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An e-delivery system based on pick-up points: demand forecast, system design and scenario assessment☆

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ABSTRACT

In recent years, e-commerce experienced significant growth, also pushed by restrictions imposed during the COVID-19 pandemic. This rapid growth has had significant both positive (e.g., economic growth) and negative (e.g., congestion and pollution) impacts on cities. In fact, in many cases, small, sprawled and failed deliveries, resulting in additional trips for carriers, are a problem to tackle in terms of both operational (internal) costs and external costs. Focusing on such a problem, this paper reviews the current literature and points out the need to overcome the current literature lacks that limit the exploitation of new ways of receiving e-purchases in a sustainable way. The current methodologies were developed mainly to simulate some aspects of e-delivering and are not able to forecast the end consumers' choice as well as the impacts due to the different measures that are implemented at urban scale which affect the e-delivery operations. Therefore, considering the limited literature analyses regarding such a delivery system, the paper proposes an assessment methodology which included an advanced behavioral modeling system able to forecast the end consumers' demand, and an optimization model for designing the pick-up system in terms of the number, location and size of the pick-up points, taking the availability of end consumers to collect their e-purchases into consideration. The approach has been applied to a real case study, and satisfactory results have been obtained. The findings of this study can contribute to the development of more sustainable urban freight transport, one of the most significant challenges facing city decision makers and authorities.

1. Introduction

Although in-store shopping remains the predominant way to buy, internet is modifying end-consumer behavior. In fact, the advancement of information and communication technologies (ICTs) has pushed more and more people to choose to shop online (Fig. 1), at least for two main reasons: to find the lowest price and to increase the availability of products. The rise of the COVID-19 pandemic has also contributed to the growth in the number of consumers using e-commerce (Mouratidis and Papagiannakis, 2021; Young et al., 2022).

This new trend can have an impact on freight traffic in urban areas because the products purchased have to be delivered to the customer (e.g., at home or in any place end consumers decide) through delivery tours (i.e., an ordered sequence of consumers/points to serve by a vehicle along the same journey) that cannot always be optimized, for example, due to small and sprawled parcels, and cause a growth of traffic impacts (Durand and Gonzalez-Feliu, 2012; Simoni and Claudel, 2018). Besides, additional costs can arise from repeated deliveries. In fact, attended home deliveries require customers and logistics service providers to agree on a service time window in order to avoid failure of delivery (Ji et al., 2022; Song et al., 2012). For logistics service providers, accepting more deliveries can yield more revenue, but it can make it harder to make deliveries within the service time windows.

From an end consumer's point of view, online retail is associated with several benefits such as greater product choice, the ability to obtain goods not sold locally and better price comparison. However, from a logistics point of view, the delivery solution is very demanding. Efficient and reliable logistics are a key factor in the economic success of online stores, and shipping costs are one of the biggest concerns for online customers. Especially the "not-at-home problem" need to be treated, which results from the delivery of goods that require the presence of the end consumer. This leads to complex planning problems within the last

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leg of supply chains, that is, the last mile for the end consumer. Therefore, although home deliveries are usually preferred by online shoppers (Morganti et al., 2014a; Unnikrishnan and Figliozzi, 2021), from a planning point of view, there is a rising interest in developing alternatives that satisfy both end-consumer demand and transport operators to optimize parcel distribution through consolidated shipments and to avoid delivery failure. Therefore, the pick-up point network has been proposed and implemented by several mail operators around the world. In Europe, pick-up points (that is, places / stores that provide parcel drop-off and pick-up services) are fast-growing solutions. Examples of pick-up point network are the Packstation network operated by DHL/ Deutsche Post in Germany (Morganti et al., 2014b) or the parcel lockers provided by Amazon (Sethuraman et al., 2024).

Assuming that in the near future e-purchases will increase and the impacts due to home deliveries could also rise, the paper investigates the opportunity to deliver to pick-up points located within the urban area. This allows deliveries (*unattended delivery system*) to be made even in the absence of the receiver. In particular, a methodology that can be used to design a pick-up system in the downtown area and to provide a sustainable solution to improve urban environment is presented. The pick-up point system could be designed in two different ways: unattended delivery systems at the *customer's home* (including the use of reception/ delivery boxes and an access control system), unattended delivery systems *away from the customer's home* (including locker banks/pick-up points). This system brings advantages to both end consumers and operators, i.e., end consumers pick up their parcels after notification of arrival not far from their home in a large time window (e.g., usually access is assured 24 h and 7/7 days), while operators solve the issues due to non-attendance of the customer at home. They can also consolidate deliveries, which can be potentially performed at any time of the day. The methodology is supported by a demand modeling system (updated from new data) that allows planners to point out the demand and that has been obtained through the investigation of factors that drive end consumers in their purchase choices.

The paper therefore proposes a methodology that can be used to design a pick-up system downtown through the use of an advanced modeling system able to forecast the end consumers, and an optimization model for designing the pick-up point system in terms of number, location and size (i.e., number of delivery slots) of the pick-up points.

The paper is organized as follows. Section 2 outlines the literature review, pointing out the lack of current literature and positioning the paper contribution. Section 3 presents the proposed methodology, while Section 3.1 discusses the results obtained in a real case study. Finally, the conclusions and the road ahead are drawn in Section 4.

2. Literature review

Urban freight distribution has been addressed from different points of view: simulation (Castiglione et al., 2022; Comi et al., 2021; Nuzzolo and Comi, 2014a), optimization (Özarık et al., 2021; Cattaruzza et al., 2017; Polimeni and Vitetta, 2014) including environmental-technological aspects (Bachofner et al., 2022; Muñoz-Villamizar et al., 2020; Taniguchi et al., 2020). In particular, simulation has been developed mainly for investigating the *acceptance* by end consumers as well as the *city benefits* produced by its implementation in terms of internal (i.e., operational) and external (e.g., pollutant emissions) costs.

Focusing on *acceptance* in choosing the parcel locker (pick-up point) for receiving the e-parcels, Encarnación and Amaya (2024) identified and analyzed the relevant factors (i.e., location, risk, ease of use) that influence consumers in choosing the parcel lockers for receiving e-purchases. However, attributes describing the service (e.g., time for accessing, reliability, costs/fees to use), and location are the main determinants that encourage users to use them. In fact, Oliveira et al. (2017) explored the willingness to use parcel lockers taking into account attributes such as cost/fees, delivery time, location, level of information, through a stated preference (SP) survey. Kedia et al. (2017) found that location (i.e., proximity to home or workplace), parking availability, safety, and security are the major determinants. Lachapelle et al. (2018) focused on the existing parcel lockers in some cities analyzing the information on accessibility, access by mode, safety, ease of use; a cluster analysis is proposed to classify the potential locations of parcel lockers. Yuen et al. (2019) argued that service reliability, time flexibility, privacy, and costs affect the user's choice of this reception mode. Tsai and Tiwasing (2021) quantified the user attitude in terms of convenience, reliability, and privacy level. Lai et al. (2022) investigated the factors that affect the satisfaction in using the parcel lockers. The findings are that reliability, security, and time savings are relevant predictors to understand the user perception of such a delivery service. Rossolov (2023) provided a model to assess the potential demand for a parcel locker system, identifying the attributes (economic and spatial) that affect the choice of end consumers. Cieśla (2023) investigated the attributes related to the performance and the service quality of the distribution using parcel lockers designing a specific survey aimed at this purpose. Also, the level of satisfaction in using parcel lockers has been

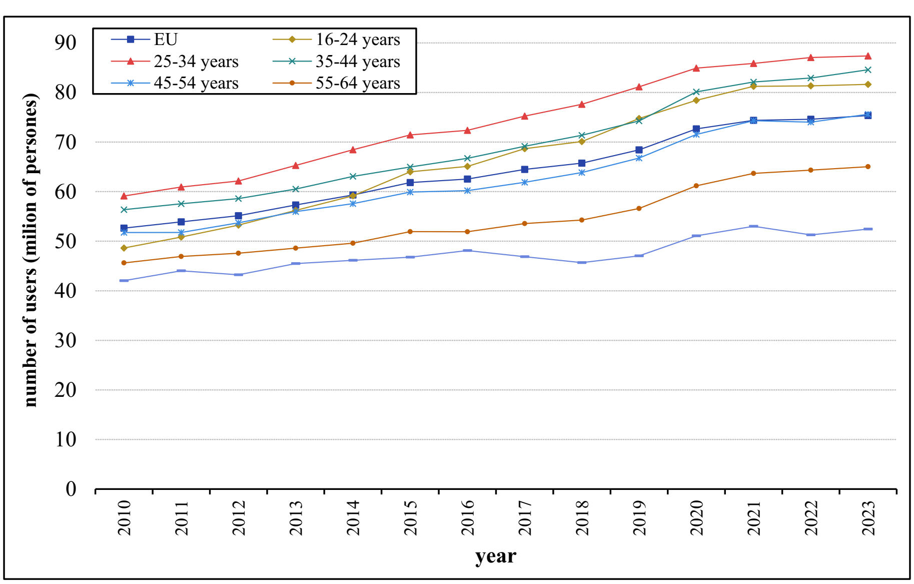

Fig. 1. Internet users in the European Union who used e-commerce by age group (Source: EUROSTAT, 2025).

studied and compared among cities as shown in Bouhouras et al. (2024), whose findings revealed how location accessibility, expedient pick-up procedures, unambiguous communication, and ensured item availability play a key-role in successful implementation of such a service.

Benefits for the city cover the different aspects of sustainability, named economy, environment, and society. In this regard, Vakulenko et al. (2018) explored the interaction between end consumers and parcel lockers, considering the value creation (i.e., functional, social, and financial) that comes from this means of delivery. van Duin et al. (2020) assessed the sustainability and the cost efficiency of the last mile delivery performed by means of parcel lockers (respect to the traditional home delivery) testing different scenarios. Strategies for including e-delivery within the traditional urban freight distribution are also a topic discussed in the literature, as shown by Di Gangi et al. (2023), Montoya-Torres et al. (2016), while actions for optimizing classical home delivery are explored by Enthoven et al. (2020).

Delivering freight from a different location to the consumer's home (generally pick-up points) is a policy that can be adopted to mitigate the externalities associated with last mile distribution (Sina Mohri et al., 2024). In any case, the different aspects of this modality should be investigated to quantify its costs/benefits and understand how it impacts end consumers' behavior.

It should be noted that a significant part of the literature on parcel lockers focuses on *optimization* of their location. Deutsch and Golany (2018) developed an approach to optimize the location, number, and the size of the parcel lockers with the aim of maximizing the courier's profit. Peppel and Spinler (2022) developed an approach to identify the optimal number and the parcel locker location with the aim to optimize the pollutant emissions and service costs. Additionally, a discrete choice model has been developed to estimate the percentage of end-consumer willing to use parcel lockers. Lin et al. (2022) formulated and solved a parcel-locker location problem with the objective of maximizing the profit taking into account the users' behavior and the competition with other delivery modes for the receipt of e-purchases. Advancement also refers to taking into consideration that the service demand can be considered as a stochastic variable. Mancini et al. (2023) formulated a problem with the aim of maximizing the number of end consumers assigned to the parcel lockers and minimizing the distance traveled by users to reach the parcel locker. Similarly, Gayen et al. (2023) developed a multicriteria approach on fuzzy environment, the aim is to identify the potential locations for parcel lockers considering a set of criteria (i.e., traffic, security, reliability, and accessibility). An assessment approach for the locations of the parcel lockers in urban area has been proposed by Moslem and Pilla (2023) and Moslem et al. (2024), developing a hybrid decision-making model that combines analytical hierarchy process and fuzzy set theory. The walking accessibility of collection and delivery points in a small urban center has been investigated using a spatial syntax methodology, calculating 5-min isochrones and evaluating walking infrastructures. The results show that good spatial accessibility of the pick-up points (parcel lockers) is not always linked to an equally good level of population coverage and the goodness of the associated pedestrian infrastructures (Russo et al., 2023).

A new task in location problem is emerging due to the introduction of mobile parcel lockers (i.e., lockers able to change their locations, also autonomous vehicles; Russo and Comi, 2024). This new function introduces an additional element of flexibility, as consumers can be in the locker area of influence multiple times on the same day. Schwerdfeger and Boysen (2020) proposed a method to optimize the location of mobile lockers with the aim of minimizing the locker fleet that will satisfy all potential consumers. Li et al. (2021) proposed a two-level problem with the aim of optimizing the travels of the locker and the transport by operator in charge of restocking them.

This brief review points out that some efforts have been made to assess the benefits and acceptance of end consumers in choosing parcel locker systems to receive e-parcels. However, the main attention has been paid to investigating acceptance as well as location issues, neglecting the relevance of taking into due consideration the coverage and the level of demand served. Therefore, an ex-ante assessment methodology that combines an advanced behavioral demand modeling able to simulate the e-purchasing is proposed. Furthermore, the operational costs and external costs are highlighted, assessing the benefits that such a delivery system can bring to the sustainability of the city.

Table 1 reports a summary of the literature analyzed above. Each column represents the main topics tackled in the papers (i.e., acceptance/demand forecast, benefit assessment, location optimization) which allow the paper contribution to emerge clearly. In fact, as shown in Table 1, this research contributes to solve the lack in taking into

Table 1
Summary of the literature.

Reference	Acceptance / Demand forecast	Benefit assessment	Location optimization
Encarnación and Amaya (2024)	SEM[1]	–	–
Bouhouras et al. (2024)	LM[2]	–	–
Cieśla (2023)	KM[3]	–	–
Deutsch and Golany (2018)	–	–	MILP[13]
Di Gangi et al. (2023)	–	CA[9]	GA[14]
Kedia et al. (2017)	SDA[4]	–	–
Gayen et al. (2023)	–	–	MCGDM[15]
Lachapelle et al. (2018)	LM[2]	–	–
Lai et al. (2022)	SERVQUAL[5] and LSQ[6]	–	–
Li et al. (2021)	–	–	EHCWH[16]
Lin et al. (2022)	TLM[7]	–	MICQP[17]
Mancini et al. (2023)	–	–	CS[18]
Moslem and Pilla (2023)	–	–	SFAHP[19]
Moslem et al. (2024)	–	–	DF[20] – AHP[21] – CODAS[22]
Oliveira et al. (2017)	SDA[4]	–	–
Peppel and Spinler (2022)	MNL[2]	–	MILP[13]
Rossolov (2023)	SDA[4]	–	
Schwerdfeger and Boysen (2020)	–	–	MIP[23]
Tsai and Tiwasing (2021)	PLS-SEM[8]	–	–
Vakulenko et al. (2018)	–	FG[10]	–
van Duin et al. (2020)	–	CEA[11], MCA[12]	–
Yuen et al. (2019)	SEM[1]	–	–
This research/paper	MNL[2]	CA[9]	MILP[13]-QE[24]

[1] structural equation model
[2] logistics model/multinomial logit
[3] Kano model
[4] statistic-descriptive analysis
[5] service quality model
[6] logistics service quality model
[7] threshold luce model
[8] partial least squares structural equation modeling
[9] comparative analysis
[10] focus group
[11] cost effectiveness analysis
[12] multi-criteria analysis
[13] mixed integer linear programming
[14] genetic algorithm
[15] multicriteria group decision-making
[16] enhanced hybrid Clark and Wright heuristic
[17] mixed-integer conic quadratic program
[18] consensus search
[19] spherical fuzzy analytic hierarchy process
[20] decomposed fuzzy
[21] analytic hierarchy process
[22] combinative distance-based assessment
[23] mixed integer programming
[24] queuing theory

account: the demand analysis,i.e., the decision of the users in using the pick-up point (parcel locker) forecasted by a probabilistic-behavioral – multinomial logit - model, and the location of the pick-up point (parcel locker) taking into account their sizing by means of queuing theory.

3. Methodology

Previous research on e-commerce delivery movements has mostly focused on describing and modeling household shopping trips (Ehmke and Campbell, 2014; Ehmke and Mattfeld, 2012; Gonzalez-Feliu et al., 2012; Nuzzolo and Comi, 2014b), but few of them have investigated the impacts of home deliveries on city sustainability and assessed alternative solutions, such as the pick-up point network, as shown in the earlier Section 2.

The proposed methodology for designing pick-up point (parcel locker) networks (Fig. 2) consists of several stages. First, from the *study area data*, the geographical area (*study area definition*) that includes the transportation system under analysis and encompasses most of the project effects is delineated; according to the delivery requirements, the set of traffic zones (*zoning*) is thus identified. Then, the number of unattended deliveries per traffic zone (*demand*) is estimated by means of an advanced demand model that takes as input the zoning and the *socio-economic data*. The output is the total number of *purchases* (*on store* and *online),* from which the number of e-purchases can be extracted (the modeling system allows the number of weekly e-purchases in each traffic zone according to different freight types to be estimated). The next stage is the optimization of the *pick-up operations* (based on the forecast demand and end consumers' requirements), obtaining an optimal *scenario* in terms of the number of *pick-up points*. The related *location* is found by solving an optimal location problem according to the demand level and the urban road network, respecting some general constraints (e.g., maximum walking distance from the end consumers' home). In addition, for each pick-up point, the *optimal size* (e.g., the number of slots to accommodate electronic purchases) is calculated according to the randomness of the daily delivery number and the preferences of the *end consumer.* Finally, the scenario is simulated, and a procedure for *performance evaluation* allows some performance indicators to be obtained. The aim is to assess how much the defined system improves delivery operations and reduces traffic impacts.

3.1. Estimation of the number of unattended deliveries per traffic zone

A key role in such a methodology is played by an advanced demand modeling system that has to capture end consumers' intention in making e-purchases. Therefore, according to a previous urban freight demand model (Nuzzolo and Comi, 2014a), model specifications and calibrations are proposed driven by the results of some surveys, as presented in the following Section 3.1.

The total number of e-purchases is estimated by using a model that correlates the number of purchases with the number of consumers, the average number of purchases, and the probability of making on-line shopping as follows:

$$N_j[online] = \sum_{i,s} N_j^{i,s}[online] = \sum_{i,s} n_j^i \cdot acq_j^{i,s} \cdot p^{i,s}[online]$$

where:

- $N_j[online]$ is the average number of weekly e-purchases made by the end consumers living in zone *j*;
- $N_j^{i,s}[online]$ is the average number of weekly e-purchases of type *s* made by the end consumers belonging to category *i* and living in zone *j*;
- n_j^i is the number of end consumers belonging to category *i* and living in zone *j*;
- $acq_j^{i,s}$ is the average number of purchases (in store and on line) of type *s* made by the end consumers belonging to category *i* and living in zone *j*;

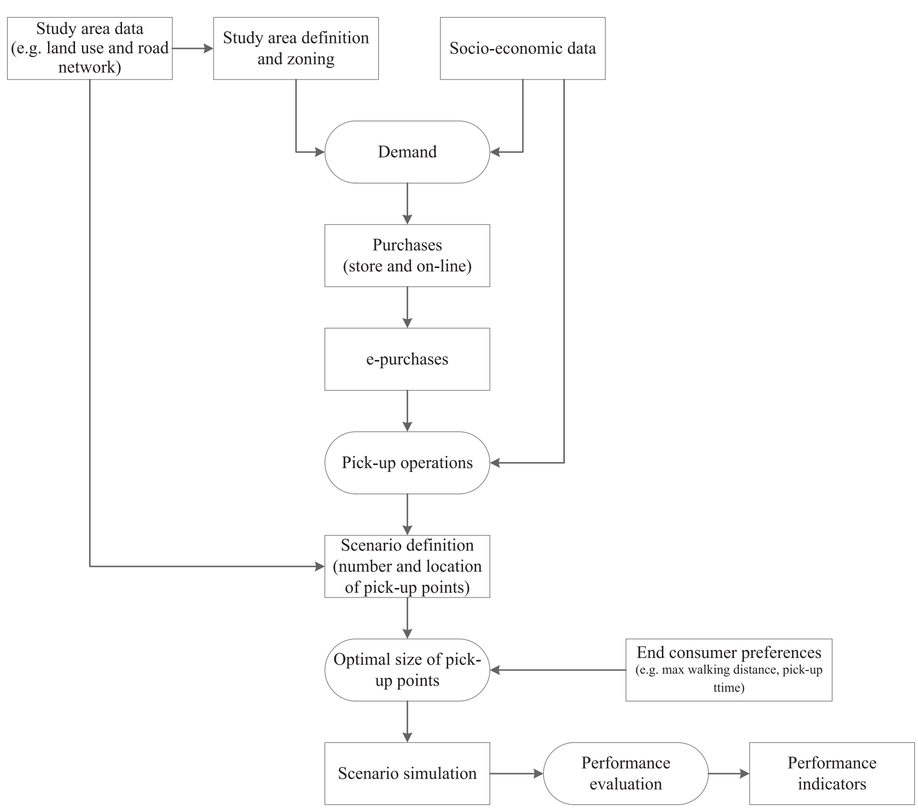

Fig. 2. The proposed methodology.

- $p^{i,s}$ *[online]* is the probability that an end consumer belonging to the category *i* made online purchases of type *s*.

The probability of making an online purchase is estimated as follows:

$$p^{i,s}[online] = p^{i,s}[purchase] \cdot p^{i,s}[online/purchase]$$

where:

- $p^{i,s}$*[online]* is the probability to purchase on line goods of type *s* by end consumer belonging to category *i*;
- $p^{i,s}$*[purchase]* is the probability to purchase goods of type *s* by end consumer belonging to category *i*;
- $p^{i,s}$*[online/purchase]* is the probability that the end consumer belonging to category *i,* conditioned to purchase on line goods of type *s*.

3.2. Definition of an optimal design scenario

The design scenario consists of defining the optimal number of pick-up points (parcel lockers) and size according to the time required by couriers to deliver (travel time and service time) and the end consumers to take their e-purchases (by means of queuing theory). Then, given a study area and the related demand in terms of deliveries, the number and the locations of pick-up points are designed in order to minimize the time spent by operators (couriers) and to guarantee an adequate level of service to end consumers (receivers). Among the constraints, it is highlighted that each zone should be served by only one pick-up point (parcel locker) and a threshold is established on the maximum walking distance accepted by end consumers.

The problem is formulated as a minimization problem, *eq. (3)*:

$$min \quad \alpha \sum_{i=1}^{n} x_i \cdot \left(t_f + \sum_{j=1}^{n} t_v \cdot d_j \cdot y_{ij} \right) + \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot y_{ij} \cdot d_j$$

s.t.

$$\sum_{i=1}^{n} a_{ij} \cdot y_{ij} = 1 \quad \forall j = 1, \dots, n$$

$$y_{ij} \leq x_i \qquad \forall i = 1, \dots, m; \forall j = 1, \dots, m$$

$$x_i \in \{0, 1\} \forall i = 1, \dots, m$$

$$y_{ij} \in \{0, 1\} \forall i = 1, \dots, m; \forall j = 1, \dots, m$$

where

- x_i is a binary variable equal to *1* if zone *i* is served by a pick-up point, *0* otherwise;
- t_f is the average stop time spent by courier delivering at each pick-up point *f*;
- t_v is the average time taken by the courier to deliver each parcel to a pick-up point *v*;
- y_{ij} is a binary variable equal to *1* if the zone *i* is served by the pick-up point located in zone *j*;
- t_{ij} is the travel time between zone *i* and *j*;
- a_{ij} is a binary variable equal to *1* if zone *i* is far less than a threshold value from zone *j*;
- d_j is the average number of deliveries to be performed in zone *j*;
- α is the homogenizing coefficient.

The objective function, *eq. (3)*, is oriented towards the minimization of the travel time, taking into account two aspects: the former is related to the service time and the stop time, the latter is related to the courier's travel time. Since such time values can be of different orders of magnitude, a homogenizing coefficient α has been introduced.

The constraint *(4)* is on the maximum distance traveled and accepted by the end consumer (from home to the pick-up point). In particular, for example, a zone *i* is served by a pick-up point located in a zone *j* only if the distance l_{ij} between *i* and *j* is less than a threshold value ℓ. Such an aspect is regulated by the variable a_{ij}. To illustrate this concept, in Fig. 3 is reported a simple case: there are *11* zones, and it is represented the distance to travel from zone *1* to the others. The radius of the circle represents the threshold value; in this example, the value of a_{ij} is equal to *1* for the origin-destination pairs *1–2*, *1–3*, *1–4*, and *1–5*, equal to *0* for all the others. The constraint *(5)* concerns the congruence of the problem variables. Finally, constraints *(6)* and *(7)* are in the domain of the variables.

After the location of the pick-up points, it is required to define their optimal size, in relation to the number of deliveries per day performed by couriers and the average time spent by end consumers to take their purchases. The assumption is that end consumers, once notified of delivery, have a given time period available to collect their items. To develop this aspect, an approach based on stochastic queues is adopted. Assuming that the arrival distribution both for couriers and end consumers follows an exponential distribution, the probability of having no slot (e.g., place in the locker available to temporally store the e-purchase) available is the following:

$$P(K > s) = \sum_{k=s+1}^{\infty} p_k = \frac{(s\rho)^s}{s!(1-\rho)} \cdot p(0),$$

while the probability that at least one slot is unavailable is:

$$p(0) = \left[\sum_{k=0}^{s-1} \frac{(s\rho)^k}{k!} + \frac{(s\rho)^s}{s!} \cdot \frac{1}{1-\rho} \right]^{-1}$$

where:

- λ is the average arrival time of the delivery;
- μ is the average time to pick up each parcel;
- $\rho = \lambda / s\mu$, it is the usage factor of slots;
- k is the number of deliveries to be placed at the pick-up point;
- s is the number of slots available to store e-purchases.

When a desired level of the service, the size of pick-up point is set in order to address such a level of service.

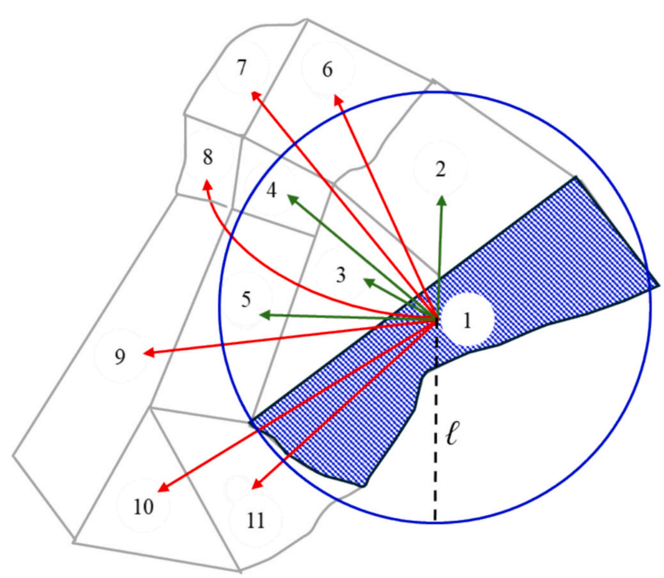

Fig. 3. Exemplification of the incidence of threshold distance.

4. Application to a real test case

The procedure proposed in the previous section has been applied in the inner area of Rome, Italy. The city of Rome, at the administrative level, is divided into 15 municipalities; a road ring surrounds the city and approximately *73%* of the population is distributed within it (Fig. 4). The findings presented in this paper are based on the results of an application in the district of Campo Marzio, a district within the *1st* municipality and the Rome Limited Traffic Zone (Fig. 5). This district, split into *90* traffic zones (Fig. 5), has *6766* inhabitants and a total surface of about *1* km^2. Some location patterns of such pick-up points are investigated, comparing transportation costs, and examining the correlation with population density, activities, and transport systems. The presented analyses showed that significant results can be obtained under the point of view of couriers/transport operators (i.e., they can consolidate and optimize their delivery tours; repeated deliveries for no-attendance of customer at home can be solved), end consumers (i.e. less expensive and non-failed delivery), collectivity (i.e., consolidated and optimized delivery tours allow traffic impacts to be reduced).

5. Models

In this section, the results of model calibration are reported, differentiated by type of freight. The considered freight classes (i.e., freight type *s*) are:

- clothing,
- electronics,
- hygiene and household products,
- other goods.

A sample of approximately 2500 people were interviewed, and the collected data are grouped into *11* groups in relation to sex, employment status, age (Table 2). For more details on the surveys carried out, readers can refer to Comi (2020).

In the calibration phase, two main alternatives are considered (Fig. 6), i.e. purchase or not purchase. If the user chooses to buy, the other two alternatives are available: purchase in store or purchase in store and online. To capture the end consumer's behavior, the choice is a function of the main characteristics (such as age, employment status, gender) and the hierarchical process depicted in Fig. 6 has been simulated. The node "to make purchases" represents a group of elementary alternatives (only in store purchases and in store and online purchases).

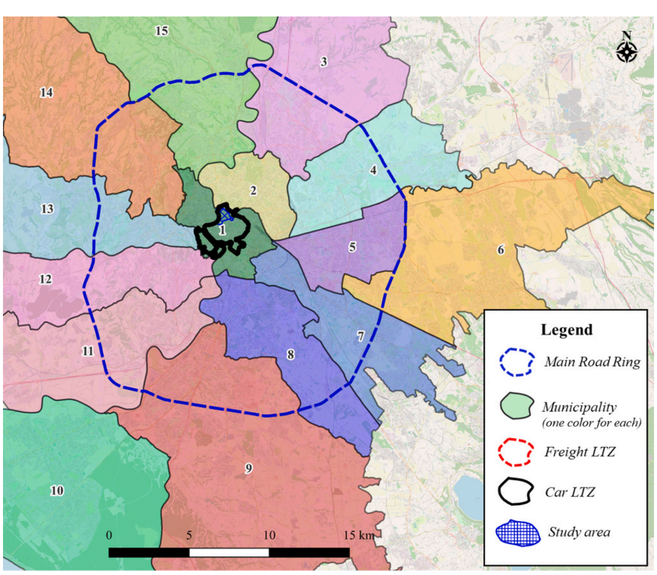

Fig. 4. Location of the study area within the city of Rome.

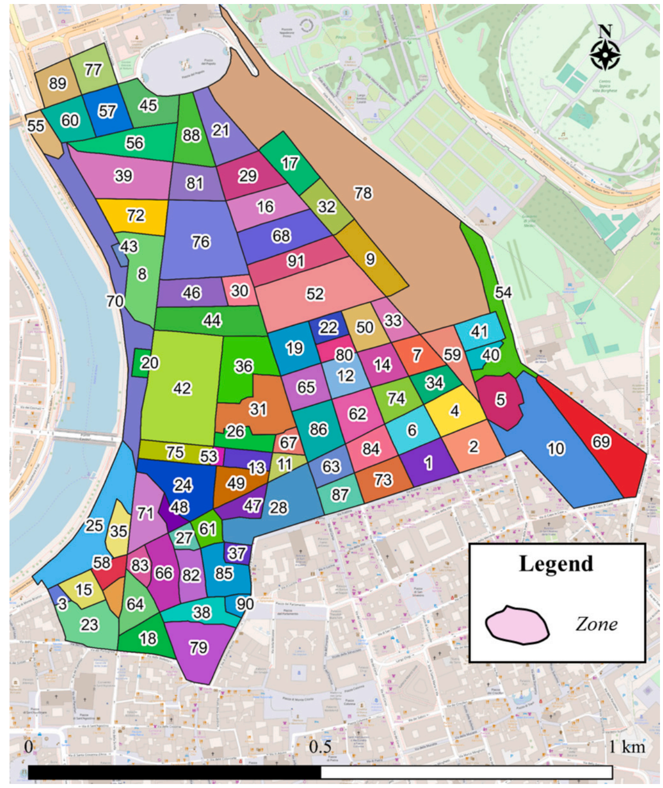

Fig. 5. Zoning the study area.

Table 2
End-consumer groups and grouping criteria.

Group	Sex	Employment status	Age
G1	male	Student	15–19
G2	female	Student	15–19
G3	male	Employed	20–44
G4	female	Employed	20–44
G5	female	Housewife	45–64
G6	male	Student	20–44
G7	female	Student	20–44
G8	male	Retired	older than 64
G9	male	Employed	44–64
G10	female	Employed	44–64
G11	female	Retired	older than 64

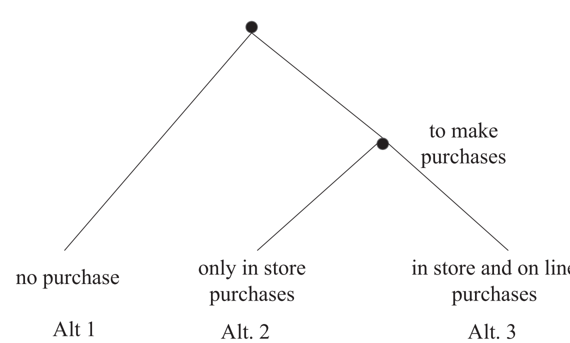

Fig. 6. Choice tree.

Starting from the root of the decision tree, the end-consumer choice whether to make a purchase or not and, in the first case, where to make the purchase, in store or on line.

The model specification has been developed using easy-to-obtain attributes in order to exploit the possibility to be used by a large floor of technicians around the world, without penalizing the model reproduction and goodness-of-fit (Table 3). The attributes used are reported in the first column of Table 3, while the second column indicates the type of attribute (e.g., if dummy or numerical variable). The calibrated parameters for clothing are reported in Table 4, and confirm the results obtained in similar literature studies (Washington et al., 2011; Comi, 2020). It emerges that women buy more in store, youngers buy online because they are friendlier with new technologies and less spending power, employees buy more online, probably they have fewer hours to shop.

The calibrated parameters for electronics reported in Table 5 indicate that men buy more in both stores and online, while students buy less in store. The results for hygiene and household products in Table 6 indicated that women and housewife buy more in store, seniors buy less online. Table 7 reports the calibrated parameters for the "other goods" class. The results emerged that males buy more both in store and online, older girls buy less both in store and online, and household members buy less both in store and online.

The calibrated models have been applied to the study area, obtaining the results reported in Fig. 7, which shows the distribution of e-purchases in relation to the different land-use and socio-economic characteristics.

6. Design scenarios

The objective of this phase is to identify the minimum number of pick-up points and their size (i.e., number of slots available for e-purchase allocation), optimizing the time spent by couriers and guaranteeing a high level of service.

The model formulated in Section 3.2, *eqs.* (3) to (7), is applied to optimize the number of pick-up points, while queue theory, *eqs.* (8) and (9), is used to optimize their size. Furthermore, the following assumptions have been introduced:

- the arrival distribution of deliveries performed by couriers and of pick-ups by end consumers follow an exponential distribution;
- the average stoppage of each parcel is *2* days (lognormal distribution with standard deviation 0.75 days);
- the desired level of service is *97*% (i.e., for the *3*% of e-deliveries there is no space available at pick-up point - no available slots);
- the maximum walking distance allowed by end consumers from home to pick-up point is 300 m.

The results indicated an optimal number of 7 pick-up points (Fig. 8), and Table 8 reports the daily demand and the optimal number of slots per pick-up point.

Finally, a comparison is made between the current situation and the design scenario. The current scenario foresees only home deliveries (attended deliveries). In relation to the design scenario, according to previous analyses carried out in the study area (Comi and Hriekova, 2024; Comi and Savchenko, 2021), it is assumed that *80*% of deliveries are unattended (i.e., at pick-up points) and the remaining *20*% are home deliveries. Each courier operator (driver) can serve each day (*7* working hours) a maximum of *20* different pick-up points, with a maximum of *50* deliveries per tour. Other assumptions are on failed deliveries (*12*%, according to the average revealed share in Europe; Visser et al., 2014) and on the number of deliveries per tour (each courier performs averagely *4* deliveries per hour). In the study area, *6* different couriers operate, with different market shares (Table 9 and Table 10).

From comparison, it emerged that the delivery time and the number of operators decrease with the pick-up system (−*43*% and − *41*%, respectively). Therefore, the system gives the opportunity to solve failed deliveries and to take less time to deliver each purchase. Furthermore, referring to delivery times, which is one of the main sources of costs supported by transport and logistics operators (*economic* sustainability), the suggested method allows for a significant reduction in delivery time, estimated in the case study of more than *43*% compared to the current scenario (home deliveries). In addition to proposing shorter routes and consolidating deliveries, trucks drive less, with significant benefits in terms of pollutant emissions (*environmental* sustainability) and

Table 3
Attributes used.

Attributes	Type
Female	dummy variable, *1* if female *0* otherwise
Male	dummy variable, *1* if male *0* otherwise
Employees (if employed)	dummy variable, *1* if employee *0* otherwise
Retired	dummy variable, *1* if retired *0* otherwise
Young (less than *20* years old)	dummy variable, *1* if young *0* otherwise
Medium (*21*–*44* years old)	dummy variable, *1* if medium-age *0* otherwise
Senior (*45*–*64* years old)	dummy variable, *1* if senior *0* otherwise
Elderly (more than *65* years old)	dummy variable, *1* if elderly *0* otherwise
Student	dummy variable, *1* if student *0* otherwise
Housewife	dummy variable, *1* if housewife *0* otherwise
Household member	numerical variable (integer)

Table 4
Calibrated parameters for clothing ($\rho^2 = 0.37$).

Attributes	Alternative 1	Alternative 2	Alternative 3
Female		0.22 *(1.63)*	
Employees		0.02 *(1.57)*	
Young			0.34 *(1.99)*
ASA	3.38 *(1.93)*	2.25 *(2.03)*	
θ = 0.48 *(2.19)*			

(−) *t*-student values.

Table 5
Calibrated parameters for electronics ($\rho^2 = 0.46$).

Attributes	Alternative 1	Alternative 2	Alternative 3
Male		1.30 *(8.93)*	1.93 *(8.42)*
Medium		0.60 *(4.05)*	0.69 *(4.30)*
Student		−0.27 *(−1.31)*	
Household member		−0.08 *(−1.26)*	−0.08 *(−1.26)*
ASA	3.08 *(5.35)*	0.53 *(1.38)*	
θ = 0.56 *(2.95)*			

(−) *t*-student values.

Table 6
Calibrated parameters for hygiene and household products ($\rho^2 = 0.45$).

Attributes	Alternative 1	Alternative 2	Alternative 3
Female		0.14 *(1.63)*	
Senior			−0.69 *(−1.99)*
Housewife		0.57 *(2.80)*	
Household member			*−0.20 (−3.07)*
ASA	3.08 *(3.29)*	2.06 *(1.75)*	
θ = 0.45 *(2.76)*			

(−) *t*-student values.

Table 7
Calibrated parameters for other products ($\rho^2 = 0.47$).

Attributes	Alternative 1	Alternative 2	Alternative 3
Male		0.70 *(5.36)*	0.70 *(5.36)*
Elderly		−0.24 *(−1.76)*	−0.24 *(−1.76)*
Retired		−0.06 *(−1.22)*	−0.06 *(−1.22)*
Household member		−0.24 *(−2.33)*	−0.24 *(−2.33)*
ASA	2.02 *(1.93)*	0.29 *(1.30)*	
θ = 0.41 *(2.89)*			

(−) *t*-student values.

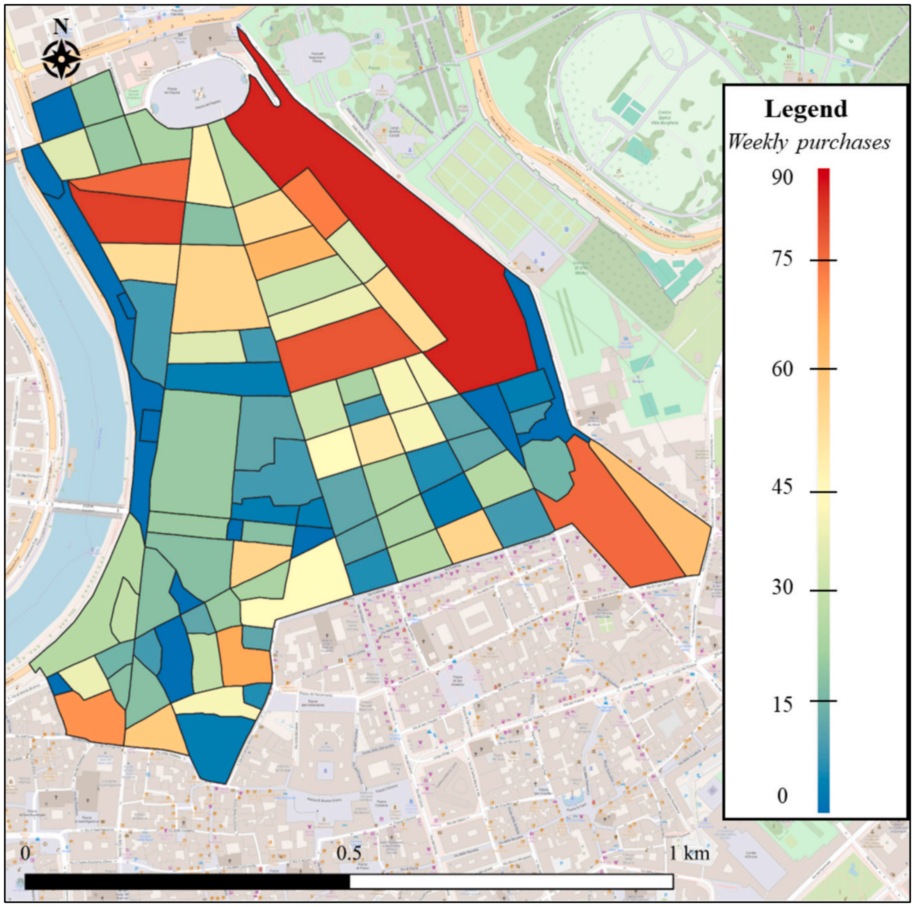

Fig. 7. Aggregate results of the model application: number of weekly e-purchases per zone.

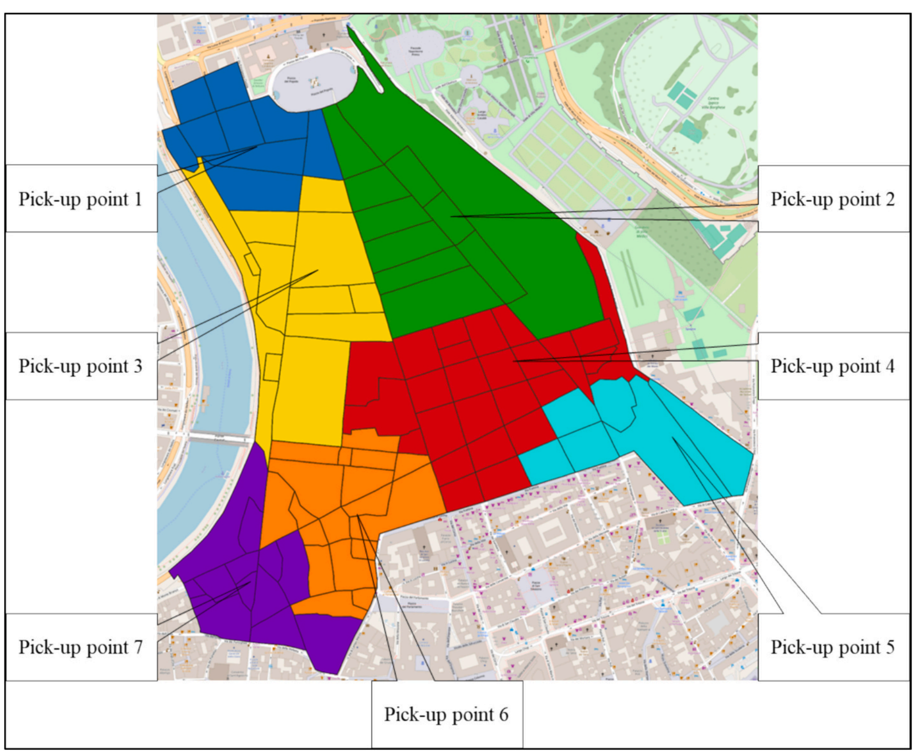

Fig. 8. Application results: position of the pick-up points (parcel lockers).

Table 8
Design of slot number.

Pick-up point / parcel lockers	Daily demand per slot	Optimal number of slots
Pick-up Point 1	22	45
Pick-up Point 2	37	78
Pick-up Point 3	12	30
Pick-up Point 4	35	74
Pick-up Point 5	17	36
Pick-up Point 6	21	43
Pick-up Point 7	18	37

Table 9
Current scenario: only home deliveries [delivery/day].

Courier [share]	Daily deliveries [delivery/day]	Hours required to deliver [h]	N. of drivers
A (*28%*)	63	15.8	3
B (*18%*)	41	10.2	2
C (*17%*)	39	9.6	2
D (*14%*)	32	7.9	2
E (*14%*)	32	7.9	2
F (*9%*)	20	5.1	1
Total	**226**	**56.6**	**12**

Table 10
Design scenario: pick-up points system and home delivery.

Courier [share]	Daily deliveries* [delivery/day]	Hours required for delivering$^{(\#)}$ [h]	N. of drivers
A (*28%*)	45 + (13)	6.34 + (3.25) = 9.59	2
B (*18%*)	29 + (7)	4.08 + (1.75) = 5.83	1
C (*17%*)	28 + (6)	3.85 + (1.5) = 5.35	1
D (*14%*)	23 + (5)	3.16 + (1.25) = 4.41	1
E (*14%*)	23 + (5)	3.16 + (1.25) = 4.41	1
F (*9%*)	15 + (3)	2.04 + (0.75) = 2.79	1
Total	**202**	**22.63+ (9.75) = 32.38**	**7**

(*) the numbers in brackets are at home deliveries - ($^{\#}$) the numbers in brackets are for the time to perform at home deliveries.

interferences with other road users (*social* sustainability). Finally, in such a case study, comparing the number of operators needed to perform home deliveries, there is a significant further reduction in the operational costs for operators (i.e., −*41*%).

7. Discussion

The sustainable development goal 11 (sustainable cities and communities) of Agenda 2030 provided by the United Nations (United Nations, 2021) aims to make cities more sustainable. Considering sustainability in economic, environmental, and social terms, here are some indications on how the results obtained in the previous section can help identify policies (and good practices) to help achieve this objective.

From an *economic* point of view, policies aimed at implementing pick-up points can reduce the number of failed deliveries (because the recipient is not at home); such a system could also reduce costs for operators who would make deliveries to a number of points (pick-up points) lower than the number of customers.

From an *environmental* point of view, pick-up points can reduce the number of kilometers traveled by commercial vehicles, with a consequent reduction in emissions and noise. Reducing travel time can push the operators to adopt electric vehicles with significant environmental benefits for local areas.

Furthermore, given that users can have access to their deliveries 7/7 days and 24/24 h (automated) or for a large portion of the day, it limits the end consumers' anxiety to receive e-purchases, while on the other hand, operators can deliver at each pick-up point, avoiding the peak hours with significant operational cost savings and contributing to the reduction of congestion and interferences with other city users (high *social* and economic benefits).

8. Conclusions and further development

The impact of internet on real life is modifying the end consumers behavior, pushing them towards online shopping. One of the results is an increase in the number of daily deliveries carried out by couriers to end consumers' homes, sometimes with negative effects on the livability of cities (e.g., congestion because of the interaction between freight vehicles and cars). To provide an alternative to home delivery, this paper focused on the implementation of the pick-up (parcel locker) network. Through such a system, the couriers make deliveries at pick-up points and, afterwards, the user collects the parcel by her/himself. The position and size of pick-up points have to be designed in order to guarantee the user's satisfaction (at the desired level of service) and meet the demand, as well as to limit the travels undertaken by end consumers for collecting their e-purchases. For these reasons, in the paper two main points have been developed:

- the estimation of a demand model to simulate the number of deliveries per day;
- a design model to optimize the location and the size of the pick-up points taking into consideration that users can have different time windows for collecting their purchase and preferences in reaching the pick-up point.

Therefore, such a methodology can contribute to the improvement of the efficiency of the delivery system, including a more optimized location of pickup / parcel lockers, as well as a reduction of the traffic impacts due to the optimized driving mileage and time. The proposed methodology has been tested on a real case study, and the benefits that can be obtained from such a system are discussed. The findings are based on the results of an application to a district within the Rome Limited Traffic Zone, and two scenarios are compared in terms of transportation costs. The analysis showed that significant results can be obtained from the point of view of:

- couriers/transport operators (i.e., they can consolidate and optimize their delivery tours; repeated deliveries for no-attendance of customers at home can be solved),
- end consumers (i.e., less expensive and non-failed delivery),
- collectivity (i.e., consolidated and optimized delivery tours limit traffic impacts).

The further developments of this study refer mainly to the improvement of the model for demand simulation (including additional attributes in the utility specification and developing further specifications able to take into consideration correlation among the identified alternatives, e.g., mixed logit), the analysis of the user's willingness to accept such a system, the evaluation of including further transport impact indicators from the point of view of end consumers, couriers and collectivity, an improved approach to modeling couriers' tours (e.g., with real data). In addition, the methodology could be extended to consider electric vehicles (this implies the introduction of new constraints in the optimization problem). Finally, advancement could consider modifying the methodology to use mobile parcel lockers. In this case, the parcel locker position would change over time, and the time spent in a position would be an additional variable in the problem.

CRediT authorship contribution statement

Antonio Comi: Supervision, Conceptualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Software, Visualization, Writing – review & editing. **Antonio Polimeni:** Methodology, Investigation, Data curation, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

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Data availability

The data that support the findings of this study are available from the Department of Enterprise Engineering, University of Rome, on reasonable request.

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