the robots and the obtained solutions are simulated in PTV Vissim simulation software (https://www.ptvgroup.com/en/solutionsproducts/ptv-vissim/). In such a way we test the results in a more realistic environment that include also traffic of bicycles and pedestrians. Finally, we will compare the traditional delivery performed by couriers. To show the efficiency of the proposed simulation, it is applied to a case study implemented in the old time of Bari, in the Southern Italy.

The paper is organized as follows. Section 2 introduces the problem and the proposed solution. Section 3 describes the case study and the obtained results. Finally, Section 4 reports the conclusions and the future research.

2. Problem description

This section describes the proposed last mile delivery approach based on the combined used of trucks and robots. The city is divided in a set of zones of an average of 2000 inhabitants. Each zone is a hub where the trucks arrive to serve the final destinations belonging to the zone (Fig. 1). The peculiarity is that the final destinations in the hubs can be reached by pedestrians, bicycles or light electric vehicles through reserved routes.

Each truck has to deliver P parcels to a set of customers belonging to its zone. We assume that the delivery is performed by a set of R robots that start from the warehouse near the truck, deliver the parcels to the customers and return to the warehouse for a new package. Hence, we assume that each zone is divided in R subzones, each subzone is served by one robot that can carry one package at a time.

The robot speed is from 6 to 8 km/h and a maximum number of N_{Max} parcels can be delivered per day using the R robots.

The operating time of the robot is of T=540 minutes (9 hours).

The success of delivery largely depends on the correct preparation of the routes, considering the characteristics of each client.

This problem is solved with the help of a traffic routing system. We took advantage of the transportation problem by optimizing the delivery time of robots to each client. Possible routes of transportation and scheduling of product delivery by users are the development of a strategy and logistics for building a customer service model.

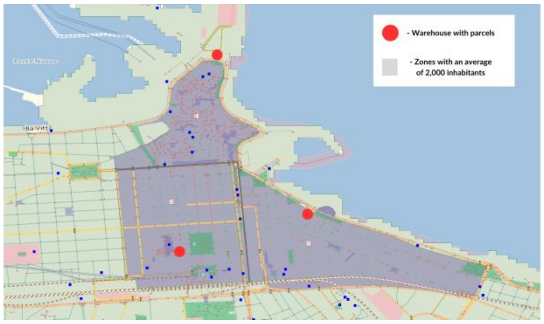

Figure 1. The city divided in hubs where the truck arrive

We summarize the variables and data of the problem in the following:

1. The total working time of the robots is T=540 minutes per day;
2. The maximum number of delivered parcels per day is P parcels and each robot can deliver N_{Max} pieces per day;
3. The zone is divided in R subzones equal to the number of robots;
4. Each subzone is partitioned in a set $A = \{a_i \mid i = 1, \dots, I\}$ of I areas;
5. Each section s_i is characterized by a given distance d_i from the warehouse and a time τ_i necessary for delivery one parcel (the time to reach the customer, delivery the parcel and return to the warehouse);
6. The requested number of deliveries for each area is of B_i pieces.

The objective is to perform the maximum number of the requested deliveries in each working day.

We denote by D_i the decision variable equal to the number of the required deliveries that can be actually performed by one robot in area a_i during time T.

The optimization problem can be defined as follows:

$$Max \sum_{i=1}^{I} D_i \qquad (1)$$

s.t.:

$$\sum_{i=1}^{I} D_i \tau_i \leq T \qquad (2)$$

$$D_i \leq B_i \text{ for } i=1,\dots,I. \qquad (3)$$

$$D_i \text{ is integer for } i=1,\dots,I \qquad (4)$$

The problem (1)-(4) is a knapsack problem with unit values (Lewandowski, A., 2010). It may be easily proved that the optimal solution is obtained by saturating the deliveries of each section in order of increasing distance until the total working time is reached.

3. The case study

In this section we solve and simulate a case study involving the city of Bari, located in the southern Italy. The considered zone for implementing the hub is the Bari old town (Figure 2).

We assume that R=3 is the number of robots and subzones, P=25 is the maximum number of deliveries per day. The subzone is partitioned in 10 areas and the loading/unloading time for each client is of 12 minutes.

We consider 4 cases:

Case 1: Robots use the minimum delivery speed of 6 km/h in all the areas;

Case 2: Robots use the minimum delivery speed in 1-5 sections and the maximum delivery speed of 8 km/h, in 6-10 areas;

Case 3: Robots use the maximum delivery speed of 8 km/h in all the areas.

Case 4: A courier performs the deliveries with a travel time of 4.2 km/h in all the areas.

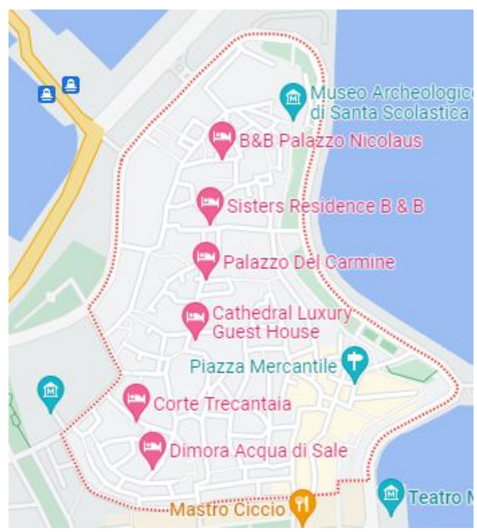

Figure 2. The Hub in the Bari old town.

3.1. Optimal solutions of the cases

The solution of each case is obtained by the "Search for a solution" method of Excel.

In Case 1 the delivery times for each section are reported in Table 1.

The solution of Case 1 is shown in Table 2. It is apparent that only 23 deliveries per day can be performed by the robot.

Table 1. Distances and delivery times for Case 1

a_i	d_i (m)	τ_i (min)
a_1	100	14
a_2	200	16
a_3	300	18
a_4	400	20
a_5	500	22
a_6	600	24
a_7	700	26
a_8	800	28
a_9	900	30
a_{10}	1000	32

Table 2. Deliveries of robot in Case 1

Areas	Clients											
	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	Parcels per day	Total time
B_i	2	3	2	3	2	3	2	3	2	1	23	540
D_i	2	3	2	3	2	3	2	3	2	3		

Now we consider Case 2 and Table 3 reports the new travel times associated with each area. Moreover, Table 4 shows the obtained results. As it is expected, if the robot moves from area 1 to 5 at a speed of 6 km/hour, and from area 6 to 10 at a speed of 8 km/hour, then it will be able to deliver 25 parcels per day.

The solution of Case 1 is shown in Table 2. It is apparent that only 23 deliveries per day can be performed by the robot.

Table 3. Distances and delivery times for Case 2.

a_i	d_i (m)	τ_i (min)
a_1	100	14
a_2	200	16
a_3	300	18
a_4	400	20
a_5	500	22
a_6	600	21
a_7	700	22.5
a_8	800	24
a_9	900	25.5
a_{10}	1000	27

Table 4. Deliveries of robot in Case 2

Areas	Clients											
	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	Parcels per day	Total time
B_i	2	3	2	3	2	3	2	3	2	3	25	540
D_i	2	3	2	3	2	3	2	3	2	3		

The travel times of Case 3 are reported in Table 5 and the optimization results are shown in Table 6. It is obvious that also in this case the 25 deliveries are performed but in lower time with respect to Case 2.

able to deliver 25 parcels per day. And, he will have free 30 minutes of time.

The delivery times of Case 5 are reported in Table 7.

Table 5. Distances and delivery times for Case 3.

a_i	d_i (m)	τ_i (min)
a_1	100	13,5
a_2	200	15
a_3	300	16,5
a_4	400	18
a_5	500	19,5
a_6	600	21
a_7	700	22,5
a_8	800	24
a_9	900	25,5
a_{10}	1000	27

Table 6. Deliveries of robot in Case 3

Areas	Clients											
	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	Parcels per day	Total time
B_i	2	3	2	3	2	3	2	3	2	3	25	540
D_i	2	3	2	3	2	3	2	3	2	3		

Table 7. Distances and delivery times performed by the courier for Case 3.

a_i	d_i (m)	τ_i (min)
a_1	100	14,86
a_2	200	17,71
a_3	300	20,57
a_4	400	23,43
a_5	500	26,29
a_6	600	29,14
a_7	700	32
a_8	800	34,86
a_9	900	37,71
a_{10}	1000	40,57

Table 8. Deliveries of courier in Case 4

Areas	Clients											
	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	Parcels per day	Total time
B_i	1	1	1	1	1	2	2	3	2	3	17	540
D_i	2	3	2	3	2	3	2	3	2	3		

We note that if the courier delivers parcels at an average speed of 4.2 km/h, then only 17 parcels per day are delivered.

We compare the numbers of parcels delivered by the courier and the robot in Figure 3.

According to the diagram, we see a significant advantage of using a robot in the delivery system with respect to a courier. Moreover, it is apparent that with a suitable selection of the robot speeds, it is possible to guarantee the requested deliveries.

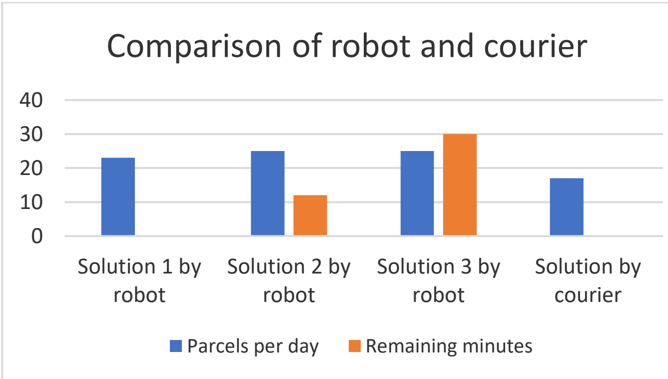

Figure 3. Comparison of robot and courier in the 4 cases.

4. Simulation results

In order to check the solutions of (1)-(4) in a slightly realistic conditions, we simulate the described system in the PTV Vissim simulation software. The Vissim program is designed for building, researching and optimizing virtual models of physical and technical objects, including control systems.

The real pedestrian roads of the Bari old town are reported from Google Map in PTV Vissim. Moreover, we divided the main road of the old town in areas from 100 m to 1000 m (Figure 4). In each area we added 3 pedestrians and 3 cyclists per hour to the traffic to obtain more realistic results and test each of the three solutions.

In addition, Tables 9 and 10 show the delivery times obtained by the simulation for Case 2 and 3, respectively. Concerning the deliveries, 19 parcels are delivered in Case 2 and 17 parcels are delivered in Case 3.

Figure 4. Robot roads in the old town of Bari in PTV VISSIM

Table 9. Robot delivery times simulated in PTV Vissim for Case 1

a_i	d_i (m)	τ_i (min)
a_1	100	13,82
a_2	200	18,36
a_2	300	19,5
a_2	400	21,4
a_2	500	25,5
a_2	600	32,6
a_2	700	36,4
a_2	800	38,6
a_2	900	45,2
a_2	1000	39,4

Table 10. Robot delivery times simulated in PTV Vissim for Case 2

Courier	d_i (m)	τ_i (min)
a_1	100	13,82
a_2	200	18,36
a_2	300	19,5
a_2	400	21,4
a_2	500	25,5
a_2	600	32,8
a_2	700	36,4
a_2	800	39
a_2	900	45,4
a_2	1000	41

Table 11. Robot delivery times obtained by PTV Vissim for Case 3

a_i	d_i (m)	τ_i (min)
a_1	100	14,26
a_2	200	18,36
a_3	300	19,5
a_4	400	23,2
a_5	500	25,5
a_6	600	32,8
a_7	700	36,4
a_8	800	39
a_9	900	45,4
a_{10}	1000	41,16

Such simulation results are summarized in Figure 5 and compared with the theoretical results obtained by the optimization (1)-(5). Moreover, we simulated the deliveries performed by the courier and the obtained delivery times are shown in Table 12. Also, in Case 4 we obtained a reduction of deliveries: 15 parcels in one day. We compare this result with the one obtained by the optimization in Figure 6.

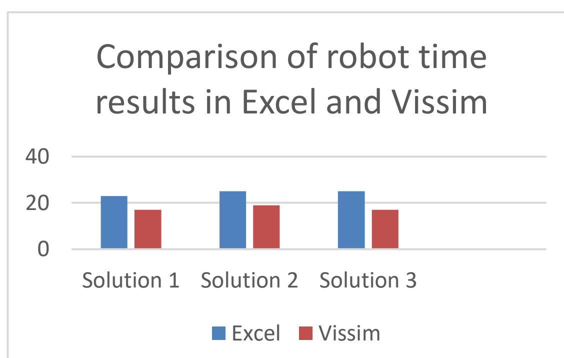

Figure 5. Comparison of robot time results by the optimization and Vissim simulation

Table 12. Courier delivery times obtained by in Vissim for case 4

a_i	d_i (m)	τ_i (min)
a_1	100	16.00
a_2	200	20.40
a_3	300	22.50
a_4	400	26.20
a_5	500	30.80
a_6	600	33.00
a_7	700	36.60
a_8	800	39.20
a_9	900	45.60
a_{10}	1000	49.20

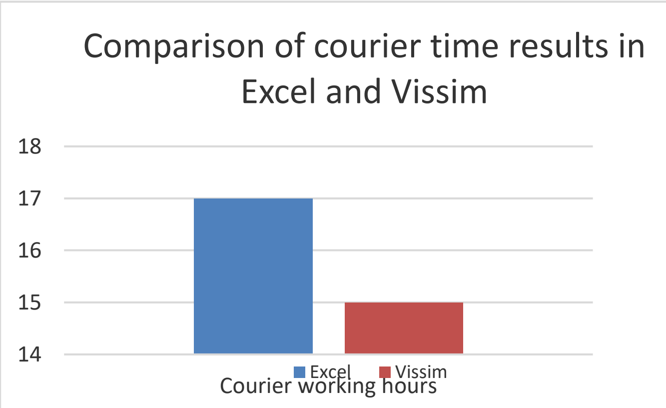

Figure 9. Comparison of courier time results in Excel and Vissim

5. Conclusions

This paper presents an approach for the last mile delivery that uses trucks and robots. The aim is reducing traffic on the roads by using pedestrian sidewalks for robots, since trucks arrive to a certain place where there is a warehouse, and do not move around the city.

The problem is solved by defining an optimization problem that is applied to a case study of the city of Bari (Italy). In order to test the solutions in a more realistic environment, we model and simulate the system in the PTV Vissim framework. To this aim the simulations are performed also in presence of road traffic that affects and worsens the system performances.

Next research will test the proposed strategy considering more robots working in the different zones of the cities. The solutions will be tested and validated in simulations that consider real traffic consitions.

Funding

This study was carried out within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-GenerationEU (Piano Nazionale Di Ripresa E Resilienza (PNRR) – Missione 4 Componente 2, Investimento 1.4 – D.D. 1033 17/06/2022, CN00000023) and is a part of the IN2CCAM project that has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101076791. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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