Delivering parcels through a metro-based underground network: an economic analysis

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Abstract: This work proposes the introduction of an innovative method to deliver parcels within urban areas through a two-echelon logistic network, exploiting underground public transportation and cargo bikes. A model simulating the delivery of parcels through underground public transportation and cargo bikes is developed and applied to the city of Milan. Different scenarios, characterized by a different number of train stations activated and a number of daily orders, are investigated. Exploiting available capacity at subway trains reduces the impact of routing empty vehicles for the public infrastructure provider. Besides, as small, capacitated vehicles, cargo cycles allow having an average higher saturation, with the possibility of running multiple trips within the same day, lowering the impact of non-value adding returns for long-haul vehicles coming from outlying distribution centers. Alongside this, the usage of light vehicles and underground infrastructures help to significantly reduce transportation impacts. Overall, the solution proposed has the potential to radically innovate and improve urban last mile delivery under both economic and environmental perspectives. The present work proposes an innovative solution to deliver parcels, showing that it is sustainable from the logistics service operators' perspective.

Keywords: Include a list of 3-5 keywords. Aaaa; Bbbb; Cccc; Dddd; Eeee.

I. INTRODUCTION

In recent years, Business to Consumer e-commerce is experiencing fast growth. Customers are increasing their confidence in e-purchasing, always more and more involved inside the purchasing processes through omnichannel strategies. Alongside this, massive urbanization is one of the mega-trends affecting lifestyles and mobility dynamics. Almost 70% of the worldwide population will live in big cities by 2050 (UNDESA, 2021). The combination of these elements generates a vicious cycle for fast and smart mobility in urban areas, characterized by a growing number of wheeled vehicles daily accessing city boundaries. Several actors are particularly committed to reducing the impact of air and noise pollution and overcrowding within urban borders; from inhabitants seeing affected their lifestyles, through municipalities wanting to preserve from urban degradation to Logistics Service Providers in search for solutions to increase cost efficiency, keeping at the same time high service levels. Under this light, last-mile logistics is growing its interest in finding innovative solutions to limit externalities, increasing performances and efficiency. It is no more possible to move on trade-off curves and the only way to generate significant improvements on all sides is to introduce innovative changes in urban delivery paradigms. This work proposes the introduction of an innovative method to deliver parcels within urban areas through a two-echelon logistic network, exploiting underground public transportation and cargo bikes.

II. LITERATURE REVIEW

Contributions in extant literature aim to provide improved solutions to frequently discussed problems in the last-mile delivery, such as routing and location problems to better predict and minimize time spent in travelling. In particular, extended versions of Vehicle Routing Problems (VRPs) and Traveller Salesman Problem (TSP)s are treated, such as Traveller Salesman Problem with Time Windows (TSPTW) (Chatterjee et al. 2016, Ghilas et al. 2016), Capacitated Vehicle Routing Problem (C-VRP)s, multi-echelon and multi-trip routing problems with time-windows (Enthoven et al. 2020, Chatterjee et al. 2016, Ghilas et al. 2016) or delivery options (Grangier et al. 2016, Zhou et al. 2018), multi-echelon formulations (Enthoven et al. (2020), or VRPs including vehicles environmental impacts (Perboli & Rosano 2019, Breunig et al. 2019, Wang et al. 2017). Alongside this, several technological solutions are being studied and developed to provide new extents in the last-mile delivery (Mangiaracina et al., 2019). The interest in involving unusual solutions in the last-mile is increasing. Drone and robot delivery (Swanson 2019, Boysen et al. 2018, Marsden et al. 2018), alternative fleet typologies as cargo cycles

(Tipagornwong & Figliozzi 2014, Clausen et al. 2016, Sheth et al. 2019), and innovative frameworks as crowdsourcing in logistics (Kafle et al. 2017, Carbone et al. 2017, Castillo et al. 2018, Qi et al. 2018, Li et al. 2016, Ji et al. 2020) are more and more frequently tackled by researchers. Undoubtedly, key limitations deal with the technological complexity and operational definition of solutions, but the real barrier towards great game-changer networks lies in the hardness in properly managing players' heterogeneous strategies, utility functions, conflicting objectives, and infrastructure control (Macharis & Kin, 2017). Therefore, it is extremely important to properly define stakeholders' characteristics and needs to generate true value for all the actors involved.

III. METHODOLOGY

The network consists of exploiting the subway network to carry the orders from the terminal metro stations to intermediate metro stations within the city and then, deliver to the final customer through cargo cycles. Public transportation refers to the use of a public means of transport, designed to carry people in the urban context, as a carrier for parcels throughout cities. As the network model is built upon two echelons, we consider as crucial three nodes: (1) the upstream node, the Terminal Metro Station (2) middle node, the Intermediate Metro Station and (3) customer node, the Delivery Point respectively. Terminal Metro Stations are transit points placed at the immediate edges of the city. In particular, the position of each depot corresponds to the terminal stations of specific lines in the subway system. In Milan, the underground system has 4 active lines with 11 terminal stations at the edges of them. Intermediate Metro Stations are hubs placed at the exact location of subway stations, occupying fixed amounts of space at the extremity of stations' platforms. As the number of stations in the full Milan metro system is 113, there is a maximum of 113 IMSs that can be used for moving goods. However, 19 of them are outside city center of Milano, which is the scope of this analysis; 12 stations have been excluded since their infrastructures was not considered suitable. Available stations are indeed 82.

Process flow

Stage 1 – First, the logistics service providers bring orders to the terminal metro stations.

Stage 2 – It is assumed that a parcel that enters a metro line can never move to another line. Therefore, the system works under the hypothesis that flows are pre-emptively balanced across the stations. At the terminal metro station, parcels from different logistic providers are collected, unpacked, and consolidated based on the destination. Here a "route box" is created: it is the transport unit later delivered to the cargo biker for the last-mile delivery. In the end, the route box is loaded into the train, following an automated or a non-automated way.

Stage 3 - Train transportation from the terminal stations to the intermediate metro stations. No specific activities are performed on trains. Due to this, no operators neither in the non-automated or in the automated case are considered at train level to limit resources over-allocation. Still, some key differences are in place depending on the automation level defined. Non-automated train systems consist of simple racks allowing the storage of parcels while traveling the network. In the automated case, train systems are conceived as vertical automated storage systems able to store and drop route boxes at scheduled intermediate metro stations.

Stage 4 - The Route-Boxes are received at Intermediate metro stations and unloaded from trains, to be routed in the ground level. IMSs are the gateway between the underground and the ground part of the system. Few handling activities are performed besides loading and unloading procedures. Once the network is defined, each intermediate metro station covers a specific area of the city, so that the sum of all the areas covered by each intermediate metro station is equal to the global urban served area by the system. In the non-automated case, one operator per intermediate station is set to access trains stopping at the platform to manually retrieve route boxes from racks. In the automated case boxes are dropped and stored automatically by the systems. The automated case disposes of one flying-operator per line, traveling the network through lines' trains to handle local problems, manage missed deliveries, and run real-time supervision and maintenance operations.

Stage 5 - Once Route-Boxes are collected and stored at the intermediate metro stations' buffers, riders are in charge of picking one Route-Boxe to perform deliveries to final customers. The main activities run by riders are (i) Route-Boxe pickup, (ii) transportation, (iii) final home delivery, and (iv) move back to the original IMS or a neighboring IMS to drop missed deliveries or take a new Route-Boxe in charge.

Cost computation

Costs are classified according to two main dimensions: (i) referenced element in the system, i.e., Terminal metro stations, Intermediate Metro Stations, Train, and Ground Level; (ii) Cost typology, i.e., fixed costs, running costs and direct costs. Fixed Costs, as una-tantum sunk costs bared and capitalized at the moment of the initial investment. Running costs, as costs bared periodically to keep up the system and to provide resources for its proper functioning. Direct costs, as costs that are directly addressable to specific operative drivers as working time or unitary elements. A cost map showing how costs have been estimated is provided in Figures 1 and 2. Figure 1 regards Terminal metro stations and train. Figure 2 regards instead Intermediate metro stations and ground level.

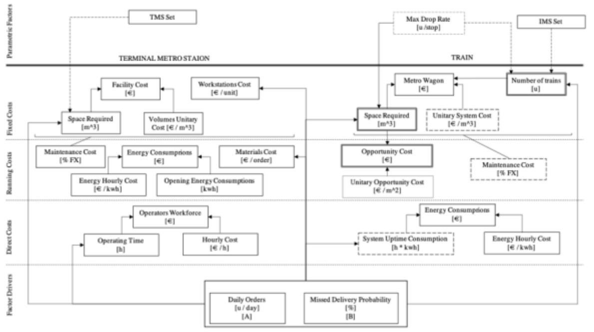


Figure 1. Cost map (1)

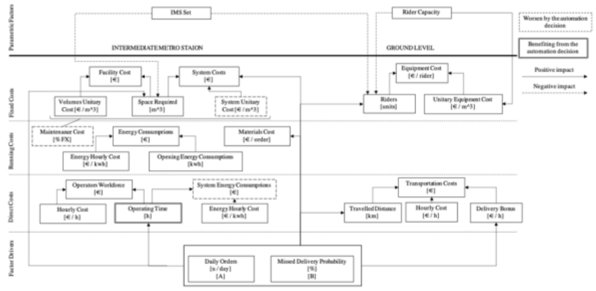


Figure 2. Cost map (2)

Model

The main objective of the model is to define, per each scenario considered, the physical sizing of the key elements of the network, as well as to assess both fixed costs and operational costs. The work proposes a local optimization model for trains and cargo cycle routing, to define the minimum size of fleets. The optimization model is composed of three steps:

1. Definition of the optimal extension of areas served by each station through a Voronoi model, and daily order allocation per station.

2. Definition of the minimal train fleet size, considering maximum drop rate constraints.

3. Definition of the minimal cargo cycles fleet size, through estimation of minimal traveling distances per each Voronoi area.

Voronoi areas. Zheng et al. (2020) describes the Voronoi diagram as an easily operated heuristic algorithm that allows dividing the research area according to an influencing factor, which in our case is the distribution of delivery nodes along the urban framework according to the demand distribution previously defined. The solution of the Voronoi diagram requires the solution of a p-median problem, evaluating the distance between the nodes and their central hub. The idea that resides behind it is to partition the plane into polygons so that each focal point, the IMS in our case, is the closest to each of the demand points that reside inside the polygon. The analytical computation of the Voronoi areas has been achieved through the Konrad library, which refers to Delaunay triangulation to generate the polygons.

Train fleet size. The minimum number of train arrivals per line is computed as the maximum of train arrivals needed per each station, per each line, considering the constraint about the volume of orders arriving at each node. In this way, the possibility of serving the most critical IMS per line is granted, thus the system is sized to serve every other IMS. The number of required arrivals is inversely proportional to the maximum drop rate of trains, which strictly depends on the automaton decision. The actual required size of the train fleet is computed by adjusting arrivals required over trains’ frequencies per day.

Once the width of intermediate metro station service areas is defined for the whole urban area, a **route optimization model** is run per each IMS sub-area to provide a sub-optimal definition to the riders’ Vehicle Routing Problem. This approach is driven by the need of having a complete but accessible method to assess routing performances realistically. The original empirical formulation proposed by Daganzo (1984) is used in this work:

$$CVRP(V^n) \simeq 2\bar{r}\frac{n}{C} + k\sqrt{nA} = 2\bar{r}m + k\sqrt{nA}$$

The CV RP(V n) defines the estimated travelled distance to serve n customers, with $\bar{r}$ as the average distance between the first customer and the depot, and C as the constant capacity constraint of the vehicle. Consequently, m = n/C is the predefined minimum number of routes, considering the fixed capacity of vehicles.

Scenario definition

Scenarios are considered to compare different possible configurations of the system to analyze how the system responds to changes in key parameters. A scenario is defined as a specific combination of parameters. Parameter factors are classified into two groups (P1, P2), according to the way they impact the model.

- P1 define the first levers to change the structure and the characteristics of the network. Acting on those parameters means acting on key variables affecting the system’s structural definition and performances. P1 include: (i) TMS set, (ii) IMS set, (iii) automation-decision, affecting (iii.i) unitary system cost per rack, (iii.ii) maximum train drop per station, and (iii.iii) system required space in trains.
- P2 parameters affect the behavior and the performances of the system, without affecting its design structure but only operational variables. P2 include: (i) cargo cycles typology, affecting (i.i) unitary cargo cycle purchasing cost, (i.ii) maximum volume and weight cargo cycle capacity, and (i.iii) cargo cycles’ average speed.

The aim of scenarios is one of assessing the impact both under operational terms and economic terms of different network configurations, varying parameters as explained above. Ten scenarios are built, each with the specific aim of responding to specific questions in the light of precedent results.

SC01, SC02 The first scenario definition was aimed to define which is the impact of growth in the capillarity of the network. Therefore, the first two scenarios were built in pairs, considering as a unique driver the number of active regions, thus stations in the UPTS. At this stage, the number of active lines is fixed and one TMS is opened per line, to grant at least to reach every station in the system. It is important to state that the number of intermediate metro stations grows with the number of opened stations (regions), but the number of the opened station does not necessarily grow if the number of intermediate metro station grows. At this stage, the aim of SC02 is the one of assessing the impact of an increase in the capillarity of the system.

Factor	Unit of measure	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09	SC10
Unitary system cost	€/unit	500	500	1400	1400	1400	1400	1400	1400	1400	1400
Automation decision	[0;1]	0	0	1	1	1	1	1	1	1	1
Cargo bike purchasing cost	€/unit	100	100	100	100	100	100	100	100	2000	2000
Maximum weight carriable by riders	kg/rider	10	10	10	10	10	10	10	10	20	20
Maximum volume carriable by riders	m^3/rider	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.25	0.25
Probability of missed delivery	%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Average rider speed	km/h	18	18	18	18	18	18	18	18	13	13
Train system volume increase	%	3	3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	50
Cost per kit		50	50	50	50	50	50	50	50	50	50
Maximum route-boxes drop capacity	Units/stop	4	4	8	8	8	8	8	8	8	8
Number of terminal metro stations	#	5	5	5	5	5	8	8	8	5	5
Number of intermediate metro station	#	**25**	**40**	25	40	47	47	73	40	25	40
Number of regions	#	**25**	**40**	25	40	43	40	40	40	25	40

Table 1. Scenarios definition

SC03, SC04 Parallelly to the first couple of scenarios, the second couple of scenarios is built to assess the impact of the automation decision. In particular, SC03 is the reflection of SC01 in the automated case, while SC04 is the reflection of SC02 in the automated case. No other parameter changes, as the only aim of this second couple of scenarios is the one of defining if the automated configuration outperforms the non-automated configuration of the system.

SC05 The fifth scenario is built with a further increase in the system capillarity, through the activation of a higher number of regions. A wider set of IMS is set to increase the coverage of the system over the urban area, to assess if a higher capillarity generates further benefits under economical terms. SC05 network shape is built based on the results obtained comparing the couples (SC03, SC04) and (SC01,SC02), both in terms of network geometry and automation decision.

SC06 The sixth scenario is built in parallel with SC05, considering as the main driver the number of active lines. An increase in the number of active lines is set with an increase in the number of active TMSs. Besides, based on the results obtained from the comparison between the first four scenarios as for SC05, the set of IMS is widened. Despite the strategy adopted for SC05, the IMS set for SC06 is not built to increase the capillarity of the system. Therefore, IMSs are added without affecting the number of active regions. The main objective of SC06 is to assess if an increase in the capacity of each region leads to economic benefits, exploiting a higher train frequency.

SC07 The scenario SC07 is built to be directly compared with SC06. The number of active TMS is kept constant, the number of active IMS is further expanded, without affecting the capillarity of the system as in SC06. IMSs are opened on current active regions. The objective of SC07 is to evaluate if a fully extended structure of the network increases efficiency through the exploitation of high train frequency and high capacity of stations.

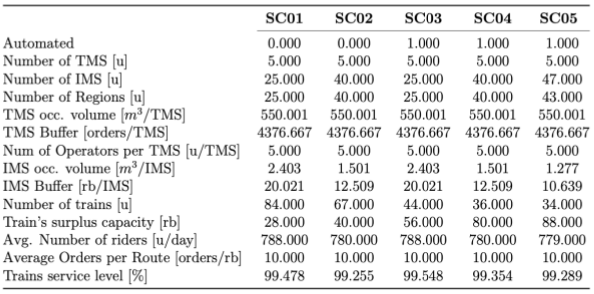
SC08 The eighth scenario is built to be directly compared with the best result obtained in the comparison between the first four scenarios. The IMS geometry is set based on the latter comparison, as well as the geometry of regions covering the urban area. The automation decision is set on the basis of the dominating solution defined above. The objective of SC08 is the one of assessing, given a fixed IMS set, the effect of a widening in the set of TMSs. In other words, SC08 is aimed to define if an increase in train frequency and availability is significant.

SC09, SC10 The last couple of scenarios is built considering as key drivers parameters on riders. Moreover, the couple (SC09,SC10) is built in parallel with the result obtained in the comparison of the first four scenarios. As for previous cases, the automation decision is defined on the basis of the results obtained above. SC09 considers the same TMS and IMS geometry of SC01 (SC03), and SC10 considers the same TMS and IMS geometry of SC02 (SC04). The objective of these couple of scenarios is the one of assessing the impact of the capacity of ground vehicles and to which extent higher capacitated vehicles affect the importance of network capillarity.

IV. RESULTS

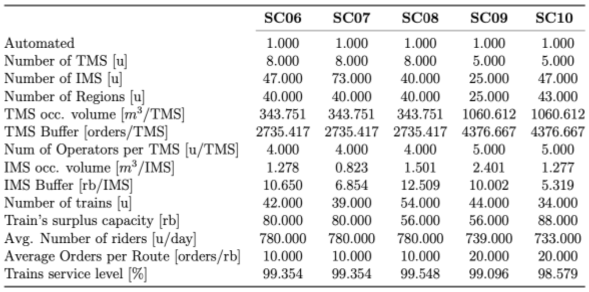
Outcomes ground on the dimensional results reached and shown in Tables 2 and 3. Both fixed and operational expenditures vary across scenarios with the configurations proposed by the model in terms of space required at nodes, fleets sizing and routing optimization.

Results obtained on CapEx reflect the capital-intensive dimension of the model. CapEx levels are mainly affected by the level of automation, and the characteristics of ground fleets of riders. Extensive results are presented in Tables 4 and 5.



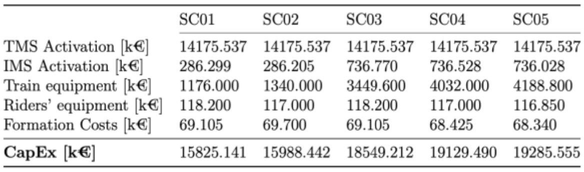
	SC01	**SC02**	**SC03**	**SC04**	**SC05**
Automated	0.000	0.000	1.000	1.000	1.000
Number of TMS [u]	5.000	5.000	5.000	5.000	5.000
Number of IMS [u]	25.000	40.000	25.000	40.000	47.000
Number of Regions [u]	25.000	40.000	25.000	40.000	43.000
TMS occ. volume [m^3/TMS]	550.001	550.001	550.001	550.001	550.001
TMS Buffer [orders/TMS]	4376.667	4376.667	4376.667	4376.667	4376.667
Num of Operators per TMS [u/TMS]	5.000	5.000	5.000	5.000	5.000
IMS occ. volume [m^3/IMS]	2.403	1.501	2.403	1.501	1.277
IMS Buffer [rb/IMS]	20.021	12.509	20.021	12.509	10.639
Number of trains [u]	84.000	67.000	44.000	36.000	34.000
Train’s surplus capacity [rb]	28.000	40.000	56.000	80.000	88.000
Avg. Number of riders [u/day]	788.000	780.000	788.000	780.000	779.000
Average Orders per Route [orders/rb]	10.000	10.000	10.000	10.000	10.000
Trains service level [%]	99.478	99.255	99.548	99.354	99.289

Table 2. Dimensional elements (1)



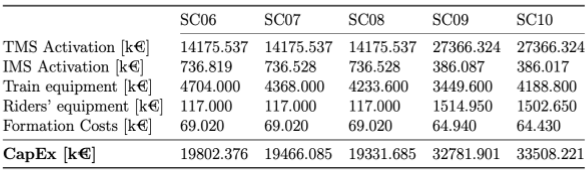
	SC06	**SC07**	**SC08**	**SC09**	**SC10**
Automated	1.000	1.000	1.000	1.000	1.000
Number of TMS [u]	8.000	8.000	8.000	5.000	5.000
Number of IMS [u]	47.000	73.000	40.000	25.000	47.000
Number of Regions [u]	40.000	40.000	40.000	25.000	43.000
TMS occ. volume [m^3/TMS]	343.751	343.751	343.751	1060.612	1060.612
TMS Buffer [orders/TMS]	2735.417	2735.417	2735.417	4376.667	4376.667
Num of Operators per TMS [u/TMS]	4.000	4.000	4.000	5.000	5.000
IMS occ. volume [m^3/IMS]	1.278	0.823	1.501	2.401	1.277
IMS Buffer [rb/IMS]	10.650	6.854	12.509	10.002	5.319
Number of trains [u]	42.000	39.000	54.000	44.000	34.000
Train’s surplus capacity [rb]	80.000	80.000	56.000	56.000	88.000
Avg. Number of riders [u/day]	780.000	780.000	780.000	739.000	733.000
Average Orders per Route [orders/rb]	10.000	10.000	10.000	20.000	20.000
Trains service level [%]	99.354	99.354	99.548	99.096	98.579

Table 3. Dimensional elements (2)



	SC01	SC02	SC03	SC04	SC05
TMS Activation [k€]	14175.537	14175.537	14175.537	14175.537	14175.537
IMS Activation [k€]	286.299	286.205	736.770	736.528	736.028
Train equipment [k€]	1176.000	1340.000	3449.600	4032.000	4188.800
Riders’ equipment [k€]	118.200	117.000	118.200	117.000	116.850
Formation Costs [k€]	69.105	69.700	69.105	68.425	68.340
CapEx [k€]	15825.141	15988.442	18549.212	19129.490	19285.555

Table 4. CapEx (1)



	SC06	SC07	SC08	SC09	SC10
TMS Activation [k€]	14175.537	14175.537	14175.537	27366.324	27366.324
IMS Activation [k€]	736.819	736.528	736.528	386.087	386.017
Train equipment [k€]	4704.000	4368.000	4233.600	3449.600	4188.800
Riders’ equipment [k€]	117.000	117.000	117.000	1514.950	1502.650
Formation Costs [k€]	69.020	69.020	69.020	64.940	64.430
CapEx [k€]	19802.376	19466.085	19331.685	32781.901	33508.221

Table 5. CapEx (2)

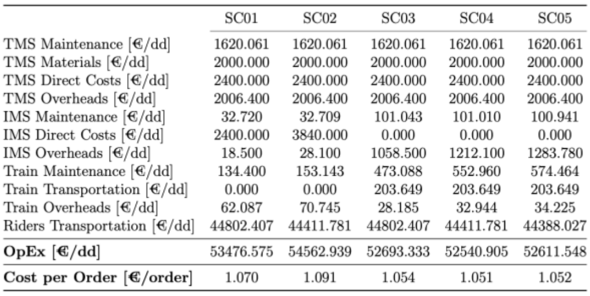
A clear significant impact depends on the automation decision. For given sets of TMSs, IMSs, and regions, the automated configuration reflects an average increase in costs of 18.42% (SC01, SC02 v SC03, SC04). This result is mainly addressable to an increase in unitary costs for IMSs and trains’ systems infrastructure, respectively of 157% and 197%.

Without considering the impact of higher capacitated vehicles, thus excluding SC09 and SC10, the higher CapEx level is reached by SC06 with 19.8 million€. This result is led by high values in the number of trains requirements. Train equipment costs in SC06 are on average 18.9% higher than the other automated scenarios.

There is no linear relationship between an increase in system capillarity and CapEx costs, as IMSs’ costs are computed over the space required. The volume needed per IMS is adjusted and lowered if an increase in the width of the IMS set occurs. Besides, the effects on fixed costs of system capillarity are reflected in a variety of variables downstream as trains and riders’ fleet sizes.

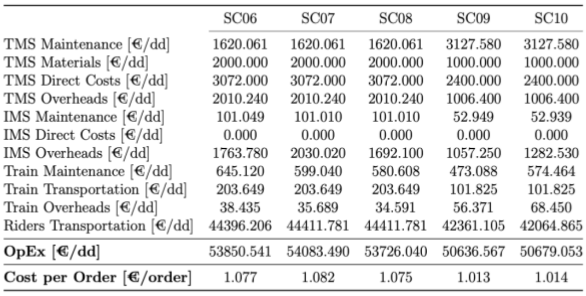
A strong impact is led by the decision on ground-level vehicle capacity. SC09 and SC10 reflect the impact on CapEx of higher capacitated cargo cycles, with higher purchasing costs. In particular, given a fixed network geometry, CapEx increases by an average of 72.56% due to an increase in riders capacity (SC09,SC10 v SC04,SC05). Despite ground level vehicles fleet have a strong weight on overall direct costs, this result is led not only by an increase in the cost of riders’ equipment (+1.190%) but also by an increase in the combined costs of TMSs and IMSs activation. This infrastructural cost growth is mainly caused by the necessity of re-balancing flows on nodes throughout the system, resulting in higher space requirements especially at TMSs.

Parallelly to CapEx, it is crucial to analyze how daily OpEx costs vary with scenarios, also considering if an increase in fixed costs can be balanced by a significant reduction in operational expenditures. OpEx daily costs obtained for this level of demand result to be very similar across scenarios. Still, potential benefits must be evaluated in the long term as these cost figures refer to the costs bared in unique days of operations. Extensive results for OpEx are reported in Tables 6 and 7.



	SC01	SC02	SC03	SC04	SC05
TMS Maintenance [€/dd]	1620.061	1620.061	1620.061	1620.061	1620.061
TMS Materials [€/dd]	2000.000	2000.000	2000.000	2000.000	2000.000
TMS Direct Costs [€/dd]	2400.000	2400.000	2400.000	2400.000	2400.000
TMS Overheads [€/dd]	2006.400	2006.400	2006.400	2006.400	2006.400
IMS Maintenance [€/dd]	32.720	32.709	101.043	101.010	100.941
IMS Direct Costs [€/dd]	2400.000	3840.000	0.000	0.000	0.000
IMS Overheads [€/dd]	18.500	28.100	1058.500	1212.100	1283.780
Train Maintenance [€/dd]	134.400	153.143	473.088	552.960	574.464
Train Transportation [€/dd]	0.000	0.000	203.649	203.649	203.649
Train Overheads [€/dd]	62.087	70.745	28.185	32.944	34.225
Riders Transportation [€/dd]	44802.407	44411.781	44802.407	44411.781	44388.027
OpEx [€/dd]	53476.575	54562.939	52693.333	52540.905	52611.548
Cost per Order [€/order]	1.070	1.091	1.054	1.051	1.052

Table 6. Opex (1)



	SC06	SC07	SC08	SC09	SC10
TMS Maintenance [€/dd]	1620.061	1620.061	1620.061	3127.580	3127.580
TMS Materials [€/dd]	2000.000	2000.000	2000.000	1000.000	1000.000
TMS Direct Costs [€/dd]	3072.000	3072.000	3072.000	2400.000	2400.000
TMS Overheads [€/dd]	2010.240	2010.240	2010.240	1006.400	1006.400
IMS Maintenance [€/dd]	101.049	101.010	101.010	52.949	52.939
IMS Direct Costs [€/dd]	0.000	0.000	0.000	0.000	0.000
IMS Overheads [€/dd]	1763.780	2030.020	1692.100	1057.250	1282.530
Train Maintenance [€/dd]	645.120	599.040	580.608	473.088	574.464
Train Transportation [€/dd]	203.649	203.649	203.649	101.825	101.825
Train Overheads [€/dd]	38.435	35.689	34.591	56.371	68.450
Riders Transportation [€/dd]	44396.206	44411.781	44411.781	42361.105	42064.865
OpEx [€/dd]	53850.541	54083.490	53726.040	50636.567	50679.053
Cost per Order [€/order]	1.077	1.082	1.075	1.013	1.014

Table 7. Opex (2)

To be consistent with precedent analysis, we can highlight how, given a fixed TMS, IMS and regions configuration, the automated cases dominate the non-automated ones (SC01, SC02 v SC03, SC04). In absolute terms, the automated cases generate an average decrease in OpEx of 1,402.63€ per day.

Among key cost figures, a strong impact in terms of cost reduction in automated cases is given by an easing of IMS direct costs. In SC01, IMS direct costs are weighted for 4.49% over the total OpEx per day. An increase in the number of IMS in SC02 causes an increase in the impact of IMS direct costs over total, reaching 7.04% of total OpEx per day. Automated configurations ease the weight of direct costs bared at the IMS level as there is no need to add one operator per each IMS opened. Reversely, this reflects a wider increase in IMS indirect costs. The higher is the number of opened IMSs, the higher are daily opening running costs. Besides, as the value of the investment increase, a slight increase in maintenance costs per IMS is accounted for. Globally, shifting from non-automated to automated IMSs has a positive effect in terms of overall IMS cost reduction, thus including the effect on direct costs, overhead costs, and maintenance costs.

The worst-case in absolute terms is SC07, with 54,083€ per day. A strong negative impact on this scenario is caused by the increase of the overall number of operators at TMSs, and by a strong increase in IMS overhead costs, due to the extensiveness of the IMS set. In particular, SC07 has overhead costs at Intermediate Metro Stations averagely higher by 57.74% in respect of all the other automated scenarios with the same rider capacity.

A strong impact on overall OpEx is given by riders’ transportation costs, which are weighted, on average, for the 83.3% of global operative expenditures per day. As ground transportation costs are not affected by the automation decision, the only two elements impacting the absolute transportation costs at this level are system capillarity and cargo cycle characteristics in terms of speed and optimal coverage capacity. SC09 and SC10 show how an increase in ground-level vehicle capacity generates a decrease in absolute transportation costs, for an average of 2,257.34€ per day.

Having built scenarios on a fixed demand level, considerations on OpEx/Order are similar to the ones presented for absolute OpEx costs. Still, it is important to highlight how neither of the scenarios analyzed shows an OpEx/Order higher than 1.09€ per order. At a first sight, this result leads to optimistic scenarios when analyzing the competitiveness of the network in respect of already existing solutions for the last mile.

As shown above, automation leads to a decrease in OpEx, thus in OpEx/Order per day, of on average 2.59%, with even more positive results when the dimension and the capillarity of the network increase. In other words, the wider is the IMS set, the higher benefit from automation due to a strong direct cost saving.

A critical element to consider is the relation between CapEx and OpEx/Order. As reported in Figure 3, despite a growth in CapEx, as expected, there is not a significant growth in OpEx/Order.

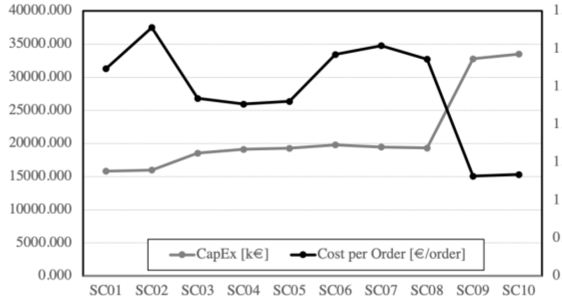


Figure 3. CapEx vs OpEx/Order

In fact, according to the model proposed, higher investments on the network can be translated into higher performances and efficiency, thus a lower OpEx/Order. As shown in Figure 3, the impact of a growth in Capital Expenditures in non-automated cases is translated in an increase in OpEx/Order. This confirms how, especially if the network widens, a growth in CapEx does generate negative in terms of OpEx/Order. Besides, it is shown how the impact of choosing a higher capacitated ground fleet causes a vertical increase in CapEx, but contemporary reflects in a strong reduction of OpEx/Order. Operatively, according to the obtained results in respect of the small cargo cycles automated cases, the reduction obtained in SC09 and SC10 with high capacity cargo cycles can generate benefits between an average of 666,518k€ and 1,206.423k€ cumulative per year, assuming 350 up-time days with a full-saturated system.

V. CONCLUSIONS

The work has highlighted how the presented system has the potential to radically innovate and improve urban last mile delivery. The greatest challenges to overcome are represented by the strategic decisions to be made in order to achieve a sustainable business model. Future research should expand the analysis of this delivery paradigm around its pivotal dimensions: parcel flows analysis and managerial feasibility. For what concerns the performance of the network, further studies should improve the development of specific optimization algorithms. The second level of studies should focus on the development of a sustainable, effective, and effcient business model. The analysis should focus on the financial implication for third-party logistic companies and it is suggested to include a survey with all the actors involved to collect the fundamental critical elements that would ensure the success of the project.

VI. REFERENCES

[1] Breunig, U., Baldacci, R., Hartl, R. F. & Vidal, T. (2019), 'The electric two-echelon vehicle routing problem', Computers & Operations Research 103, 198–210.

[2] Boysen, N., Schwerdfeger, S. & Weidinger, F. (2018), 'Scheduling last-mile deliveries with truck-based autonomous robots', European Journal of Operational Research 271(3), 1085–1099.

[3] Carbone, V., Rouquet, A. & Roussat, C. (2017), 'The rise of crowd logistics: a new way to co-create logistics value', Journal of Business Logistics 38(4), 238–252.

[4] Castillo, V. E., Bell, J. E., Rose, W. J. & Rodrigues, A. M. (2018), 'Crowdsourcing last mile delivery: strategic implications and future research directions', Journal of Business Logistics 39(1), 7–25.

[5] Chatterjee, R., Greulich, C. & Edelkamp, S. (2016), Optimizing last mile deliv- ery using public transport with multi-agent based control, in '2016 IEEE 41st Conference on Local Computer Networks Workshops (LCN Workshops)', IEEE, pp. 205–212.

[6] Clausen, U., Geiger, C. & Pöting, M. (2016), 'Hands-on testing of last mile concepts', Transportation Research Procedia 14, 1533–1542.

[7] Enthoven, D. L., Jargalsaikhan, B., Roodbergen, K. J., uit het Broek, M. A. & Schrotenboer, A. H. (2020), 'The two-echelon vehicle routing problem with cov- ering options: City logistics with cargo bikes and parcel lockers', Computers & Operations Research 118, 104919.

[8] Figliozzi, M. A. (2009), 'Planning approximations to the average length of vehicle routing problems with time window constraints', Transportation Research Part B: Methodological 43(4), 438–447.

[9] Ghilas, V., Demir, E. & Van Woensel, T. (2016), 'A scenario-based planning for the pickup and delivery problem with time windows, scheduled lines and stochastic demands', Transportation Research Part B: Methodological 91, 34–51.

[10] Ji, Y., Zheng, Y., Zhao, J., Shen, Y. & Du, Y. (2020), 'A multimodal passenger-and- package sharing network for urban logistics', Journal of Advanced Transportation 2020.

[11] Kafle, N., Zou, B. & Lin, J. (2017), 'Design and modeling of a crowdsource- enabled system for urban parcel relay and delivery', Transportation research part B: methodological 99, 62–82.

[12] Li, B., Krushinsky, D., Van Woensel, T. & Reijers, H. A. (2016), 'The share-a-ride problem with stochastic travel

times and stochastic delivery locations', Trans- portation Research Part C: Emerging Technologies 67, 95–108.

[13] Mangiaracina, R., Perego, A., Seghezzi, A. & Tumino, A. (2019), 'Innovative so- lutions to increase last-mile delivery efficiency in b2c e-commerce: a literature review', International Journal of Physical Distribution & Logistics Management .

[14] Marsden, N., Bernecker, T., Zöllner, R., Sußmann, N. & Kapser, S. (2018), Buga: Log–a real-world laboratory approach to designing an automated transport system for goods in urban areas, in '2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)', IEEE, pp. 1–9.

[15] Perboli, G. & Rosano, M. (2019), 'Parcel delivery in urban areas: Opportunities and threats for the mix of traditional and green business models', Transportation Research Part C: Emerging Technologies 99, 19–36.

[16] Qi, W., Li, L., Liu, S. & Shen, Z.-J. M. (2018), 'Shared mobility for last-mile delivery: Design, operational prescriptions, and environmental impact', Manufacturing & Service Operations Management 20(4), 737–751.

[17] Sheth, M., Butrina, P., Goodchild, A. & McCormack, E. (2019), 'Measuring delivery route cost trade-offs between electric-assist cargo bicycles and delivery trucks in dense urban areas', European transport research review 11(1), 1–12.

[18] Swanson, D. (2019), 'A simulation-based process model for managing drone deploy- ment to minimize total delivery time', IEEE Engineering Management Review 47(3), 154–167.

[19] Tipagornwong, C. & Figliozzi, M. (2014), 'Analysis of competitiveness of freight tricycle delivery services in urban areas', Transportation Research Record 2410(1), 76–84.

[20] UNDESA, '2018 revision of world urbanization prospects'. https://www.un.org/development/desa/en/news/population/2018- revision-of-world-urbanization-prospects.html

[21] Zhou, L., Baldacci, R., Vigo, D. & Wang, X. (2018), 'A multi-depot two-echelon vehicle routing problem with delivery options arising in the last mile distribution', European Journal of Operational Research 265(2), 765–778.