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Last Mile Delivery with Parcel Lockers: evaluating the environmental impact of eco-conscious consumer behavior

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Abstract: In recent months, online sales have experienced a sharp surge also due to the COVID pandemic. In this paper, we propose a new location and routing problem for a last mile delivery service based on parcel lockers and introduce a mathematical formulation to solve it by means of a MIP solver (Gurobi).

The presence of parcel locker stations avoids the door-to-door delivery by companies but requires that consumers move from home to collect their parcels. Potential location of locker stations is known but not all of them need to be opened. The problem minimizes the global environmental impact in terms of distances traveled by both the delivery company and the consumers deciding the optimal number of stations that have to be opened.

How much do the number and location of lockers impact on environment? Is the behavior of consumers a critical aspect of such optimization? To this aim we have solved 1680 instances and analyzed different scenarios varying the number of consumers and potential parcel lockers, the maximum distance a consumer is willing to travel to reach a locker station, and the maximum distance we may assume the same consumer is willing to travel by foot or by bicycle.

The experimental results draw interesting conclusions and managerial insights providing important rules of thumbs for environmental decision makers.

Keywords: Last Mile Delivery, Parcel Lockers, Vehicle Routing Problem, Carbon Emissions, Consumer Behavior

1. INTRODUCTION

As pandemic lockdown and movements restrictions became the new normality, e-commerce (in particular B2C) and home deliveries have been witnesses of a new strong growth becoming the natural substitutes of traditional goods sources as superstores. Recent statistics show that during the COVID pandemic, consumers prefer to avoid crowded areas and directly go for shopping online.

The United Nations Conference on Trade and Development published an interesting report United Nations Conference on Trade and Development (2021) concerning the impact of COVID on e-commerce focusing on data concerning both e-retailers and consumers belonging to different economies, both emerging and developed (including Italy) to better understand the impact of the pandemic on online shopping. The results emphasize how consumers' habits have changed a lot also due to the pandemic and how a larger number of consumers shopped online more frequently than in the past (before Covid's spread out).

The growth of e-commerce flows has led to an impressive increase in the number of vans and commercial vehicles entering the cities. In turn, this has raised many concerns regarding the sustainability of this trend in terms of increased air pollution and traffic congestion in urban areas with the consequent impact on people's quality of life and safeness. As a direct consequence of the covid pandemic, many consumers have also radically changed their personal priorities by bringing out new important goals such as health, safety, and sustainability (recently named "reimagined customers" by Accenture 2021).

In this paper, we analyze a location-routing problem to minimize environmental impact of last mile delivery systems. The goal is to evaluate the environmental advantages of a locker-based last mile delivery with respect to a more traditional door-to-door delivery systems. Minimizing the global emissions associated with a last mile delivery system based on parcel lockers implies to account for distances travelled by both the company involved with the delivery and consumers that need to collect their parcels at the locker. The paper tries to reply to some important issues such as measuring the environmental impact caused by setting different values of two types of distance: the maximum distance accepted by consumers to reach a parcel locker using any transport mean and the maximum distance they are willing to travel without generating emissions (by foot or by bicycle, for example).

The computational results, obtained by solving the mathematical model on a comprehensive set of instances, provide interesting insights on the problem, emphasizing how the

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role of consumers (their eco-conscious behavior) is one of the main drivers for controlling the environmental impact.

The paper is organized as follows. In the next section, we briefly present recent literature on delivery problems with a special focus on those based on the use of parcel lockers. In Section 3, we introduce the location and routing problem with parcel lockers and provide its mathematical formulation. In Section 4, we present the results obtained and provide an extensive analysis on the environmental impact of consumer behaviour. Finally, we draw some conclusions in Section 5.

2. LITERATURE REVIEW

Following the provisions of the European Commission to reduce by 15% the g/Km of CO_2 emissions by 2025 Council of the European Union (2021), many authors have investigated the environmental impact of current last mile practices, such as the use of very narrow time windows (Manerba et al., 2018) or electric vehicles (Siragusa et al., 2022). A considerable research effort has been devoted to the evaluation of efficient, innovative, and environmentally sustainable delivery options. Interested readers can refer to Boysen et al. (2020) for an extensive survey on all the main delivery options, from automated lockers to drones. In specialized literature, parcel lockers are seen as an effective solution to reduce, at the same time, carbon emissions and failed deliveries. Parcel lockers are automated collection and delivery points (CDP) from which consumers can autonomously collect their parcels.

Tilk et al. (2021) develop a Vehicle Routing Problem with Delivery Options in which each consumer indicates a preferred delivery method. Objective of the company is to serve all the consumers minimizing routes' cost while complying with constraints on the time windows associated with delivery locations, the vehicle capacity, and the minimum service level for each consumer. Moreover, Grabenschweiger et al. (2021) consider consumers' satisfaction by introducing heterogeneous locker stations in a VRP with the objective of minimizing travelling cost plus a compensation cost to encourage consumers to collect their parcels at lockers. These studies, however, do not consider the side-effects of last mile delivery systems on the environment. Edwards et al. (2010) assess the environmental impact of failed deliveries from a carbon-auditing perspective. The authors examine different failure rates in home delivery and estimate the cost (in terms of grams of CO_2) for each additional journey. They provide an exhaustive study based on different types of collection and delivery points proving that CO_2 emission can be reduced by up to the 87% when the distance of consumers from the lockers is, on average, about 1.2 Km. Jiang et al. (2019) study the reduction in cost and emission of a Travelling Salesman Problem that incorporates a pickup cost calculated as consumers' willingness in using CDP. According to their results, carbon emissions can be reduced by up to the 51.2% in those areas where lockers are highly accepted. Finally, an approach including emissions produced by both company and consumers is presented in Schnieder et al. (2021). The authors assess how integrating CDP in a delivery system is not always a sustainable choice but strongly depends on the environmentally conscious choices made by consumers. They set a priori the delivery method (home delivery or CDP) for each consumer and assume that when consumers are using delivery points they always travel to the nearest locker by car. Unlike this work, we present a comprehensive impact analysis that includes the possibility for consumers to make sustainable choices when deciding the mean of transport used to reach a locker, regardless of its distance. Moreover, in our formulation, we treat the decision to open or not a locker as a variable to investigate the optimal delivery configuration in reducing the overall CO_2 emissions.

3. PROBLEM DESCRIPTION

The Last Mile Delivery Problem with Lockers Selection (LMDP-LS) is a location-routing problem that can be modeled as a variant of VRP where vehicles have to deliver parcels to a set of consumers that can be served directly at their home or, as an alternative, to a locker station. Objective of the problem is to decide which locker stations to open to minimize the environmental impact, i.e. the carbon emission (g/Km of CO_2) with regards to both company vehicles and consumers travelled distance. Let $V_C = \{1, ..., n\}$ be the set of n consumers and $V_L = \{n + 1, ..., n + m\}$ be the set of m possible lockers' stations. The problem can be defined over a complete directed graph $G = (V, A)$ representing the road network where $V = \{0\} \cup V_C \cup V_L$ is the node set with node 0 representing the depot, and $A = \{(i, j) : i, j \in V, i \neq j\}$ is the arc set. We indicate as d_{ij} and t_{ij} the non-negative distance and travel time between any two nodes $i, j \in V$, respectively. We assume that distances satisfy the triangular inequality. Each node i is associated with a service time t_i. We indicate as d_{max} the maximum distance consumers are willing to travel from home to collect their packages. To separately account for arcs travelled by consumers, we define as $V_L^c \subset V_L$ the subset of potential parcel lockers located at a distance lower than or equal to d_{max} from consumer c. In addition, we define as d_{green} (Green Distance) a maximum distance threshold below which we assume any consumer is willing to reach a locker by foot or by bicycle (the emissions to collect packages can be neglected). According to the current EU Regulation on CO_2 emissions, we define an emission factor e_v for commercial vehicles and a different emission factor e_{cl} for private vehicles depending on the distance d_{cl} between the consumer home c and the parcel locker l: $e_{cl} = e_p$ where e_p is a constant value for private transportation when $d_{green} < d_{cl} \leq d_{max}$,and $e_{cl} = 0$ if $d_{cl} \leq d_{green}$. Deliveries are performed by a fleet of homogeneous vehicles $K = \{1, ..., k\}$ with non restrictive capacity. Also, locker stations are assumed with unbounded capacity.

3.1 Last Mile Delivery Problem with Parcel Lockers

Let us define, for each arc $(i, j) \in A$, a binary variable x_{ij} taking value 1 if arc (i, j) is traversed by any vehicle and 0 otherwise. Moreover, for each arc (i, j) we define a continuous variable z_{ij} indicating the time of arrival of a vehicle at node j when arriving from i. For each set $S \subset V$, let $\delta^+(S) = \{(i, j) \in A : i \in S, j \notin S\}$ and $\delta^-(S) = \{(i, j) \in A : i \notin S, j \in S\}$ be the set of arcs leaving and entering set S, respectively, with

$\delta^+(i) = \delta^+(\{i\})$ and $\delta^-(i) = \delta^-(\{i\})$. The decision to open a locker at any location $l \in V_L$ is regulated by the binary variable y_l taking value 1 if the locker is opened and 0 otherwise. Finally, binary variable $w_{cl}, c \in V_C, l \in V_L^c$ is equal to 1 when consumer c travels to locker l and zero otherwise (the consumer receives the parcel directly at home).

The problem aims at finding which lockers to open so to minimize the total environmental impact computed as the sum of the emissions produced by the consumers and by the company vehicles in charge with last mile delivery.

The mathematical formulation is as follows:

$$\min \sum_{(i,j)\in A} e_v(d_{ij}x_{ij}) + \sum_{c\in V_C}\sum_{l\in V_L^c} e_{cl}(2d_{cl}w_{cl}) \quad (1)$$

subject to:

$$\sum_{(i,c)\in\delta^-(c)} x_{ic} = \sum_{(c,i)\in\delta^+(c)} x_{ci} = 1 - \sum_{l\in V_L^c} w_{cl} \quad c \in V_C \quad (2)$$

$$\sum_{(i,l)\in\delta^-(l)} x_{il} = \sum_{(l,i)\in\delta^+(l)} x_{li} = y_l \quad l \in V_L \quad (3)$$

$$\sum_{(0,j)\in\delta^+(0)} x_{0j} = \sum_{(j,0)\in\delta^-(0)} x_{j0} \le |K| \quad (4)$$

$$w_{cl} \le y_l \quad c \in V_C, l \in V_L^c \quad (5)$$

$$\sum_{(i,j)\in\delta^+(i)} z_{ij} - \sum_{(j,i)\in\delta^-(i)} z_{ji} = \sum_{(i,j)\in\delta^+(i)} (t_{ij}+t_i)x_{ij} \quad i \in V_L \cup V_C \quad (6)$$

$$(t_{0i} + t_{ij} + t_i)x_{ij} \le z_{ij} \le (T - t_{j0} - t_j)x_{ij} \quad (i,j) \in A \quad (7)$$

$$z_{0i} = t_{0i}x_{0i} \quad i \in V_L \cup V_C \quad (8)$$

$$z_{ij} \ge 0 \quad (i,j) \in A \quad (9)$$

$$x_{ij} \in \{0,1\} \quad (i,j) \in A \quad (10)$$

$$w_{cl} \in \{0,1\} \quad c \in V_C, l \in V_L^c \quad (11)$$

$$y_l \in \{0,1\} \quad l \in V_L \quad (12)$$

The objective function (1) minimizes the total environmental impact computed as the total travelled distance by both vehicles and consumers multiplied by the emission factors. For the consumers, the distance is multiplied by 2 to consider the round trip. Constraints (2) impose that each consumer $c \in V_C$ is served either at home ($\sum_{l\in V_L^c} w_{cl} = 0$) or at a locker station ($\sum_{l\in V_L^c} w_{cl} = 1$), hence consumers are included in a tour only when they are not travelling to any locker. Inclusion of lockers into routes is regulated by Constraints (3), stating that a vehicle needs to visit a locker only if it is open. Constraints (4) ensure that at most K vehicles are used. Constraints (5) state that a consumer can travel to a locker only if it has been opened and served by one vehicle route. Constraints (6) determine the arrival time at two consecutive nodes, thus working as sub-tour elimination constraints. In particular, if node j is visited immediately after node i, the time elapsed between the arrival in the two nodes is equal to the time t_{ij} needed to travel between the two nodes plus the service time at note i. The lower and upper bounds of variable z_{ij} are regulated by Constraints (7), stating that if arc (i,j) is traversed, then the arrival time at node j must be greater than the time required to leave the depot and serve the consumer i ($t_{0i}+t_i$) and lower than the allowed tour length (T) minus the time required to serve the consumer j and return to the depot ($t_j + t_{j0}$). Constraints (8) ensure that the time needed to travel from the depot to any visited node i (when $x_{0i} = 1$) is equal to t_{0i}. Non-negativity and binary conditions on variables are defined in Constraints (9) to (12).

4. COMPUTATIONAL RESULTS AND ENVIRONMENTAL IMPACT ANALYSIS

In this section, we present the results obtained by investigating how conscious consumer behaviour can affect the total emissions of a last mile delivery system. All test have been run on an Ubuntu 20.04.2 machine with an AMD Ryzen 9 3950x CPU, 16 cores, 32 threads, and 32 GB of RAM. Gurobi 9.1.2 has been used as mixed integer linear programming solver. A time limit of 8 hours have been set for solving each instance.

4.1 Benchmark Instances

We have solved and evaluated the problem on a total of 60 benchmark instances. In Table 1, we report the characteristics of solved instances: for each combination of number of consumers $|V_C|$ (50,100), number of lockers $|V_L|$ (5,10,15), and number of available vehicles $|K|$ (2,3) we have generated 5 random instances ($\#Inst$). Consumer locations are uniformly random generated in a 15km×15km city area in which the speed is assumed to be constant and equal to 30 km/h. The area has been partitioned into $|V_L|$ zones equal to the number of required lockers and we have imposed the presence of a potential locker in each zone. In this way, we have guaranteed that each consumer has at least one pick-up station in a 5 km distance. Finally, depot location has been generated near the edges of the squared area to simulate its position in an industrial area outside the city center. Service times for both home deliveries and lockers service vary between 3 and 10 minutes. The working shift length T is equal to 8 hours. The emission parameters used for commercial vehicles (e_v) and consumer vehicles(e_p) are equal to 161.2 g/Km and 127.0 g/Km, respectively. These are the average values for new cars and vans in 2019 European Environment Agency (2020a,b).

Table 1. Instances: structure and size

$\lvert V_C\rvert$	$\lvert V_L\rvert$	$\lvert K\rvert$	$\#Inst$
50	5	2	5
		3	5
50	10	2	5
		3	5
50	15	2	5
		3	5
100	5	2	5
		3	5
100	10	2	5
		3	5
100	15	2	5
		3	5

We have considered 7 possible values for d_{max} and d_{green} (0m, 500m, 750m, 1000m, 1500m, 2000m, and 5000m), which have given rise to 28 meaningful combinations. For example, when d_{max} is set to 750m, the possible values for d_{green} are 0, 500, and 750m. The 0-0 combination represents a problem involving only home deliveries since consumers are not willing to travel any distance to collect their orders. In total, considering that each benchmark instance has to be solved for every d_{max}-d_{green} pair, in

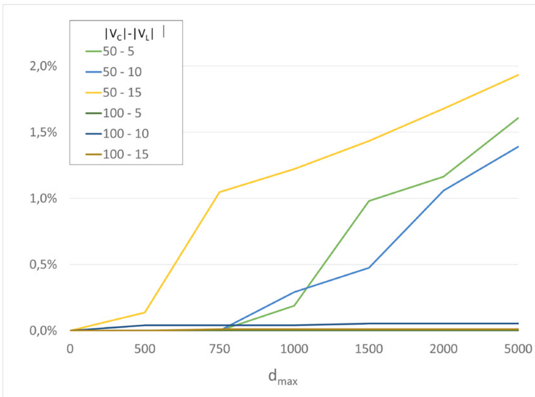

Fig. 1. Decrease of emissions over d_{max} values.

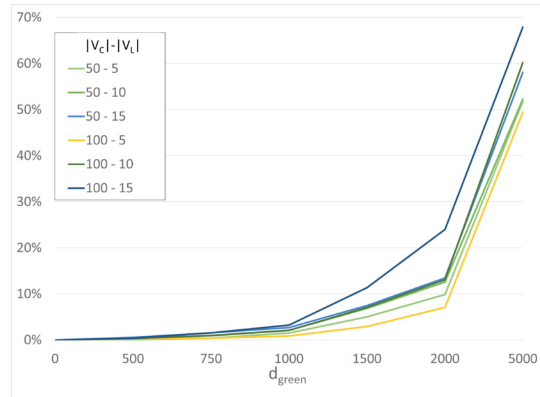

Fig. 2. Decrease of emissions over d_{green} values.

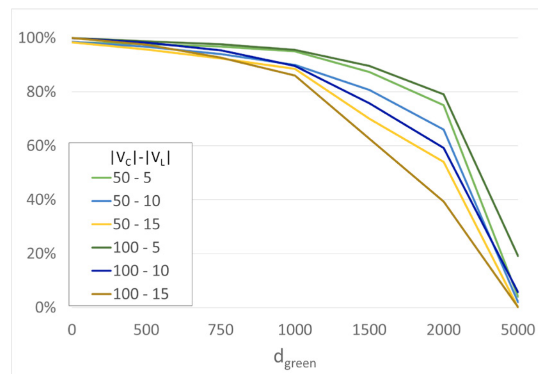

Fig. 3. Consumers served at home over d_{green} values.

our study we have analyzed 1680 instances of which 1608 have been solved to optimality within the computational time limit. Analyzing in detail the 72 instances not solved to optimality, we have noticed that they share the same value of d_{max} equal to 5000m and among them those with $d_{max} = d_{green} = 5000m$ are the hardest ones to solve. The median optimality gap value is 2%; if we exclude two instances with an average gap greater than 30%, for the remaining ones the average gap to optimality drops to 6% . If we aggregate all the instances according to the value of d_{max}, we notice that for $d_{max} = 0$ the average solution time is equal to 600s (the easiest instances), whereas for $d_{max} = 5000m$ is equal to 2000s; in all the remaining cases, it is on average equal to 1100s. If we aggregate results according to d_{green}, we have an average time always equal to about 1100s with the only exception of $d_{green} = 5000m$ that requires 6100s.

4.2 Environmental Impact Analysis

Figure 1 shows the average percentage reduction of emissions keeping $d_{green} = 0$ while increasing d_{max} value. We have aggregated the results considering each tested combination of $|V_C|$ and $|V_L|$. It is interesting to notice that, even assuming that consumers are willing to travel up to 5 Km to collect their parcels at a locker, the emissions reduction is very limited, reaching only 1.93% for the case with 15 lockers, $d_{max} = 5000m$ and 50 consumers. The reduction is even worse for instances with 100 consumers: there is basically no emissions reduction, with the highest value equal to 0.05% for all instances with $d_{max} \geq 500$ and 10 lockers. These results indicate that, when consumers are not willing to use zero-emissions transportation means (i.e. they do not behave in an eco-conscious way), the introduction of lockers does not have a meaningful impact from an environmental point of view. With parcel lockers there are not missed deliveries. This evaluation might change when considering them, as shown in Edwards et al. (2010).

Figure 2 shows the same analysis but considering different values of d_{green} instead of d_{max} (which is kept at 5000m). In this case, the percentage reduction is more significant, even when considering a value of d_{green} as low as 1000m. Starting from $d_{green} = 1500m$, the emissions reduction is greater than any value obtained while increasing d_{max}. There is also a noticeable drop in emissions when the consumers are willing to travel up to 5000m in an eco-conscious way. In this case, we can see a percentage emission reduction that jumps from the interval 7.1%-24% in the 2000m case, to the interval 49.4%-67.9%.

Figure 3 reports how the percentage of consumers, that receive their parcels directly at home, changes when d_{green} increases. The percentage drops rapidly when d_{green} increases over 1000m, reaching values close to 0% for $d_{green} = 5000m$. If we exclude the latter value, only in the case with 100 consumers, 15 lockers and $d_{green} = 2000m$, over half of the consumers are served through lockers. These values, along those presented in Figure 2, suggest that, in the setting we used, in order for a locker-based approach to be environmentally effective, consumers need to be willing to travel over 1.5Km by using green means of transportation.

Figure 4 provides the same analysis but with respect to d_{max} when setting d_{green} to zero. For the sake of clarity, we have used a bar graph instead of a line one, since the percentages are all very close to each other. If we exclude the case of $d_{max} = 0$ where all consumers are, as expected, visited at home, when d_{max} increases the percentage of consumers served at home only slightly decreases always remaining stationary above 96.2%. Although one can observe that by increasing the maximum distance the number of lockers reachable by each consumer increases (for instance, one consumer out of 3.5 has a locker within 1500m from home; this ratio increases to one consumer out of two when distance grows to 2000m) thus making more likely that a consumer will move from home to collect his/her parcel in an optimal solution, the presence of lockers do not seem to strongly change the traditional structure of a

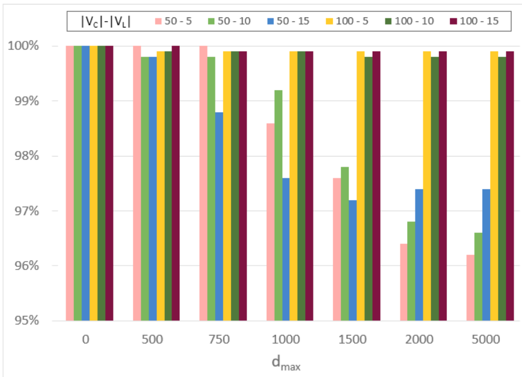

Fig. 4. Consumers served at home over d_{max} values.

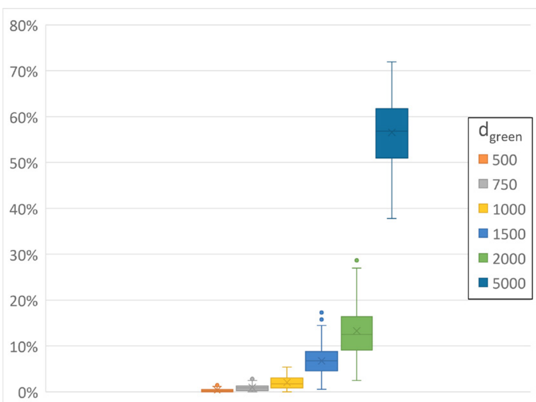

Fig. 5. Emissions reduction for different values of d_{green}.

door-to-door delivery if consumers are not willing to move from home for collecting their parcels (d_{green} is kept to zero).

In Figure 5, the boxplots report the percentage emissions reduction for different values of $d_{green} > 0$ when compared to the case $d_{green} = 0$. Differently from what has been analyzed in Figure 2, we consider all possible values of d_{max}. For example, when considering $d_{green} = 1500m$, we include the (d_{max}-d_{green}) pairs $(1500-1500)$, $(2000-1500)$, and $(5000-1500)$. We then compute the percentage emissions reduction with respect to the pairs $(1500-0)$, $(2000-0)$, and $(5000-0)$. We can see that there is not much variability in the results given a specific value of d_{green}. For $d_{green} \leq 1000$, the maximum difference between the highest and lowest percentage value is about 5%. If we consider $d_{green} = 2000$ and $d_{green} = 5000$, this gap increases to 17% and 26%, respectively.

Figure 6 presents a similar analysis for different values of d_{max}. Given a value of d_{max}, we consider all the instances with positive d_{green}, e.g., for $d_{max} = 1000$, we include instances with d_{green} equal to 0, 500, 750, and 1000m. The huge number of outliers for this boxplot is mainly due to instances with $d_{max} = d_{green}$. Once again, the results confirm that the key parameter for the problem is d_{green} and not d_{max}, since for high values of d_{green} we obtain results that are clear outliers and do not follow the trend established when increasing d_{max}. In fact, if we look at the median percentage values of emissions reduction for different d_{max} values, it is evident how they are way below

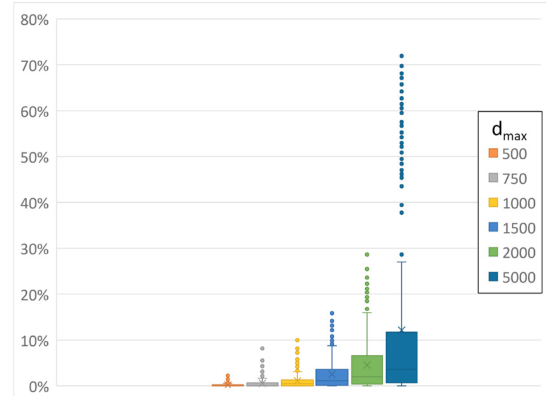

Fig. 6. Emissions reduction for different values of d_{max}.

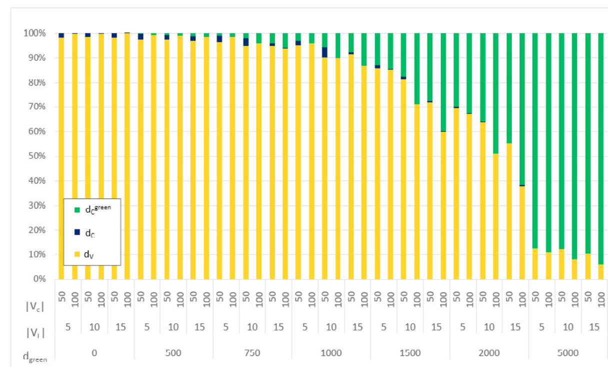

Fig. 7. Travelled distances over d_{green} values: company vs non-green consumers vs green consumers.

all the outliers, going from 0.00% (for $d_{max} = 500$) to only 3.59% (when $d_{max} = 5000$).

Figure 7 shows how the total travelled distance is distributed between the company's vehicles (d_V), non-green consumers (d_C), and green consumers ($d_{C^{green}}$) for different values of d_{green}. For values of d_{green} lower than or equal to 1000m, over 90% of the travelled distance is due to the company vehicles, except for the case with $V_C = 100$, $V_L = 15$, and $d_{green} = 1000m$, for which it is 87%. We can also notice a marginal contribution from non-green consumers, without a particular trend. As d_{green} increases, the percentage of travelled distance due to green consumers increases, and it reaches values around 90% for $d_{green} = 5000m$. For this value of d_{green}, there is no contribution from non-green consumers, but even for values of d_{green} equal to 1500m or 2000m, their impact is negligible.

Figure 8 presents the distribution of emissions between the company vehicles and the consumers, for different values of d_{max} and for each combination of $|V_C|$ and $|V_L|$. Coherently with what has been shown in previous results, a consumer rarely collects a parcel at a locker outside his d_{green} limit. Hence, the maximum percentage of emissions due to consumers never exceeds 5%. A clear trend is evident only beyond 750m when $|V_C|$ is equal to 50: the percentage of emissions due to consumers increases from less than 1% to slightly above 4%. For $|V_C| = 100$ an increasing trend could emerge for higher values of d_{max} and $|V_L|$. However, since a value of $|V_L|$ equal to 15 when $|V_C| = 100$ is already realistic, we can infer

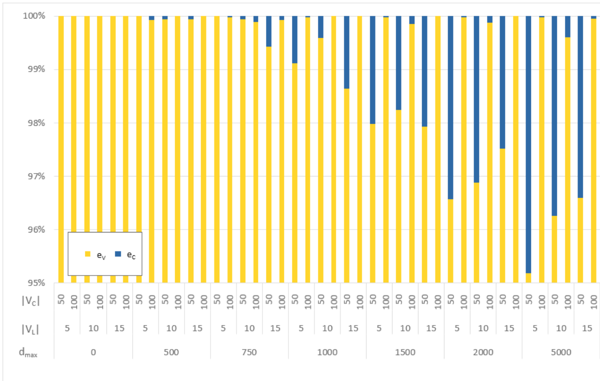

Fig. 8. Emissions distribution: company vs consumers.

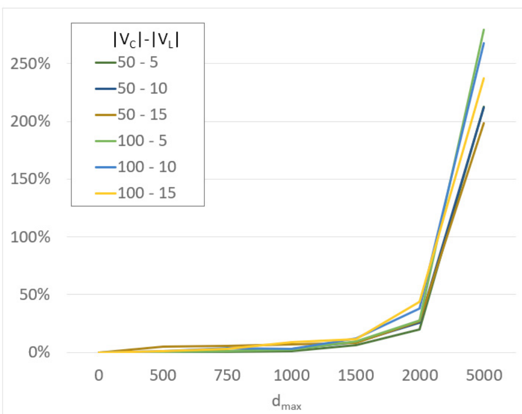

Fig. 9. Emissions increase over d_{max} values when $e_{cl} = 0$, for all $c \in V_C$ and $l \in V_L$.

that consumer emissions for high values of $|V_C|$ can be considered negligible.

Finally, we present in Figure 9 the percentage increase of emissions for different values of d_{max} when consumers' environmental impact is not considered in the objective function (i.e., when $e_{cl} = 0 \forall c \in V_C, l \in V_L$) with respect to the case in which it is. This is a situation often considered when evaluating the efficiency of a locker-based solution. If consumer emissions are not taken into account, optimal solutions require usually less kilometers traveled by the company, but the overall environmental impact can be far greater. Percentages are relatively low up to $d_{max} = 1000m$, where the maximum value is equal to 8.7% for the 100-15 case. Beyond this threshold, the percentages increase very steeply, reaching almost 50% when $d_{max} = 2000m$ and over 250% when $d_{max} = 5000m$.

5. CONCLUSIONS

Comparing alternative last mile transport models and their environmental impact is a complex task that takes into consideration different aspects and actors. In this paper, we have analyzed the transition from a last mile door-to-door delivery service (consumers receive goods directly at home) to that based on parcel lockers (consumers collect parcels in a hub), evaluating their impact in terms of CO_2 emissions. We have proposed a mathematical formulation that minimizes the emissions of the travelled distances by both the company in charge with delivery and consumers reaching the lockers, while deciding the number (and position) of lockers that has to be opened. The model directly accounts for the behaviour of consumers by dealing with two parameters: the maximum distance a consumer accepts to travel (with any transport mean) to reach a locker and the maximum green distance a consumer is willing to travel by foot or bicycle (producing no CO_2 emissions). The results obtained on more than 1600 instances provide relevant rules of thumb for environmental decision makers underlying how lockers installation does not represent the main driver to reduce emissions but the eco-conscious behaviour of consumers. As a future development, it would be interesting to consider a stochastic version of the problem that accounts for failed deliveries.

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