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Parcel Delivery with Drones: Multi-criteria Analysis of Trendy System Architectures

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***Abstract*— New technologies, such as Unmanned Aerial Vehicles (UAVs), are transforming facilities and vehicles into intelligent systems that will significantly modify logistic deliveries in any organization. With the appearance of automated vehicles, drones offer multiple new technological solutions that might trigger different delivery networks or boost new delivery services. Differently from the related works, where a single specific delivery system model is typically addressed, this paper deals with the use of UAVs for logistic deliveries focusing on a multi-criteria analysis of trendy drone-based system architectures. In particular, using the cross-efficiency Data Envelopment Analysis approach, a comparative analysis among three different delivery systems is performed: the classic system based on trucks only, the drone-only system using a fleet of drones, and the hybrid truck and drone system combining trucks and drones. The proposed technique constitutes an effective decision-making tool aimed at helping delivery companies in selecting the optimal delivery system architecture according to their specific needs. The effectiveness of the proposed methodology is shown by a simulation analysis based on a realistic data case study that pertains to the main logistic service providers.**

***Index Terms*— UAVs, Drones, Parcel delivery, Multi-criteria decision making, Data Envelopment Analysis.**

I. Introduction

In the field of logistics, the concept of last-mile refers to the delivery of items form a logistic hub to its final destination (i.e., customers) and it is the most expensive segment in distribution logistics, ranging from 13% to 73% of the total distribution cost [1]. The last-mile delivery has recently become more challenging due to the continuous growth of online commerce and the exponentially increasing demand of same-day deliveries [2]. These trends cause several negative externalities, such as the presence of high amount of vehicles on the urban road infrastructure, with consequent impacts on congestion, noise, and CO_2 emissions in urban areas [3].

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To cope with these issues, both in the academic literature and in the commercial sector several multi-faceted solutions have been proposed, including the use of more beneficial delivery vehicles. For instance, using electric vehicles allows reducing noise and CO_2 emissions. In order to alleviate also traffic congestion, fleets of drones are considered as a possible solution to last-mile delivery transport. In addition, the use of drones allows reducing delivery time and delivery costs, resulting in a remarkable investment for delivery companies. In particular, the commercial sector is aiming at defining novel and efficient architectures for parcel delivery systems. The aim is to ensure an efficient and cost-effective transportation mode that can be used combined with or as an alternative to the full truck delivery. For instance, in 2013 Amazon announced the deployments of its first drones to ship small packages, called parcels [4]. The Amazon's drone delivery service, Prime Air [5], is a drone-only delivery system, for which the company proposes the use of an octocopter for the transportation of a parcel. Despite limiting constraints such as a lower payload capacity (2.3 kilograms) and autonomy time (30 minutes) with respect to classical vehicles, drones have positive benefits on the delivery process by reducing lead time, makespan, and transportation cost. Differently, the Workhorse company proposes a hybrid architecture where drones and trucks cooperate. In particular, the drone can depart/land from the top of a truck and delivers the parcel to final customers [6]. Similar systems are the "Project Wing" of Google, the "Parcelcopter" of DHL, and a system created in cooperation between the Swiss Post and the startup Matternet [7].

As for the literature contributions, the majority of works aim at addressing the Unmanned Aerial Vehicles (UAVs) design and their routing and coordination under a technological innovation perspective. In particular, in [8] and in [9] the problem of transporting a payload connected by means of a cable to a UAV is analyzed, proposing different control lows to minimize the oscillations of the parcel. The work in [10] aims at improving the design of UAVs for the delivery sector, focusing on the management of the UAV battery so as to minimize the electricity consumption and reduce the delivery time. Differently, in [11] the authors focus on UAVs' routing problems to minimize delivery costs and time. Finally, a prototype system for delivering goods by autonomous drones is presented in [12].

As it emerges from the literature review, there is a lack of contributions that propose an effective decision-making technique to support delivery companies in optimally se-

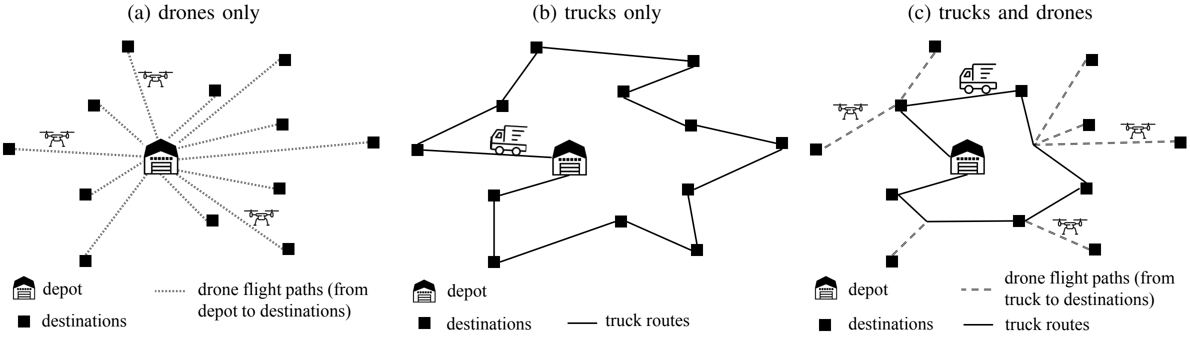

Fig. 1. Schematic overview of the three analyzed architectures.

lecting the delivery system architecture (that is, the most efficient one for their organization and according to the specific needs).

This paper aims at fulfilling this gap by proposing the application of a Multi Criteria Decision Making (MCDM) technique to compare and rank different parcel delivery systems. In particular, we propose the use of the cross-efficiency Data Envelopment Analysis (DEA) approach [13], that is a well-known mathematical method in the class of MCDM techniques, able to support the decision-making process in the presence of a large amount of data, often heterogeneous and typically conflicting each other. Among the existing MCDM approaches, DEA is one of the most commonly adopted techniques, thanks to its rigorous mathematical formulation [14]. In addition, DEA allows considering both quantitative and qualitative data at the same time. Finally, thanks to its flexibility, DEA can be used in different situations and with different purposes [15]. However, DEA lacks in discriminating among the efficient Decision Making Units (DMUs), since it is typically used to evaluate how far a single DMU is from the Pareto-optimal efficiency frontier. To overcome this limitation, several methods exist, among which the cross-efficiency evaluation [16] is one of the most commonly adopted approaches [17]. The aim is to assess each DMU by all the weights of the other DMUs (in addition to its own weights), thus providing a relative efficiency value. Hence, here we propose the application of the cross-efficiency DEA to perform a comparative analysis among three parcel delivery systems (i.e., the classic system based on trucks only, the system using drones only, and the truck and drone system combining trucks and drones) to support logistics decision makers in evaluating and comparing the different alternatives in terms of investment costs, CO_2 emissions, energy consumption, delivery time, and maximum reachable distance.

II. The Proposed Architectures: a Multi-criteria Analysis Framework

In this section we first present the three parcel delivery architectures that, according to the state of the art, can be implemented in the freight logistics sector. Subsequently, we introduce the basic concepts of the cross-efficiency Data Envelopment Analysis approach.

A. Parcel Delivery Systems Architectures

The two considered architectures of the drone delivery system are based on two projects: (1) the Prime Air project developed by Amazon (Fig. 1.a), to which we refer as a drone only delivery system architecture [5]; and (2) the truck and drone delivery project developed by AMP Electric Vehicles and the University of Cincinnati (Fig. 1.b), combining an electric truck with a fleet of drones, to which we refer as a hybrid truck and drone delivery system [18]. Both architectures are alternatives to the classic full-truck delivery system (Fig. 1.c), where the truck departs from a depot and delivers the parcels to the scheduled customers following a predetermined route.

The drones only delivery system architecture (Fig. 1.a) is based on a completely autonomous shipping service, needing no human intervention during the shipping of parcels. In particular, the system is based on small drones that can deliver parcels weighting up to five pounds, with a delivery time equal to 30 minutes or less. Drones depart from a common depot and serve customers once at a time. The main actors involved in this system are: the costumer, who makes the order through PC/Mobile, the warehouse manager, who ensures the entire and correct flow of materials through an organization server and warehouse PC, and the drone manager, a new job figure, who deals with the management of the drone - identifying early signs of potential problems, having 360 degrees view of aircraft and flight, recommending proactive maintenance, reporting and tracking services performed, generating customized operational reports, meeting regulatory reporting requirements, getting notified of potential problems and setting thresholds on key indicators. The involved devices are the costumer PC/Mobile, the organization server, the delivery drone, the drone fleet Management Software, the warehouse PC and External Notification Service, and the taking off/landing station and charging stations for the drone. This means that an organization needs additionally to build them. As reported in [19], a drone only delivery system requires three systems to manage the delivery activities and related information, detailed as follows.

System 1 allows a client to place an order from a personal device to the warehouse ERP (Enterprise Resource Planning) system following the steps reported below:

- a client places an order and the related information is transferred from the device to the organization's server;
- the organization transfers information about the order to its store;
- an employee places the order in the drone and sends it off and then enters the information about drone parcel delivery status into the ERP system (e.g., order 'x' is shipped with drone 'y');
- the warehouse ERP system transfers information about the order being shipped to the organization, which, in turn, transfers the order status to the client device.

System 2 manages the interaction between the drone and the organization server as follows:

- the commercial drones are GPS-navigated and connected with the server. The drone sends the information about its current location during the delivery service;
- the organization checks the server at a preset time interval (e.g., every 30 seconds) and receives the data about the drone location, calculating the remaining distance from the destination location.

System 3 manages the integration of an external notification service with the organization as follows:

- as soon as the organization receives the information from the server that the drone is, for example, 5 minutes away from the destination, it passes the data to the external notification service. The external notification service sends notifications to the user about the package status. Notifications may vary: they can be push notifications, SMS, notifications sent to the browser, etc;
- once the external notification service receives the information about the order status from the organization, it sends a notification to the client.

The hybrid truck and drone delivery system architecture (Fig. 1.b) is particularly useful when the distribution center is located far from the customers. In this type of architecture, the delivery service is performed by combining the use of drones with electric delivery trucks. At first, the delivery truck departs from the depot carrying a drone and all the parcels to deliver. The truck and the drone work in parallel: the drone is launched from the truck, and it delivers parcels to individual customers, meanwhile the truck proceeds on its route and delivers parcels to scheduled customers.

The main actors involved in the hybrid system are: the costumer, who places an order though PC/Mobile, the warehouse manager, who ensures the entire and correct flow of materials through an organization server and warehouse PC; since the drone is autonomous, it does not need any intervention from the truck driver, who is required only to load parcels, replace batteries, recover the drone, and drive the truck. The devices necessary to perform the service are the delivery drone, the truck charging docking station implemented for the drone, a drone fleet Management Software, and an External Notification Service to communicate with the costumer. Eventually required further infrastructures are: a parking area dedicated to the truck and a take off/landing station, plus charging stations for the drone.

In the hybrid system, the delivery process follows the steps reported below:

- the truck delivery driver loads the package and launches the drone from the truck through the Management Software;
- the drone autonomously departs from the roof of the delivery truck, proceeding to the delivery location;
- at the delivery location, the drone automatically descends and delivers the parcel;
- the drone returns to the truck at a planned stop and autonomously re-docks and recharges for its next delivery;
- while the drone is performing the respective delivery service, the truck follows its own route to deliver the parcels to the next scheduled customer. Then the drone and the truck meet at the subsequent location [20].

To avoid uncertainties in the delivery process performed by the drone, GPS and GSM can be interfaced with the drone. In particular, GSM is used for security issues, i.e., when the drone reaches the destination, the customer must provide a pass-code to allow the drone discharge the package; if this activity is not executed the customer receives a message notifying the failure of the delivery [21].

B. *The Cross-Efficiency Data Envelopment Analysis*

DEA is a non-linear programming technique aimed at computing the efficiency of homogeneous operating units, called Decision Making Unit (DMU). Let us consider a set of n DMUs (in our case the alternatives) to be evaluated on the basis of m input criteria (i.e., non-beneficial parameters, to be minimized) and s output criteria (i.e., beneficial parameters, to be maximized). Denote by x_{ij} $(i = 1, \dots, m)$ and y_{rj} $(r = 1, \dots, s)$ respectively the generic i-th positive input and r-th positive output criteria for the j-th DMU $(j = 1, \dots, n)$.

For each DMU its efficiency is defined as the ratio between the weighted sum of the outputs and the weighted sum of the inputs; such a score has to be maximized as follows:

$$E_j = \max \frac{\sum_{r=1}^{s} u_{rj} y_{rj}}{\sum_{i=1}^{m} v_{ij} x_{ij}} \tag{1}$$

$$\text{s.t.:} \quad \sum_{r=1}^{s} u_{rj} y_{rk} / \sum_{i=1}^{m} v_{ij} x_{ik} \leq 1, \; k = 1, \dots, n \tag{2}$$

$$u_{rj} \geqslant 0, \; \forall r = 1, \dots, s \tag{3}$$

$$v_{ij} \geqslant 0, \; \forall i = 1, \dots, m. \tag{4}$$

Hence, for the j-th DMU the problem (1)-(4) is to determine the non-negative weights u^*_{rj} and v^*_{ij} so that efficiency is maximized, while being lower than or equal to 1.

The fractional non-convex problem (1)-(4) can be linearized through an input-oriented formulation, by minimizing the weighted sum of the input criteria while keeping fixed and equal to 1 the weighted sum of the outputs, as follows:

$$g_j = \min \sum_{i=1}^{m} v_{ij} x_{ij} \tag{5}$$

$$\text{s.t.:} \quad \sum_{r=1}^{s} u_{rj} y_{rj} = 1 \tag{6}$$

$$-\sum_{r=1}^{s} u_{rj} y_{rk} + \sum_{i=1}^{m} v_{ij} x_{ik} \geqslant 0,\ k = 1, \ldots, n \tag{7}$$

and eqs. (3)-(4).

The efficiency value is then computed as follows:

$$E_j = 1/g_j,\ \forall j = 1, \ldots, n. \tag{8}$$

A DMU is efficient if it achieves an efficiency score equal to 1, otherwise, it is inefficient. The efficient DMUs act as a benchmarking standard for future improvements.

Despite its simplicity, the above model has a relevant drawback, due to the lack of ability to discriminate between efficient DMUs. In effect, the DEA technique is typically used for preliminary self-assessments (i.e., a single DMU evaluates how far it is from the Pareto-optimal efficiency frontier). When just few DMUs are to be assessed against a high number of criteria, other variants of the classical formulation are typically adopted [15]. In particular, among such variants, we consider the so-called cross-efficiency evaluation [16]. According to this method, each DMU is also assessed by all the weights of the other DMUs (in addition to its own weights). More in detail, as shown in Table I, a cross-efficiency matrix is determined. First, the diagonal elements are computed by solving n optimization problems (5)-(8) (that is, $E_{jj} = E_j$). Then, the remaining $n(n-1)$ efficiency values are obtained by using for each k-th DMU (with $k \neq j$) the weights obtained as a solution of problem (5)-(8) for the j-th DMU. Hence, denoting these optimal weights as u^*_{rj} ($\forall r = 1, \ldots, s$) and v^*_{ij} ($\forall i = 1, \ldots, m$), the following efficiency values are then computed:

$$E_{jj} = \frac{\sum_{r=1}^{s} u^*_{rj} y_{rj}}{\sum_{i=1}^{m} v^*_{ij} x_{ij}}, \forall j = 1, \ldots, n \tag{9}$$

$$E_{kj} = \frac{\sum_{r=1}^{s} u^*_{rj} y_{rk}}{\sum_{i=1}^{m} v^*_{ij} x_{ik}}, \forall k = 1, \ldots, n, k \neq j. \tag{10}$$

Overall, n relative efficiency measures are obtained for each DMU, constituting a cross-efficiency $n \times n$ dimensional matrix reported in Table I.

Finally, the cross-efficiency value of the j-th DMU can then be computed as the mean value of the relative efficiencies E_{kj} ($k = 1, \ldots, n$):

$$\bar{E}_j = \frac{1}{n} \sum_{k=1}^{n} E_{kj},\ \forall j = 1, \ldots, n. \tag{11}$$

III. Case Study

In this section we show the effectiveness of the proposed technique. In particular, we consider the case of a logistics service provider company that aims at optimally selecting the most efficient delivery system architecture for its own organization. The alternatives are defined as follows: 1) the trucks only parcel delivery system, which is composed of a single diesel truck; 2) the drones only system, and 3) the hybrid truck and drone system, which is composed of an electric truck and a drone. We assume that the logistics company interested in developing the delivery architecture is equipped with an ERP system, which allows managing the whole delivery process. We also assume that the truck is diesel powered with a capacity of 1495 kg and 80 liter tank [22], the delivery drone is equipped with a LiPo battery 6S or 10S of 37 V and 10,000 mAh [5], and the e-truck is equipped with a battery LiFePo4, 2 x 120kWh, 400 V [23].

TABLE I

The cross-efficiency matrix.

Cross-efficiencies	DMU 1	DMU 2	...	DMU n
DMU 1	E_{11}	E_{12}	...	E_{1n}
DMU 2	E_{21}	E_{22}	...	E_{2n}
DMU 3	E_{31}	E_{32}	...	E_{3n}
⋮	⋮	⋮	⋮	⋮
DMU n	E_{n1}	E_{n2}	...	E_{nn}
Mean cross-efficiencies	$\bar{E}_1$	$\bar{E}_2$	...	$\bar{E}_n$

The case study refers to the metropolitan city of Bari, in the Southern Italy. Since the analysis refers to urban logistics, we assume that the depot is located in the industrial area of the city. We consider three different groups of customers, which are located in three different areas, within a 12 km distance from the depot (so that the autonomy of drones is ensured). Without loss of generality, we assume each group includes four customers. Zones 1 and 3 are within the city of Bari, respectively on the north-west and in the south-east sides of the city, while zone 2 is a nearby town within the metropolitan area and located south-west of the city. Figure 2 shows the required routes for each of the three delivery systems; in particular, Fig. 2 (a) shows the route of the truck only system, Fig. 2 (b) those of the drones only system, and Fig. 2 (c) those of the hybrid system. For system 1) and 3) we assume that the capacity of the trucks is sufficient to serve all the considered customers. Conversely, in system 2), due to the weight limitations, a fleet of drones (or a single drone going back and forth) is assumed to be available.

In order to (1) evaluate the efficiency of the considered alternatives under different and conflicting criteria, and (2) obtain a ranking of the considered delivery systems, thus supporting the company in selecting the most appropriate alternative, we implement the cross-efficiency DEA analysis described in Section II.B. Table II reports the set-up data for the considered case study. More in detail, column I shows the DMUs under analysis (i.e., the three considered delivery systems), column II shows the corresponding index of the DMUs, columns from III to VI show the values of the corresponding input criteria (that is, parameters to be minimized), namely: x_{1j} is the overall travelled distance [km]; x_{2j} is the corresponding operating cost [€]; x_{3j} the total CO_2 emissions [tons CO_2^{eq}]; x_{4j} the required delivery time [min]. Finally, columns from VII to X show the selected output criteria (to be maximized): y_{1j} is the customer satisfaction [Likert scale, [24]]; y_{2j} is the reliability of the delivery system [Likert scale, [24]] (e.g., to take into account that adverse weather conditions may limit the possibility of using drones); y_{3j} and y_{4j} respectively represent the maximum allowed weight per parcel [kg] and volume per parcel [m^3]. Note that such evaluating criteria are selected

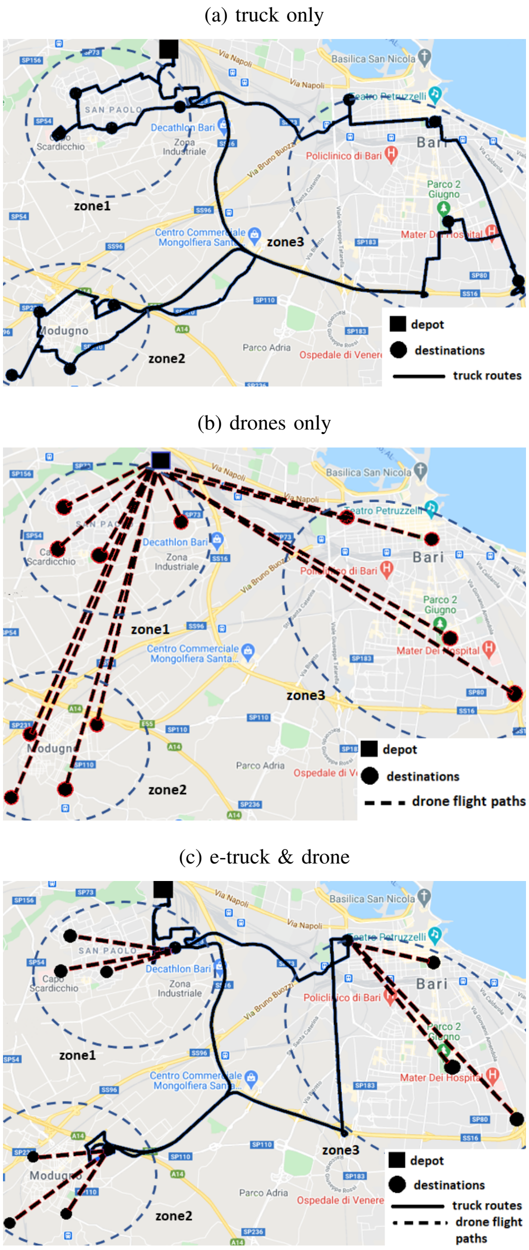

Fig. 2. Overview of connections among zones: the route using a full-truck (a), drones only (b), and the e-truck & drone (c).

based on a survey conducted over 200 logistics companies in the considered area.

As for the estimation of the values assumed by the above criteria, the x_{1j} inputs (for j=1,2,3) are calculated on Google Maps [25]. In particular (see Fig. 2), the routes of the truck only system are determined solving a classical vehicle routing problem, those of the drones only system are determined by directly connecting the depot with each client, while the routes of the hybrid system are computed by assuming that, for each zone, the truck stops in the closest client to the depot and the remaining customers are visited by the drone. As for the operating costs (i.e., x_{2j}), for DMU 1 we consider a diesel-powered truck, which consumes 0.11 [l/km] [22] of fuel, with an average cost of 1.56 [€/l] [26]; for DMU 2 we assume the battery capacity of each drone equal to 0.0154 [kWh/km], and an industrial cost of electricity (in Italy) equal to 0.15 [€/kWh] [27]; finally, for DMU 3 we assume the truck and drone system is composed by an electric truck, whose battery capacity is 0.9 [kWh/km] [23], with the same electricity cost as above. The CO_2 emissions (i.e., x_{3j}) are computed based on the total travelled distances in x_{1j}. In particular, the CO_2 emissions for the diesel-powered truck (that is, DMU 1) are determined using the EcoTransIT computation tool [28]; for DMU 2 (i.e., drones only) the CO_2 emissions are 80% lower than those of the truck only system [29]; finally, for DMU 3 (i.e., the e-truck & drone system), the CO_2 emissions are 55% lower than those of the truck only system [30]. The delivery time (i.e., variables x_{4j}) is estimated using the Google Maps website. In particular, the delivery time of the truck only system corresponds to the traveling time reported in Google Maps; the delivery time of the drones only system is determined by dividing the total travelled distance by the average drone speed of 80 km/h [5]; while for the hybrid system the two approaches are suitably combined according to the corresponding routes.

As regards the output criteria, both the customer satisfaction (i.e., y_{1j}) and the reliability criterion (i.e., y_{2j}) are based on a subjective evaluation quantified by means of the Likert scale [24], where values from 1 to 4 respectively correspond to poor, good, very good, and excellent evaluations. As for the maximum allowed weight for each parcel (i.e., variables y_{3j}) and the maximum allowed volume per parcel (i.e., y_{4j}) we consider the standard weight and dimensions admitted in [5] for all the architectures.

Based on the data in Table II, the cross-efficiency DEA method is applied to assess and rank the efficiencies of the considered systems according to eqs. (5)-(8) and eqs. (9)-(11). The corresponding linear programming problems are solved in MATLAB R2021a, requiring just few seconds for the considered case study. The obtained results are reported in Table III, which collects the cross-efficiency matrix, the final cross-efficiency values (in the second-last row), and the corresponding ranking (in the last row).

Table III shows that the hybrid truck and drone system is the most efficient architecture, which guarantees a low delivery time, without limiting dimensions and weights of the parcels. The second ranked system is the truck only delivery, which is penalized by the high operating costs and CO_2 emissions. The drones only system is ranked as the worst architecture, due to the maximum allowed weight and volume for each parcel. It is to be noticed that drones with higher capacity in terms of weight and volume are available in the market. Clearly, this will affect the obtained results, which can largely vary depending on the specific features of the devices and systems adopted for each logistics architecture. Also note that, given the low computation time of the presented methodology, other scenarios (e.g., when varying the number and locations of customers, and/or the systems' characteristics) can be easily analyzed, thus providing the decision makers with a useful tool for what-if analysis.

TABLE II

SCENARIOS SET-UP.

DMU	j	x_{1j} Overall traveled distance [km]	x_{2j} Overall operat. cost [€]	x_{3j} CO_2 emissions [tons CO_2^{eq}]	x_{4j} Delivery time [min]	y_{1j} Custom. Satis. [Likert Scale]	y_{2j} Reliability [Likert Scale]	y_{3j} Weight per parcel [kg]	y_{4j} Volume per parcel [m^3]
Truck only	1	51	8.75	0.0032	167	2	4	12	0.04
Drones only	2	116	0.27	0.0006	147	4	2	2.3	0.01
E-truck & drone	3	72	4.02	0.0017	135	3	3	12	0.04

TABLE III

CROSS-EFFICIENCY EVALUATION MATRIX.

Cross-efficiencies	Truck only	Drones only	E-truck & drone
Truck only	1	0.19	1
Drones only	0.02	1	0.05
E-truck & drone	0.81	0.23	1
Mean cross-efficiencies	0.61	0.47	0.68
Rank	2	3	1

IV. CONCLUSIONS AND FUTURE WORKS

This paper proposes the application of a multi-criteria decision making technique to evaluate the efficiency of alternative delivery system architectures. The aim is to support logistic service providers in comparing and assessing the efficiency of novel delivery systems based on unmanned aerial vehicles with respect to the classical truck-based ones. The effectiveness of the proposed methodology -based on the cross-efficiency Data Envelopment Analysis- is shown through a realistic data case study that performs a comparative analysis among three different delivery systems: the trucks only parcel delivery system (i.e., a single diesel truck), the drones only system, and the hybrid truck and drone system (composed by an electric truck and a drone). Upon suitably identifying and correctly evaluating a set of pertaining criteria, the approach turns out to be a powerful guideline for delivery companies in automatically selecting the most efficient delivery system architecture for their own organizations and according to their specific needs.

Future works will extend the decision model to take into account additional evaluating criteria and the uncertainty that affects the decision parameters.

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