The location and sizing of urban freight loading/unloading lay-by areas

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The volume of freight vehicles operating within city boundaries is steadily increasing, which contributes to road congestion, especially in urban areas with a parking deficit. The proper identification of the location and size of commercial parking lay-by areas, where delivery vehicles can park for a limited time to perform loading/unloading operations, can relieve road congestion. Compared to the existing literature, this paper presents an improved two-stage approach, which includes a mathematical program and a simulation model for determining the location and sizing of lay-by areas. The robustness and soundness of the results from a methodological and practical point of view are discussed using an example application.

Keywords: urban logistics; commercial lay-by areas; facility location; covering model; simulation

Introduction

The distribution of goods in urban areas ensures the fulfilment of both commercial (i.e., stores replenishment) and residential freight demand (i.e., home delivery of goods purchased via the e-commerce channels), thus providing a vital link between manufacturers and final customers (Crainic, et al., 2004). This last leg of the supply chain can constitute up to 28% of the total cost of delivering goods (Wang et al., 2016). The volume of freight vehicles moving within city limits is steadily increasing due to several factors: from the pressure towards inventory policies that emphasize the reduction of space for storage to the increase in the number of e-tailers generating significant volumes of home deliveries related to online shopping (Morganti et al., 2014; Mohamed et al., 2017). Furthermore, urban populations are steadily growing and, in Europe, more than 75% of the population already lives in urban agglomerations (Dezi et al., 2010). Hence, cities concentrate massive flows of goods in relatively limited areas.

However, freight transport operations produce negative externalities, including pollutant emissions, noise, and risk of traffic accidents (Browne et al., 2007; Demir et al., 2015; Pinto et al., 2016). Further, in urban areas with a parking deficit, delivery vehicles tend to park in active traffic lanes (i.e., double-parking), compromising road capacity (Alho and Silva, 2014). Regarding this last issue, this paper addresses the location and sizing of loading/unloading lay-by areas (also referred to as commercial vehicle parking areas or commercial loading/unloading zones) in urban centres. In these areas, delivery vehicles can stop for a short amount of time in order to perform freight loading and unloading operations without jeopardizing the traffic flows.

The goal of lay-by areas is to guarantee the execution of delivery operations and prevent the issues created by undesirable truck driver behaviours, such as double-parking or other forms of illicit parking that cause obstruction to pedestrians and other road users (McLeod et al., 2011). Although undesirable driver behaviours may also depend upon other factors, such as the configuration of the streets, the limited time available, the accumulated delays, and the level of enforcement of parking rules, lay-bys areas (especially the lack or incorrect design thereof) can have a substantial influence on the traffic flows and on the efficiency of the urban freight transport system. For example, a survey in the city of Bologna (Italy) reported that more than 85% of the stops by commercial vehicles for loading/unloading operations are performed outside dedicated lay-by areas (Dezi et al., 2010); this generates acute congestion and access problems, especially in the central districts of the cities, which are characterized by a historical urban heritage. However, the number of lay-by areas cannot be too high, as there should be an acceptable amount of parking stalls for residents and shops clients. Many European cities suffer from the same condition: thus, the location and sizing of lay-by areas in a city must be addressed.

Extending a previous model presented by the authors (Pinto et al., 2016), this paper discusses a mixed analytic-simulation approach for determining the optimal location and size of the lay-by areas according to the demand and location of the business activities. With respect to the previous research, the approach presented in this paper extends the simple covering model with the possibility of optimizing the number of stalls in each lay-by area and uses the simulation as a solution robustness assessment tool under the uncertainty implicated in the random processes of arrival and service.

The goal of the approach is to ensure the efficient fulfilment of freight demand by providing a high availability of parking places with a minimum number of parking stalls and to minimise the hindrance to traffic flows caused by irregular parking practices (Maggi, 2001).

The paper is organized as follows: the next section provides background information to frame the context and the elements of the research, and positions our contribution within existing research. Next, an outline of an exemplary application case is provided to support the discussion about the development of the proposed approach to the problem of locating and sizing commercial parking lay-by areas. The proposed approach is then illustrated, and the formulation of the analytical model and the simulation model devised in the research is introduced. Next, one example of application and its numerical results are discussed. Finally, conclusions as well as suggestions for future research are provided.

Background

Due to the current increase in freight demand within urban areas, land use for parking must be carefully planned. As underlined by Cherrett et al. (2012), urban authorities usually consider city logistics interventions only as a reaction to complaints made by residents and other road users. Currently, most cities seem to pay little attention to this issue and do not take an active role in managing individual freight delivery movements. According to Alho and Silva (2014), "in the literature, freight supporting infrastructures are sometimes ignored in the myriad of approaches that attempt to minimize the detrimental effects of urban freight transportation". The issues arising from this negligence may be exacerbated by the fact that, in several instances, passengers and freight movements may be competing for the usage of the available transport infrastructures (Mangiaracina et al., 2016). However, it is conceivable that this may change in the near future, particularly where traffic problems are intensified by freight deliveries (Chen and Conway, 2016). The fact that a large percentage of freight vehicles are parked illegally (between 50% and 86%, according to different studies) (Cherrett et al., 2012; Dezi et al., 2010) requires the optimization of the location and number of parking lay-bys. Indeed, parking policies and transport infrastructure supply are considered the most powerful means that urban planners and policymakers can use to manage travel demand and traffic congestion in urban centres (Alho and Silva, 2014).

Recently, Chen and Conway (2016) have summarized the characteristics of commercial vehicle parking issues in a residential area in New York City. They underlined that parking and land use regulations have not kept up with the recent growth in demand, which has resulted in increased traffic congestion following the increase in the demand for residential delivery.

Figliozzi and Tipagornwong (2016) analyse how parking availability levels affect commercial vehicle parking costs in congested urban areas. In fact, the non-availability of parking areas may force drivers to stop far from the delivery point, or even in forbidden zones. The authors combine logistics and queuing models and conclude that the impact and costs of non-availability can be substantial. Thus, the appropriate sizing and positioning of the parking areas is important. Alho and Silva (2014) address the analysis of the level of service (defined as the number of commercial and residential activities served by a single loading bay) of the loading/unloading parking infrastructure in the city of Lisbon (Portugal). Part of the work focuses on the hypothesis that illegal parking by non-freight vehicles has an impact on the availability of parking.

Despite this relevance, the extant body of literature regarding optimization of the location of urban parking areas is scant. This gap can be ascribed to the fact that scientific literature has begun to deal with this topic only in recent years (Lagorio et al., 2016). One of the most relevant papers on the subject is that by Dezi et al. (2010), which describes some solutions for the management of stop areas for freight vehicles to mitigate traffic congestion. Through an experiment conducted with a series of on-site surveys and subsequent studies, the authors propose solutions to develop the urban freight transport in an area of the city of Bologna (Italy). The authors, however, do not present specific models supporting the decisions related to the location and sizing of lay-bys that are addressed in this paper.

Cherrett et al. (2012) underline that understanding freight vehicle dwell times (i.e., the period that the vehicle remains stationary during loading and unloading operations) is an important aspect of any type of freight service plan. In line with Allen et al. (2000), Cherrett et al. (2012) report the main factors influencing dwell times among which the location where the vehicle parks and the distance between the parking area and the premises being served are mentioned.

Gardrat and Serouge (2016) suggest an approach based on the CERTU method and on FRETURB model to evaluate the numbers of vehicles and the movements of pick-up and delivery to estimate the quantity of loading/unloading spaces needed for the delivery operations. In a follow-up study, Muñuzuri et al. (2017) found the optimal number of loading/unloading areas needed for the deliveries operations and thus resolved the location-allocation problem. One limitation of these works is that they only consider stalls[1] and not areas. However, it is very common that municipalities create lay-by areas with multiple stalls, usually identified with different band colours and have specific road signs (i.e., to indicate the time window during which the lay-by area is reserved for commercial vehicles). In some cases, a lay-by area can be reserved for commercial vehicles for a portion of the day (i.e., from 7:00am to 10:00am), whereas the area is free for other vehicles outside that time window. Bundling stalls into areas eases the enforcement, reduces the building costs, and avoids confusion for the drivers looking for parking. Further, the solution to the location-allocation problem discussed in Muñuzuri et al. (2017) does not ensure that each destination point is "close enough" to a lay-by area: indeed, in some cases, the distance between the delivery point and the closest lay-by area may be longer than the longest distance a delivery operator is willing, or deems reasonable, to walk from the lay-by area to deliver the goods. This might influence the behaviour of the drivers.

To overcome these limitations, the model proposed in this paper starts with the identification of the number and location of the lay-by areas in the city according to a "covering principle" based on a radius (i.e., the longest distance a delivery operator is willing to walk from the lay-by area) and the definition of the number of parking stalls in each lay-by area based on the demand.

The coverage approach has proved to be a useful and intuitively appealing measure of performance for facility siting decisions when a minimum threshold of service is desired

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[1] A parking stall represents the physical space that a commercial vehicle can occupy in the lay-by area. The stall size must be defined according to the local or national road code. The number of stalls determines the number of commercial vehicles that can simultaneously park in a lay-by area.

(Pirkul et al., 1989). Although covering models are not new, they are very attractive for research, and reviews on the subject appear regularly in the scientific literature (e.g., Berman et al., 2010; Farahani et al., 2012 Garcia et al., 2015). In particular, the capacitated version of the covering model, originally discussed by Current et al. (1988) and Pirkul et al. (1991), addresses the case in which the facilities providing the service are subject to capacity constraints. In our case, the lay-bys are assimilated to the facilities to be located, and the capacity is represented by the number of stalls. The capacitated version of the model appears under-investigated in the literature (Farahani et al., 2012). Among the few contributions, Haghani (1996) proposed two formulations and two solution procedures for the problem of capacitated maximum covering location. In particular, one formulation presents a multi-objective function that combines the maximization of the weighted covered demand with minimization of the average distance from the uncovered demands to the located facilities. Correia and Captivo (2003, 2006) introduced the Modular Capacitated Location Problem, which aims at finding the location and capacity level of the facilities and their assignment to the customers to minimise total costs, when the capacity of each potential location must be chosen from a finite and discrete set of possible capacities. This formulation, recently addressed by Yin and Mu (2012), who have proposed a Modular Capacitated Maximal Covering Location Problem, is, however, better suited to problems aiming to locate emergency services, when the capacity is defined by the number of stationed emergency vehicles.

The model proposed in this paper extends the classical location-allocation problem for lay-by areas (adopted for example in Muñuzuri et al., 2017), including the radius as a further parameter, which affects the number of required parking stalls. Then, the solution is assessed and fine-tuned using a simulation approach to evaluate the impact of stochastic factors and the variability of times. We also consider all the factors introduced by the literature on urban freight logistics, such as the distance of the points of delivery (i.e., mainly shops and retail points, but also private demand points for the delivery of e-commerce purchases) from the lay-by areas. A good location plan of the lay-bys should ensure the proximity of at least one lay-by area to each delivery point. In our opinion, such a model can better balance the needs of the municipality with those of the carriers and shop owners.

More sophisticated and technology-based approaches have also been developed to address the issue of efficiently managing the existing lay-by areas. McLeod and Cherrett (2011) discuss the concept of lay-by areas advance booking to guarantee the availability of loading/unloading areas and at the same time discourage undesirable driver behaviour, such as double parking. Such a system can today benefit from the advance in sensors and wireless communication, resulting in only a fraction of the cost with respect to few years ago, using, for example, a mobile app such as the Area DUM project in Barcelona (Area DUM, 2015). However, such systems would still need technological integration of all the carriers operating in a city and those coming from outside, which would require significant efforts given the fragmentation and competitiveness of the transportation market. Moreover, these systems introduce the problem of enforcing the reservations against unauthorized occupation which is excluded from this study.

Hence, in this paper, we do not consider the possibility of implementing a booking system, and we use a first-come-first-served policy for stall occupation.

Exemplary application case outline

To provide a supporting background to the discussion, as well as a reference for the development of the proposed approach, it is beneficial to refer to an exemplary case. Due to the authors’ location, the discussion is organized with reference to a central district of the city of Bergamo. The selection of an example in a geographical area easily accessible to the authors allowed for direct observations of some features relevant to the study and for the collection of information about the requirements of delivery recipients (see next section). This area has a strong commercial presence that requires freight delivery during the day and presents time limitations to commercial vehicles for parking (Figure 1).

INSERT FIGURE 1 HERE

Figure 1. Reference area for the development of the proposed approach (Pinto et al., 2016).

Data collection

Modelling the complexity of urban freight transport requires large amounts of data related to delivery practices, dwell times, business time, time windows, and more (Muñuzuri et al., 2010). Transport companies, operating in a very competitive environment, are normally reluctant to provide sensitive data, which are considered commercially confidential (Morris et al., 1998). Moreover, little public data regarding freight operations is collected (perhaps with the exception of vehicle traffic counts, which are relatively uninformative [Cherrett et al., 2012]). In general, data sources suitable for characterizing urban freight activities for research purposes are both difficult to obtain and scarce (Alho and Silva, 2014). Thus, the collection of data to represent and model urban freight deliveries is an expensive and difficult task.

Due to the goals of the research, two main categories of information are required:

- *Spatial information*: information about the position of all business activities in the analysed area and information about the location of the eligible spaces to host lay-by areas. This data can be retrieved from different sources, such as regional/local cartographic databases or even on-field inspections. For the case discussed in this paper, it was possible to resort to digital maps available on a Geographic Information Systems (GIS). The choice of the geographical location allowed for an on-field inspection to validate the information retrieved from the GIS and the maps, as well as to fill gaps and errors, especially for the identification of the parking spaces that may be destined to host a lay-by area (Figure 1). In doing this, urban planning and physical constraints that were not represented on the maps (such as street furniture or private parking places) were also identified.

- *Business information*: information about the requirements of the business activities, including the number and frequency of deliveries and the time required for loading/unloading activities. Usually, this information is gathered via on-field inspections, surveys, and interviews. Thus, compared to the spatial information, business information usually requires substantially more effort. As the aim of this paper is to develop a general method rather than a solution for a specific area, we limited the data collection to a sample of the delivery destinations in the example area. Thus, we interviewed a sample of shop owners, as well as some delivery companies, to understand their practices and needs. In addition, we complemented the information using secondary sources (i.e., projects' reports, such as North Florida TPO, 2015) to obtain robust reference input values for the model.

Table 1 summarizes the main types of data usually required to address the problem discussed in this paper.

INSERT TABLE 1 HERE

Table 1. Types of required data.

Proposed approach

The interaction of all the elements involved in the problem under analysis makes the overall problem complex and difficult to address with a single, all-encompassing method. The study of the locations of the lay-by areas may be addressed as a long-term facility location problem (i.e., once the lay-by areas have been positioned, they are unlikely to be subject to repositioning in the short term), whereas the correct sizing of the parking stalls implies the analysis of the dynamics of the parking requirements for commercial vehicles over time. Therefore, a two-stage approach has been devised:

(1) *First stage: location and sizing of the lay-by areas*. This stage addresses the design of the parking system, that is, the identification of the location and size of the *lay-by areas* in the considered urban space. In our definition, a lay-by area is a space along the road devoted to commercial parking which can contain one or more parking stalls. To this end, an analytical model is suitable because the location of the lay-by areas is based mainly on spatial information, which is deterministic in nature (or, at least, not subject to large variability over time).

(2) *Second stage: performance assessment and tuning of the size of the lay-by areas*. The second stage addresses the analysis of each lay-by area defined by the analytical model at the first stage to assess the most suitable size (i.e., number of parking stalls) to ensure acceptable performance in terms of parking availability. In this stage, the main information used is the demand for delivery generated by the commercial activities and the delivery times; this information can be subject to variability in terms of magnitude (i.e., number of deliveries per day) and time (i.e., from one day to another, or from one season to another). Therefore, a simulation model to assess the

performance of the resulting design decision is implemented.

The proposed model considers the perspectives of the different stakeholders involved, such as the carriers and drivers, who need to park as close as possible to their delivery destinations, and urban planners, who are seeking the best trade-off between the space dedicated to load/unload activities and the space available for public parking.

This paper does not address routing decisions (which are defined by the transport providers) nor the interaction with other urban flows, such as public and private urban transport. In the next subsections, the models underpinning the two-stage approach are defined and discussed.

First stage: location and sizing of the lay-by-areas

To define the best locations for the lay-by areas (stage 1), a discrete set covering location model (ReVelle at al., 1976; Current et al., 2004) was implemented. This model aims at determining the minimum number of lay-by areas that can "cover" all the delivery destination points (i.e., shops and commercial and residential buildings), where a point is considered covered if there exists a lay-by area not farther than a distance *R*, which is called the radius. The radius represents the longest distance that a delivery operator is willing to walk from the lay-by area to deliver the goods. This approach requires the following steps. First, from the spatial information set and the field inspection, the space eligible to host a lay-by area must be identified (Figure 1). The parking areas can be considered with their coordinates in the continuous space (Easa and Dezi, 2011). This paper instead illustrates a discrete model, which allows for a simpler formulation with minor impact on the accuracy of the location. Another benefit of a discrete representation is that it allows for avoiding the issues related to infeasible solutions that could emerge from considering the coordinates as continuous. Thus, each eligible space has been discretized in a finite number of lay-by areas that contain one or more stalls. The size of each stall is defined according to the national road code (i.e., in Italy, about 6.5 m x 2.5 m) (Figure 2).

INSERT FIGURE 2 HERE

Figure 2. Discretization of the eligible parking space (Dezi et al., 2010).

Second, the notion of coverage should be adapted to the constraints of the field. In fact, with reference to the example reported in Figure 3, it is not always correct to consider covered a destination point within the circle of radius *R* centred in the lay-by area; in fact, a point is covered if it is within a *walking distance* of *R* meters from the centre of the lay-by area. In Figure 3, the delivery point *D* is, thus, not covered by the lay-by *L*.

INSERT FIGURE 3 HERE

Figure 3. Covered area vs real walking distance (Pinto et al., 2016).

Given these assumptions, the set covering model can be described as follows. Let us consider a set *M* of delivery points and a set *N* of feasible lay-by areas. Each delivery point $j \in M$ requires an average number of v_j deliveries in a day, and each delivery requires an average of t_j minutes. The number of deliveries, v_j, and the duration of the delivery, t_j, may vary according to the type of destination (i.e., location and respective demand, type of business, or type of goods delivered). Each lay-by area $i \in N$ can host a number q_i of stalls, where q_i is a parameter defined according to the available space in the *i*-th area. We assume that each lay-by area is available for commercial parking for T_i minutes during the day (available delivery window).

The model aims to define a set of locations, $U \subseteq N$, where the lay-by areas should be placed and the number of parking stalls in each area. Locations $i \in U$ (i.e., selected for placing a lay-by area) are called *active*. All the delivery points in *M* must be *covered*: formally, a delivery point $j \in M$ is covered if there exists one active location $i \in U$ such that the walking distance $d(i, j)$ is shorter than a pre-specified distance *R* (still called the radius). The covering possibilities can be represented using a binary matrix, *C*=*N*×*M*, whose entries are defined as follows:

$$c_{ij} = \begin{cases} 1 & \text{if } d(i,j) \leq R \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

This representation of the covering possibilities allows for the specialization of the radius *R* according to the type of destination (i.e., *R* is written as R_j): for example, delivery points requiring the delivery of heavy goods may require a shorter radius.

Each active area $i \in U$ covers a subset $B_i \subseteq M$ of delivery points, with $\bigcup_{i \in N} B_i = M$. To simplify the formulation of the model, we require that $\bigcap_{i \in N} B_i = \varnothing$ so that each delivery point $j \in M$ is covered by one active lay-by.

To calculate the number of stalls to be implemented in an active area $i \in U$, the following assumptions are put forward: given a non-empty set, B_i, all the deliveries departing from the *i*-th area occupy a single stall during the day for a time $\tau_i = \sum_{j \in B_i} t_j \cdot v_j$. If

$\tau_i \leq T_i$; then, a single stall in the *i*-th area is theoretically enough to accommodate all the deliveries departing from *i* during the period T_i. Otherwise, if $\tau_i > T_i$, theoretically a minimum of $W_i = \left\lceil \frac{\tau_i}{T_i} \right\rceil$ stalls is required, where the $\lceil . \rceil$ represents the ceiling operator. Clearly, W_i should be considered as a best-case scenario in which the arrivals are "well distributed" over time T_i. This result will be fine-tuned in the second stage of the approach, which considers the effect of stochastic factors.

Due to the parameter q_i constraining the number W_i of stalls for each area, the resulting problem can be infeasible. To avoid this case, we express W_i as the following sum:

$$W_i = S_i + X_i, \tag{2}$$

where S_i represents the number of stalls subject to the constraint $S_i \leq q_i$ (referred to as *regular stalls* in the remainder), and X_i represents the number of stalls required beyond q_i (referred to as *extra stalls* hereafter). Whereas the space for the q_i regular stalls is considered already accounted for before solving the model (i.e., the decision maker is willing to use all the space necessary to accommodate up to q_i stalls in each area $i \in N$), each extra stall may require some further interventions to the area (i.e., moving the street furniture or removing private parking space); therefore, the extra stalls are required when the maximum number of regular stalls q_i in an area *i* is not enough to accommodate all the demand in that area. The decision of adding extra stalls is very much contingent to the specific situation, and should be evaluated by the decision maker. As a consequence, such decision is not considered in the model.

Model formulation

Given the assumptions discussed in the previous section, the model can be formulated as follows:

$$\min \sum_{i \in N} \left(S_i + \omega \cdot X_i \right) \tag{3}$$

$$\sum_{i \in N} Y_{ij} = 1 \qquad \forall j \in M \tag{4}$$

$$Y_{ij} \le c_{ij} \qquad \forall i \in N \;\; \forall j \in M \tag{5}$$

$$S_i + X_i \ge \frac{\sum_{j \in M} t_j \cdot v_j \cdot Y_{ij}}{T_i} \qquad \forall i \in N \tag{6}$$

$$S_i \le q_i \qquad \forall i \in N \tag{7}$$

$$\delta_i \le q_i - S_i \qquad \forall i \in N \tag{8}$$

$$\delta_i \ge \frac{q_i - S_i}{q_i} \qquad \forall i \in N \tag{9}$$

$$X_i \le \left(1 - \delta_i\right) \cdot M \qquad \forall i \in N \tag{10}$$

$$\begin{gathered} S_i \ge 0,\; X_i \ge 0,\; W_i \ge 0 \quad \forall i \in N \\ Y_{ij} \in \{0,1\} \qquad \forall i \in N \;\; \forall j \in M \end{gathered} \tag{11}$$

The objective function (3) minimizes the number of stalls and distinguishes between *regular* and *extra* stalls. The coefficient $\omega > 1$ represents the cost of an extra stall with respect to a regular one (i.e., the ratio between the cost of an extra stall and the cost of a regular stall), and in general cases, ω may depend upon *i*. Given the higher cost of extra stalls, the model tries to exploit all the available regular stalls first.

In constraint set (4), the binary variable Y_{ij} is equal to 1 if the delivery point $j \in M$ is served by the lay-by area $i \in N$. Thus, constraint sets (4) and (5) stipulate that each delivery point must be covered by one lay-by area among those within a walking distance *R*, where c_{ij} is the matrix defined in (1). Because of these constraints, uncovered delivery points are not allowed. In turn, this assumption may also result in cases in which isolated delivery points require their dedicated lay-by area. Such corner cases, which are easily identifiable in the solution, can be subject to further cost-benefit analysis to exclude them or confirm the solution. Such analysis, however, is case-specific and depends upon the decision makers' goals, constraints, and degrees of freedom and is thus excluded from this paper.

Constraint set (6) defines the theoretical number of stalls in each area, while constraint set (7) limits the number of regular stalls, S_i, to a pre-specified value q_i. Extra stalls beyond q_i may be implemented at a higher cost. Clearly, an extra stall in the area *i* may be implemented (that is, a variable X_i can be positive) if and only if $S_i = q_i$: in fact, it is not optimal to activate an extra stall if regular ones are still available. This condition is represented via the binary variable δ_i and the constraint sets (8), (9), and (10), where *M* is a large enough number. In fact, δ_i is forced to 1 when $S_i < q_i$, thus signalling that regular stalls are still available, in turn forcing X_i to 0. Given $\omega > 1$, these constraints are redundant, as the model would use all the cheaper, feasible regular stalls first; however, they proved experimentally to help reduce the average solution time. This formulation can be considered a special case of the capacitated set covering location problem (Current et al., 1988), in which all the demand from one destination is assigned to the same location. Making use of the slack variables, X_i, the model is feasible provided the following condition holds:

$$\sum_{i \in N} c_{ij} \geq 1 \qquad \forall j \in M \tag{12}$$

The equations (12) stipulate that for each delivery point $j \in M$ there exists at least a lay-by area $i \in N$ at a distance smaller than *R*. A violation of this condition makes the problem infeasible due to constraint set (4) (i.e., there is at least a customer that cannot be served). In such a case, the decision maker should explore other potential areas to be added to the set *N* until the condition (12) is satisfied.

Regarding the construction of the set *N*, a further condition worth mentioning is the following:

$$\sum_{j\in M} c_{ij} \geq 1 \qquad \forall i \in N \tag{13}$$

Equations (13) stipulate that each lay-by area $i \in N$ must cover at least one delivery point $j \in M$. This condition is not related to the problem feasibility; however, any lay-by area violating condition (13) does not contribute to the final solution and can be removed from the problem data. Thus, condition (13) represents an *a priori* requirement for a lay-by area for its inclusion in the set *N*.

Solving the first stage, the covering model allows defining the locations of the lay-by areas and the number of stalls required to satisfy the requirements of the delivery points associated with them. If the solution requires some extra stalls (i.e. $X_i > 0$ for some *i*), then the decision maker should decide whether to incur the extra costs for such a decision or to elaborate alternative plans (this alternative has not been addressed in this paper).

Second stage: performance assessment and size tuning of the lay-by areas

As discussed in the previous section, the definition of the number of parking stalls in each area is influenced by several parameters, such as *i*) the number of delivery points served from each lay-by area (B_i); *ii*) the number of expected delivery vehicles per delivery point per day (v_j); *iii*) the time-window available for the loading/unloading operations (T_i) (i.e., from 7:00 am to 10:00 am, or the whole day); *iv*) the average duration of the loading/unloading operations (t_j); and *v*) the possibility to reserve the stalls in advance, thereby scheduling the arrival of the delivery vehicles (not considered in this study). However, the model presented in the first stage considers only deterministic parameters, whereas, in reality, arrival and occupation times are better represented by random variables. The actual capacity required in terms of parking stalls may be higher than determined by the optimization model, as the arrivals of vehicles may overlap (Muñuzuri et al., 2017). To deal with these stochastic factors, and fine-tune the size of the lay-by areas in order to provide a robust solution, it is necessary to assess the performance of the design decision provided by the model (3)–(10) under different stochastic conditions. To this end, a simulation model that can handle different scenarios and provide performance indicators to the decision makers was designed. In fact, simulation is a well-known approach suitable to deal with uncertain parameters.

The unit of analysis for the simulation model is the lay-by area: that is, the parking process at each lay-by area is simulated separately from the others. The reason underpinning this decision is that once the lay-by areas have been optimally placed via the first stage of the proposed approach, each driver will naturally drive to the closest or assigned location, thus reducing or even eliminating the interactions with the other locations. Similarly, we did not explicitly model the interaction with the traffic flows (i.e., such as private and public transport vehicles); these simplifications open the way to further extensions of the proposed approach. Based on these considerations, we opted for simulating the arrival process of the delivery vehicles at each parking area by sampling from the probability distributions defined by the data collected.

The decision process of the drivers was modelled, as depicted in Figure 4. When a driver arrives at the lay-by area, there are two main options: either a stall is available (thus, the driver can park and perform the delivery), or all stalls are occupied. In the latter case, the driver can decide *i*) to wait for a stall becoming vacant or *ii*) to occupy another parking place not reserved for the delivery operations (i.e., parking in a lot destined to cars, or even double-parking; in any case, this choice produces a negative effect on the traffic). It is assumed that there is no system that allows the driver to remotely know the actual stall availability in a lay-by area, so that situation at a lay-by area becomes known to the driver only upon arrival. The driver's decision process in case a parking stall is not available is modelled with a random choice governed by a probability *p*, referred to as *waiting probability*; if a stall is not available, there is a probability *p* that the driver will wait for a vacant stall (thus influencing the traffic flow), whereas with a probability *1-p* the driver decides to park in another, non-reserved area, thus generating potential issues with other road and parking users. Such a probability is generally difficult to assess precisely in real applications: however, a sensitivity analysis that considers different hypothetical values can be performed.

INSERT FIGURE 4 HERE

Figure 4. Model of the stall occupation process (adapted from Pinto et al., 2016).

Numerical results and example of application

To illustrate the application of the approach, this section discusses an exemplary case selected in the city of Bergamo, as previously introduced in the background and case outline section. The purpose of this section is to discuss the process and the models rather than the final results: indeed, the final decisions depend upon the use of the provided information by the decision makers. At the end of this section, we also provide the numerical results obtained on a set of randomly generated problems.

Example of application

In the considered area, we identified 111 commercial activities that require deliveries using public parking stalls. The space eligible for hosting the lay-by areas has been discretized in 49 candidate lay-by areas. The locations of the delivery points and the candidate lay-by areas allowed for the computation of the walking distance between each pair of origin and destination. As noticed before, these distances are not Euclidean (straight-line), but must consider the walking path of the driver from the parking stall to the delivery point. To this end, a combination of Google Maps and direct data collection has been used. With this data, using a walking distance R = 50 m, as found in the literature (CERTU, 2009; Muñuzuri et al., 2017) (for the sake of simplicity, we considered the same value of R for all the delivery points; this parameter can be adjusted, though, to consider specific requirements), the covering model was implemented and solved on a Xeon machine with 8GB of RAM using Gurobi Solver 6. The solution defined the activation of 23 parking areas and 39 regular stalls (Table 2). No extra stalls were required.

INSERT TABLE 2 HERE

Table 2: Solution of the covering model with $R = 50$ m and $T_i = 120$ minutes.

These lay-by areas allow covering all the destination points. Further, a sensitivity analysis is shown in Table 3: as expected, once the radius R is set, the number of areas and the number of stalls decrease with the increase of the service time windows, T, as it is possible to accommodate a larger number of vehicles in the same lay-by area. Analogously, once the service time window, T, is set for each area, the number of areas and the number of required stalls decrease as the radius, R, increases, as one lay-by can serve a larger number of destinations, and it is therefore possible to exploit the pooling of the resources.

INSERT TABLE 3 HERE

Table 3: Sensitivity analysis changing the radius R and the service time windows T.

The second stage of the process involves the fine tuning of the size of the parking areas. To this end, the simulated model of the arrival process for each parking area was implemented in Python.

Let us consider the parking area 01, which serves 12 delivery points. On average, these 12 delivery points require about 12 delivery vehicles per day. The service time window of the lay-by area 01 for freight delivery is $T_{01} = 120$ minutes. Each delivery in the area requires from 20 to 30 minutes, aligned with data found in literature (Dezi et al., 2010; Cherrett et al., 2012).

The minimum number of stalls in area 01 defined by solving the covering model (four in this case) would work well (i.e., drivers find parking as soon as they arrive) only if the access to the area could be regulated or planned via a remote booking system. If such a system is not available, the availability of a stall is subject to stochastic factors such as the number of delivery vehicles arriving per day, the average loading and unloading time, and the probability that the driver will wait. Consequently, a decision maker can evaluate the possibility to increase the number of stalls above the minimum (four stalls in this case) to guarantee a higher availability and reduce the risk that drivers will engage in illicit behaviours. Alternatively, the decision maker can reduce the number of stalls below four to use less road space, knowing that this will likely increase the conflicts with other road users.

To provide support in taking such a decision, the performance of the lay-by area 01 under the stochastic factors and a varying number of stalls were assessed. Twelve different scenarios that considered the following aspects were defined:

- The number of stalls (a decision variable) varies between three and five.
- The number of delivery vehicles arriving during a day varies stochastically around the average of 12, between 10 and 14. The vehicles arrive

independently from each other, uniformly distributed during the time window T_{01}; however, because the minimum service time is 20 minutes on average, it is assumed that the last delivery vehicle arrives no later than 100 minutes from the beginning of the time window T_{01}. In fact, after 120 minutes, the area will be accessible again to private vehicles.

- The duration of the delivery time t_{01} varies stochastically between 20 and 30 minutes.
- The probability that the driver would wait for a commercial parking stall in case he/she arrives at a parking area at a time when no stall is available varies between 0.5 and 1. In this context, “waiting” means that the driver stays on the road looping to find a free stall later.

In conclusion, the cases reported in Table 4 were simulated; each case was simulated 1,000 times, and an excerpt of the results is reported in Table 5 and Figure 5. The same procedure should be performed for each lay-by area defined by the covering model, and the values in Table 4 should be adjusted accordingly.

INSERT TABLE 4 HERE

Table 4. The twelve simulation cases used to measure the performance of the lay-by area 01 under stochastic factors and varying number of stalls.

The results reported in Table 5 and Figure 5 are meant to support decision makers in performing what-if analysis. Indeed, the numbers and the charts do not provide a single answer: such data must be used to analyse trade-offs according to the specific needs and constraints of the considered area. For example, the average numbers of vehicles not served upon arrival and the average waiting times in Table 5 provide an indication of the magnitude of the impact of different behaviours and design decisions. Similarly, the charts in Figure 5 provide relevant information that can be considered in the decision-making process.

INSERT TABLE 5 HERE

Table 5. Results summary (1.000 runs per case; times in minutes).

INSERT FIGURE 5 HERE

Figure 5. Average waiting time distributions (dashed line = median; to render the chart properly, the values on the axes are different row by row).

Numerical results

The optimization model (3)–(10) has been further tested on a set of random problems of different sizes, with the aim to assess the time required to attain an optimal solution. The random problems were generated as follows:

- the number *n* of lay-by areas were selected in the set $\Sigma_1 = \{25, 50, 100, 150\}$;
- the number of delivery points *m* were obtained by multiplying *n* by the numbers in the set $\Sigma_2 = \{1, 1.5, 2, 5\}$ to keep a proportion between the parking lay-bys and the delivery points;

- for each destination point, the average number of daily requests was randomly selected in the set {0.5, 1.0, 1.5, 2.0, 3.0, 5.0}; similarly, the average duration of the delivery was selected in the set {15, 20, 25, 30} minutes;
- for each lay-by area, the maximum number of regular stalls q_i was randomly selected in the set {1, 2, 3, 4};

Overall, 30 problems for each pair $\{(\sigma_1, \sigma_2) \mid \sigma_1 \in \Sigma_1, \sigma_2 \in \Sigma_2\}$ for a total of 480 problems were generated and solved on a Xeon machine using Gurobi Solver 6, with a time limit of 600 seconds. Within this limit, 89.6% of the problems (430 instances) were solved at optimality, with the majority being solved within 300 seconds (Figure 6).

INSERT FIGURE 6 HERE

Figure 6. Cumulated percentage of problems solved at optimality for different values of the runtime.

The remaining 10.4% of the problems (50 instances) reached the 600-second time limit. However, even for these problems, the gap attained in the allotted time was very small: the maximum gap was 3.44%, with 36 instances (about 7.5% of the whole sample), with a gap that was smaller than 2%.

Similar conclusions can be drawn regarding the simulation model. In fact, considering a set of 44 random problems with the number of trucks varying between 15 and 45 in a single day of operations, the average time required to complete a 1.000-run trial (i.e., simulating 1.000 days) was about 2.3 seconds, with a maximum value of about five seconds. Such a result, however, can greatly vary according to the available hardware.

In our opinion, these results support the practical use of the proposed model. In fact, real-time decisions are usually not required in the type of problem addressed in this paper. Further, the low frequency at which this kind of problems requires to be solved allows for the use of the proposed model with a time limit much larger than 600 seconds. Finally, larger problem instances may be separated in smaller instances regarding smaller areas, thus contributing to the reduction of the solving time.

Implications

The proposed approach aims to support researchers and local authorities in analysing and assessing their decisions about the location of lay-by areas in a city area. In particular, the use of a combined optimization and simulation approach allows designing a new system of lay-by areas by considering the effect of uncertainty.

Given the differences in the layouts and constraints characterizing the cities, the aim of our model is to provide a flexible tool that can be used in different settings, rather than provide general and exhaustive solutions. Nonetheless, our model highlights some general guidelines when addressing the location and sizing of lay-by areas illustrated hereafter.

First, it is essential to collect all the necessary data in the area of interest in the city. Our model requires relatively little information, including the delivery destinations and their average demand, the location of existing lay-by areas, and the possible locations of new lay-by areas. To this end, it is important to gather data from all the possible sources (i.e., open data, publicly available data, or data provided by private actors), that should be integrated with on-field inspections. Regarding the sources of data, Golini et al. (2018) provide some useful guidelines.

Second, it is important to define the degrees of freedom available to the decision makers in exploring the solution space. Such degrees of freedom are instantiated in the range of values that the main parameters of the model can assume (i.e. the radius R, the available delivery windows T_i, and the waiting probability p). The ranges of variation of these parameters should be defined in agreement with the stakeholders (e.g., municipality, carriers, shop owners) and according to the characteristics and regulations of the area under investigation (i.e., from limitations on the delivery windows to space availability for the location of new lay-by areas).

Third, after the two-stage model have run, the decision makers need to evaluate the feasibility of the proposed solution. For instance, there may not be physical space for extra stalls in one area, thus such a suggestion from the model should be disregarded or the parameters must be revised. Another case could be one lay-by area that serves only one isolated shop. In this case, the decision maker can decide whether to create an area just for one shop. Finally, other factors can be introduced in the decision process, such as political and social factors.

Fourth, after a feasible solution has been identified, the decision makers need to agree on the most *robust* solution using the simulation approach Though for practitioners it may sound flawed to think in terms of expected outcomes and probabilistic effects, the goal of the analysis should be to reach a robust solution (i.e., robust to changes in the demand and times of arrival) rather than an optimal solution which minimizes the number of stalls for the current situation. This last part shows how the proposed approach has not been conceived as a substitute for the human decision makers; instead, it has been designed with the goal to support the decision makers in improving the quality and robustness of their decision.

Limitations

The most relevant limitations of the proposed approach can be summarized as follows. The interaction between the freight flow and the public and private traffic flows is limited: that is, the effect of private vehicles parking in commercial lay-by areas during the time window has not been considered. However, this effect should be limited by the presence of local authorities enforcing the reservation of the parking areas to commercial vehicles during the specified time windows.

Similarly, the impact of commercial vehicles unable to find a parking stall in the lay-by areas upon arrival has not been explicitly addressed. The analysis of the interaction between different traffic flows requires a different approach. However, the models proposed in this study provide information, reported in Table 5, regarding the magnitude of the impact.

Conclusions

Unlike other contributions, this paper considered two perspectives: that of the carriers and drivers, who need to park as close as possible to their delivery destinations to increase the efficiency of their operations, and that of the urban planners, who are seeking the best trade-off between the space dedicated to load/unload activities and the space available for public parking. Both groups must encounter a trade-off and constraints that call for decision support tools and procedures that balance the needs of the businesses with the needs of other road users.

The two-stage approach illustrated in this paper enables a thorough performance analysis of a typical design decision in urban environments. The combination of an optimization model (based on deterministic data) with a simulation model (which introduces random data) allows for a robust understanding of the available alternatives. In particular, Table 5 and Figure 5 provide information that a decision maker can consider against the costs in order to make a final decision regarding design according to his/her overall goal.

Indeed, the two-stage approach presented in this paper does not provide a single, optimal solution. Instead, it represents a what-if analysis tool by providing information that can be used by the decision makers to determine the most robust solution. Thus, the proposed approach provides a systematic way for supporting decision makers insofar the final decision depends upon factors that cannot be easily included in an algorithmic approach. Indeed, it is rather difficult to provide an exhaustive solution, as it is generally case-specific and depends upon the decision makers' goals, constraints, and degrees of freedom. Further, due to the multi-dimensional trade-off that must be considered in this type of problems (usually involving several stakeholders with different, not to say conflicting, objectives), a completely automated approach (even for very large problem instances that, however, may be decomposed in smaller instances) would hardly work.

We believe that providing a suitable interface that clearly shows the results of the computations, the decision makers and the stakeholders can improve their awareness of the issues and the potential impact of their decisions. In our opinion, the proposed model can better balance the needs of the municipality with those of the carriers and shop owners.

To expand on this study, the simulation model can be extended to consider further alternatives for the drivers and to include the possible interaction between different lay-by areas: for example, it may be relevant to investigate the effect of the driver's decision to park in a lay-by area that is farther than the pre-specified radius R when a stall in the lay-by where he is supposed to park is not available. Finally, a simulation model encompassing more than one lay-by area can be developed to better assess the interactions between different areas and analyse the trade-off between model complexity and the accuracy of the results.

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