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Last-mile delivery by automated droids. Sustainability assessment on a real-world case study

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ABSTRACT

This paper presents the outcomes of the sustainability assessment of a last mile delivery service introduced in a real-world case study. The methodology used integrates multi criteria decision making analysis, sustainability pillars and scenario analysis to best reflect the conflicting needs of stakeholders involved in the last mile delivery system. The case study provides an application of the framework to the delivery system of the Joint Research Centre of the European Commission where six alternative solutions were analysed and compared: i) the existing service using a manually-driven Euro 4 light commercial vehicle (LCV); ii) the same service using a Euro 6 LCV; iii) the same service using an electric LCV (eLCV); iv) a service composed by an automated delivery droid (robot) coupled with a Euro 4 LCV; v) a service with the delivery droid coupled with a depot station; and vi) a service with the delivery droid coupled with the eLCV.

The results show that low-capital investment in delivery droids could lead to significant savings on the operational costs, whilst improving the environmental performance of the system. Nevertheless, there are potential social sustainability shortcomings in terms of safety and equity.

1. Introduction

Demand for logistic services in our cities is said to continue to increase, due to shift toward business to consumer (B2C) e-commerce, intensified by the current Covid-19 pandemic (COVID-19 Impact on e-Commerce & Online Payments, Worldwide, 2020). As compared to the traditional offline market, e-commerce creates new issues for the companies as well as other stakeholders– the main one being the complexity of logistics, and in particular the last-mile delivery, aimed at delivering the products from the transport hub to the final customer (Allen *et al.*, 2018). The last mile is the least efficient leg of the delivery process, making it the most expensive for the companies, because of challenging target service levels, the small dimension of orders and the high level of dispersal of destinations (Macioszek, 2018). Apart from operational complexity, there are numerous environmental and social externalities related to last-mile delivery, Ranieri et al., (2018), point at air pollution, greenhouse gas (GHG) emissions contributing to climate change, noise pollution, infrastructure wear and tear, congestion and road accidents among others. Therefore, it's of vital importance to thoroughly assess and estimate the impact that innovation in last-mile delivery could have on cities, before their implementation.

This work aims to lay out a multiple-criteria decision making analysis (MCDA) framework altered for sustainability assessment of innovation in the last mile delivery and apply it to real case study. The framework was adapted to investigate and assess the conflicting needs of the system stakeholders. The authors hope that it could be used by regional policymakers and service providers, as decision making support tool for planning and development of future, carbon neutral transport system. Moreover, the study includes an application of the framework to the last-mile delivery system of the Ispra site of the Joint Research Centre (JRC) of the European Commission in Italy. The case study lays out and assesses six alternatives of handling the postal services: i) currently used Euro 4 light commercial vehicle (LCV), ii) Euro 6 LCV, iii) electric LCV, iv) delivery droid (robot) coupled with Euro 4 LCV, v) delivery droid coupled with a depot station and vi) delivery droid coupled with eLCV. The assessment is one of the first studies to investigate automated delivery droids, which could become a frequent addition to the urban landscape in the near future.

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The analysis is structured as follows, first, the literature review of the topic is given, following with the steps required for the assessment support framework and implementation methodology. In the following chapter, results of the analysis concerning last mile delivery system are presented, with discussion and policy impact and conclusions as subsequent chapters.

2. Literature Review

Last mile logistics is part of a complex freight transport system interrelated with a variety of urban ecosystems. In order to increase efficiency and support growing environmentally conscious movements, numerous companies already use solutions such as tricycles or bicycles (also known as cargo bicycles) and alternatively fuelled vehicles (mainly electric or hybrid LCVs) or even vehicles typically reserved for movement of people such as trams (Pietrzak & Pietrzak, 2021), with further concepts of light freight railway (Pietrzak et al., 2021). Moreover, high grossing companies (such as Amazon, DHL or Google) or entirely new start-ups (such as Starship or Yape) have started to test out innovative solutions like unmanned aerial vehicles (also known as drones) and automated droids moving on land (Shaheen & Cohen, 2020).

With last mile delivery gaining significance, researchers have turned their interest towards its broad impacts. A literature review conducted by Kiba-Janiak et al., (2021) suggests that, before the popularization of e-commerce in 2016, a limited number of studies focused on optimising traditional last-mile solutions, whereas, after 2016 and the establishment of the e-commerce industry, a steeply growing number of academics focused on introduction and analysis of innovation in last mile delivery solutions. A further study connecting external factors impact on e-commerce and following environmental implications was proposed by Cheba et al., (2021). The authors found a link between internet and mobile access, macroeconomic conditions and social situation and the degree to which shopping is made online, confirming the complexity of future freight demand.

As new mobility solutions have been proposed, studies to assess their potential impacts have also started to appear. Literature proposes a variety of tools and methods for impact assessment, starting with Life Cycle Assessments (LCA) and environmental impact assessment, going through diverse frameworks proposed by numerous researchers (Ramani et al., 2011; Sala et al., 2015; Yigitcanlar & Dur, 2010) and ending with system dynamics and MCDA models.

For instance, in the field of last mile delivery, De Mello Banderia et al., (2019) have developed a framework that allowed a comparison of diesel LCVs, eLCVs and an electric tricycle in terms of social, environmental, and economic impacts. Giordano et al., (2018) followed a LCA method to compare diesel LCVs against battery electric vehicles. The two studies analysed total capital and operational costs as well as GHG emissions. Moreover, Giordano et al., also considered air quality and (de Mello Bandeira et al., 2019) heart rate of the postman.

Extended MCDA analysis for delivery using mobile depots complemented by cargo bicycles was performed by Verlinde et al (2014) measuring the economic, societal, environmental and transport impact . Economic (capital and operational costs) and environmental (carbon monoxide, nitrogen oxides, non-methane hydrocarbons, particulate matter, and GHG emissions) impact assessment of mobile depots was also a topic of a case study performed in Buenos Aires (Marujo et al., 2018). MCDA was conducted by Navarro et al., (2016) while assessing the alternative urban freight system, that relies on cargo micro-distribution and electric tricycles in Barcelona and Valencia. The authors have focused on economic (capital and operational costs), environmental (PM, SO_2, NOx, VOC, CO and GHG emissions), transport energy (the fuel consumption and energy consumption) and operation (vehicles used, shipments, vehicles km, shipments/km, weight, tour-driving time) dimensions.

Impact assessment of another type of bicycle, namely a cycle rickshaw trolley, was performed by Sadhu et al (2014). The authors have conducted a survey with drivers to assess the impact on environment (CO, CH_4, NO_X, PM and GHG emissions), fuel savings, traffic congestion and wellbeing of rickshaw drivers (safety, employment and psychological impact).

For what concerns automated freight innovations, to the best of the authors' knowledge, there is still only a limited number of studies due to the limited information concerning the capabilities and the characteristics of these new systems. Among the first attempts to study the impact of new mobility solutions, Chiang et al., (2019) have performed a green vehicle routing problem (GVRP) study for drones supported by internal combustion engine delivery vehicles, focusing on costs and sustainability implications. The authors opted for a comparison of GHG emissions and variable costs of delivery for business as usual, delivery using the drones and combination of vehicles. Moreover, Stolaroff et al., (2018) have estimated the energy consumption and total life cycle emissions of parcel delivery with drones, based on assumed warehouse development according to the current battery ranges of the drones. As for the delivery droids, Jennings and Figlozzi, tried to estimate their impact on freight efficiency (2019) as well as total energy consumption and emissions Figliozzi and Jennings (2020). Nevertheless, none of the studies focused on a full operational and sustainability assessment of delivery droid against other popular last-mile delivery systems, which is the aim of this study.

3. Sustainability assessment framework

The framework was developed based on the relevant literature briefly outlined in Section 2. However, additional material from other fields was also used to structure the four step methodology, so that the assessment reflects a comprehensive last-mile delivery assessment (Mansourianfar & Haghshenas, 2018; Santoyo-Castelazo & Azapagic, 2014). To reflect the importance of quality of the last-mile delivery solutions, the operational assessment was added alongside the traditional three sustainability pillars assessment (economic, environmental and social). Additionally, the used indices and objectives were aligned to fit the last-mile delivery scope. The choice of the indices drew from the general economic indices used for the project assessment, previous sustainability and environmental assessments performed in the field, as highlighted in section 3.3, and additional indices agreed with experts responsible for the postal delivery at the case study location. The authors believe that the set of indices presented in the study could prove to be a good starting point for the last-mile delivery assessments and could thus be the basis for future studies in the field.

This section further presents the following steps of the proposed assessment framework, in sub-sections 3.1, 3.2, 3.3 and 3.4 (Figure 1).

1. Choice of last mile delivery solutions to consider
2. Development of operational strategies for the analysed options
3. Selection and specifications of operational, financial, environmental and social indicators to be used for measuring the sustainability of each option
4. Creation of prioritisation scenarios (considering the needs of a variety of involved stakeholders) with integration in the MCDA framework

3.1. Choice of last mile delivery solutions

The first step of the sustainability assessment framework is aimed at identifying last mile delivery solutions that could be applied within an analysed system, taking into account the specific characteristics of potential end-users as well as the considered region. Upon the selection of technologies, vehicle attributes such as load capacity, energy source, emissivity, price, rolling coefficient, drag coefficient, size and weight need to be identified to proceed with the analysis.

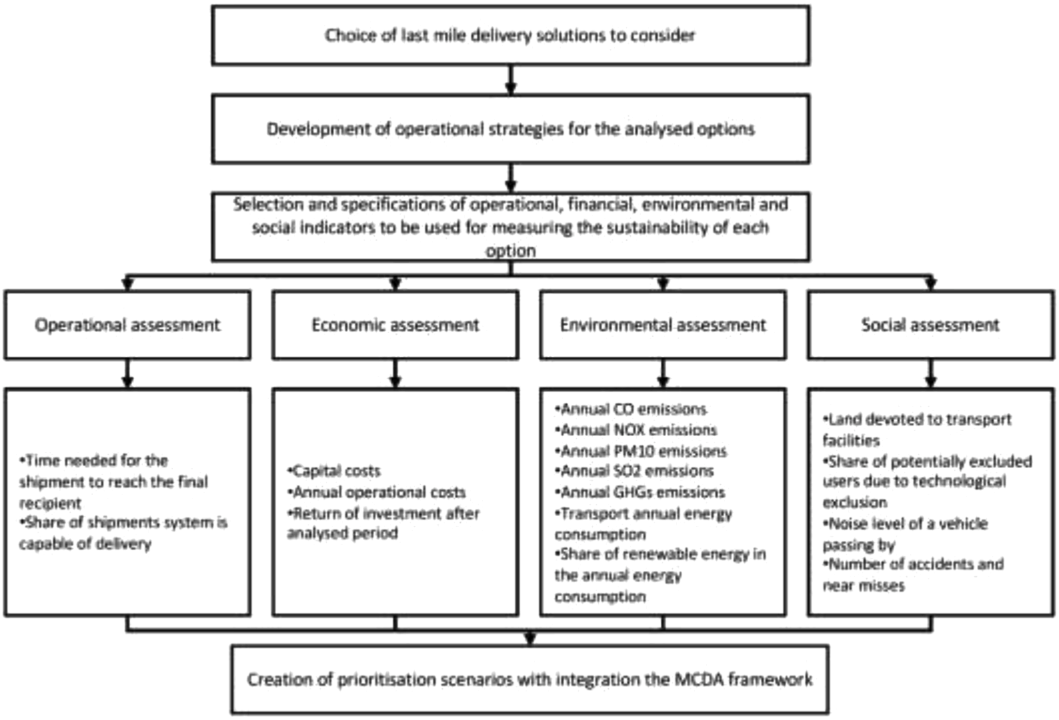

Figure 1. Sustainability assessment framework

3.2. Development of operational strategies for the analysed options

Implementation of new technologies is often (but not necessarily) linked to entirely new operational scenarios. Therefore, a careful development and examination of the implementation strategy of each of the considered new solutions is needed. It is vital to define the locations of the warehouses or depot station, potential delivery routes and timings, limitations connected to the regulatory vehicle requirements in the region, as well as the manner in which the delivery services are ordered. Moreover, as the delivery solutions become more compact, those considerations should include the delivery limitations tied to as well finite load capacity.

If one of the solutions considered is not capable to carry the entire postal services, the solution could be disregarded in further analysis. Alternatively, a new operational strategy could be developed in which the limited solution is assisted by another last mile delivery method.

3.3. Selection of sustainability indicators

To perform a sustainability assessment four analysis dimensions were chosen. The selection of sustainability dimensions, was based upon the three traditional pillars of sustainability – economic, environmental and social (Basiago, 1998) with an additional operational dimension. For each of the dimensions, a set of objectives was created to match the aims and directions found in global and regional mobility policies and trends. Thereafter, for each objective, an adequate indicator (or set of indicators) was defined, based on the findings of previous research on the sustainability of last mile delivery and relevant policy evaluation criteria.

A set of illustrative objectives and indicators to consider is proposed in the remaining part of the subchapter. Depending on the aim and characteristics of the analysed system, those objectives and indicators could vary. Nevertheless, it is crucial in each of the further sustainability assessments to consider all of the proposed dimensions and aim to capture the direct and indirect impact of the system transformation.

A summary of the chosen dimensions, objectives and indicators is presented in Table 1.

Table 1
Dimensions, objectives and indicators used in the assessment support framework

Dimension	Objective	Indicator
Operational	Quality of service	Time needed for the shipment to reach the final recipient
		Share of door-to-door deliveries
Economic	Economic productivity	Capital costs
		Annual operational costs
		Return of investment after analysed period
Environmental	Air pollution prevention	Annual CO emissions
		Annual NOX emissions
		Annual PM10 emissions
		Annual SO_2 emissions
	Climate stability	Annual GHG emissions
	Energy efficiency	Transport annual energy consumption
		Share of renewable energy in the annual energy consumption
Social	Community development	Land devoted to transport facilities
		Employment turnover
	Equity	Share of potentially excluded users due to technological exclusion
	Noise minimalization	Noise level of a vehicle passing by
	Safety and security	Number of accidents and near misses

3.3.1. Operational dimension

The main operational objective is the quality of the service, the evaluation of which is made through two indicators – the time of delivery and the coverage of delivery demand. The time of delivery is the time passed from registration of shipment at the postal office to its delivery to the final recipient. The coverage of the delivery demand is the share of parcels and letters that the solution is capable of delivering in a door-to-door manner. The second indicator was chosen as compact last mile delivery solutions could have a limited cargo space and load capacity and would not be able to carry all parcels.

3.3.2. Economic dimension

Three economic indicators are used to measure economic productivity objective: capital costs, total annual operational costs and return of investment after five years. Capital costs are the costs of obtaining the fleet of new last mile delivery solutions. The annual operational costs comprise maintenance costs, insurance costs and fuel/electricity consumption costs. The annual operational costs were chosen as an indicator, as it was found important by the expert responsible for the postal services in the location of the case study. As explained, minimising an annual outgoing cashflow is an important factor of financial sustainability of an organisation. This is especially the case of organisations founded with public means, which often have a rigorous budget.

The last indicator represents the share of the investments cost returned after five years, due to savings on operational costs, as compared to the expenditures tight to the currently used system. The indicator was chosen to reflect the profitability of investment in innovative systems, which might be more cost-consuming at first, but secure lower operational costs.

3.3.3. Environmental dimension

The analysis includes three environmental objectives chosen according to the global and regional goals and strategies to enhance quality of life in urban areas and achieve carbon neutral and efficient transport systems: air pollution prevention, climate stability and energy efficiency.

The environmental indicators that reflect the air pollution prevention objective are total annual emissions of Carbon Monoxide (CO), Nitrogen Oxides (NOx), Particulate Matter (PM), and Sulphur Oxidise (SO_x) which according to epidemiological studies are the most important air pollutants in cities (Friedrich & Quinet, 2011) and were used as indices in previous environmental assessments of last mile delivery (Marujo et al., 2018; Navarro et al., 2016; Verlinde et al., 2014). Additionally, annual GHG emissions are an environmental indicator representing the climate stability objective. This reflects the struggle of multiple regional and national governing bodies, to achieve carbon neutrality of transport and prevent rapid progression of climate crisis.

The energy efficiency is also a crucial objective that both private and public sector are struggling to enhance. It is reflected through remaining two environmental indices – total annual energy consumption and share of renewable energy in the total energy consumed.

3.3.4. Social dimension

Lastly, there are four objectives reflecting social sustainability, in line with global and regional policies that aim for a sustainable and inclusive future in dense urban areas. These objectives are: community development, equity, noise minimisation, as well as safety and security.

The community development is often an important goal of local governments, reflected in the analysis with land devoted to transport facilities and the employment turnover indicators. The transport's need of urban space usage (such delivery bays or loading zones) is increasing. With, most urban areas struggling with an imbalance between the loading zone supply and the demands of freight transport operations (Chen et al., 2018), which causes variety of parking issues such as double-parking of freight vehicles which park illegally on street. This makes bottlenecks and therefore leads to increase congestion and increasing emissions (Iwan et al., 2018). With the sprawl of urban areas contributing to the negative transport externalities, it is vital to reclaim the land dedicated to transport facilities in the centres as well as on the outskirts of cities. The reclaimed areas could be used to propagate community development, with Barcelona's superblock serving as a perfect example (Braubach et al., 2017; *"Superblocks" Free up to 92% of Public Space in Barcelona*, n.d.). Community development could also be determined by the employment turnover indicator, as studies suggest that communities with higher share of unemployed workers, could suffer from higher crime and violence rates, as well as poorer health of individuals and worse academic performance of children (Jenkins, 1982; Nichols et al., 2013.).

Equity as an objective is included, as some of the newly introduced last-mile delivery solutions could require the end-user to operate smart phones applications. Implementation of such solutions could lead to further marginalisation of digitally excluded, which should be accounted for before their deployment.

Noise minimisation is an objective considered as it has been a concern of numerous regional governments. Long-term exposure to environmental noise, could be particularly harmful, with estimates it causes 12 000 premature deaths and contributes to 48 000 new cases of ischaemic heart disease per year in the European territory (European Environment Agency, 2020).

Finally, safety and security of road traffic is a major concern of all national and regional governing bodies and their citizens. This concern could be amplified by the close presence of new technology, for which trust has not been sufficiently built in the society.

3.4. Definition of prioritisation scenarios

The final, fourth, step of the assessment framework allows to compare the solutions, using the MCDA. MCDA is often used to assess numerous, possibly conflicting, criteria in a structured manner. The ordered and controlled assessment that accounts for all previously set objectives is especially important with system changes that involve numerous stakeholders with opposing views. There are numerous MCDA methods to evaluate a system and any of those could be used in the assessment support framework. Multi-attribute value theory (MAVT) has been selected, as one of the most widely used methodologies. MAVT constitutes from determining partial value functions based on established weight for each criterion to capture the global value function in a following manner (Azapagic & Perdan, 2005).

$$V(s) = \sum_{i=1}^{I} w_i u(s) \tag{1}$$

Where:

$V(s)$ is a global value function, representing the total obtained score for an analysed last mile delivery solution s
w_i is a weight of importance for sustainability indicator i
$u(s)$ is a value function, determined through ranking, reflecting the performance of solution s on indicator i. In the ranking value the lesser value is assigned to the most desirable outcome and the highest value to the solution that performs the worst in a given indicator.
I is the total number of indicators

The last mile delivery is a system that involves and impacts a variety of stakeholders realising different vision and aiming for diverse objectives. Therefore, the assessment of the systematic change should not only consider and evaluate the previously mentioned sustainability indicators, but also try to measure the value that each of the indicators could bring to a given stakeholder. With that in mind, four assessment scenarios were created to evaluate each of the last mile delivery solutions from a stakeholder perspective in a MCDA. The developed scenarios and considered weights were designed to represent the main stakeholders of the last-mile delivery systems and their priorities and needs. Apart from understanding the perspective of each of the stakeholder group the four prioritisation scenarios served as a sensitivity analysis, allowing to measure the impact of weight change on the final outcomes of the assessment.

The definition of prioritisation scenarios, results in identification of weights (w) used in the sustainability assessment. The steps to obtain the prioritisation scenario, require the understanding of strategic aims of the decision maker or stakeholder. Once the priorities in terms of analysed dimensions are understood, the weights could be obtained in the following manner:

1 A constant sum (100) is assigned to all the dimensions of the analysis - *operational, economic, environmental and social* (e.g. in the first

scenario they are assigned equally giving each dimension a 25 point importance).

2 Within each of the four dimensions, the corresponding weight is distributed equally for each of the corresponding objectives (e.g. within the environmental dimension, the three objectives – *air pollution prevention, climate stability and energy efficiency* – are assigned 8,33 point each).

3 The weights within each objective are distributed equally among the corresponding indicators (e.g. within the energy efficiency objective, the two indices – *transport annual energy consumption and share of renewable energy in the annual energy consumption,* are assigned both 4,165 points).

The first scenario was developed to assess the relatively most optimal setup in which all the dimensions have the same importance. The scenario was created as a base and to support stakeholders whose intentions and priorities could be different than those presented in the remaining scenarios.

The second scenario, reflects the focus of a national or multi-national policy maker, such as EC. The strive for environmentally sustainable future with clean and efficient energy and transport sectors has been a clear mission of the EC, as well as similar regulatory bodies, through programmes such as The European Green Deal, Horizon 2020, Horizon Europe or Concerto. Therefore, this scenario highlights the importance of environmental sustainability by assuming the environmental dimension to be thrice as important as each of the remaining dimensions.

The third scenario highlights the significance of finance and operational effectiveness which would be of highest importance for a last mile delivery service provider. Therefore, the economic and operational dimensions are assumed to be of equal importance and twice as important as an environmental and social dimension.

The fourth scenario looks from the perspective of a city government or other regional governing body, which aims to increase the quality of life for citizens within a given area. Those stakeholders would strive to implement solutions brining the biggest value in the environmental and social dimensions, aiming to reduce air and noise pollution and create collaborative, inclusive and safe environment. Therefore, in the fourth scenario, environmental and social dimensions are twice as important as the financial and operational one. Moreover, safety and equity would be important decision-making factors for governments valuing the safety and inclusivity of implemented solutions. Therefore, those objectives are valued as twice as important as the remaining objectives in the social dimension.

The final weight assigned to each indicator in all scenarios is presented in Table 2.

4. Case study: The Joint Research Centre's Ispra site

The case study analysis is set on the Joint Research Centre's (JRC) Ispra site. The JRC is the EC's science and knowledge service, providing independent scientific research to support policymaking, with its biggest site located in Ispra - a town in northern Italy. The setting was chosen, as the site could stand for micro urban environment with its size (167 ha), population (almost 2700 employees), infrastructure (36 km of roads connecting 230 buildings) and the demand for external and internal postal services[1].

The map of the JRC Ispra site is presented on following Figure 2.

The postal services on site serve as representation of last mile delivery system – the Italian post as well as courier services deliver mail and parcels to post office found on site. Thereafter, the incoming mail is delivered, and the outgoing mail is taken from each building on site (approx. 600 incoming and 300 outgoing deliveries per week). Additionally, to the external mail services, internal deliveries of goods and letters between buildings on site are handled every day (approx. 75 deliveries per week).

The demand for postal services was created as an exemplary week of all postal services carried out at the JRC Ispra site. The information on the number of parcels processed by various postal services was obtained during the interviews with the service responsible. The input from the interviews indicated that some services of the JRC obtain and send mail daily, involving some specific buildings of the JRC Ispra site. Therefore, to create the demand, it was assumed that the delivery services would serve those buildings every day. While the rest of the employees are equally likely to obtain a parcel within a given day. Following this assumption, the demand for the parcels was obtained using a Monte Carlo sampling (5000 draws) from a probability distribution obtained using the number of employees per building. The obtained weekly sample is not significantly different from the distribution of people per building (Z-test =1,176), and therefore is assumed to be an adequate representation of the sample.

4.1. Choice of last mile delivery solutions

For the purpose of the assessment, six types of delivery solutions are considered, with the first three being a traditional choice for last mile delivery: LCVs. In particular, three types of LCVs were considered: Euro 4 LCV with gasoline engine from 2006 (the vehicle that currently handles the postal delivery), a new 2020 Euro 6 vehicle with gasoline engine (the LCV with the highest number of new vehicle registrations in the country of setting) and a 2020 eLCV.

The three LCV-based services are compared with an automated last mile delivery service operated by delivery droids. The not yet widely implemented solution is considered as there was already an initial acceptance of the technology by the employees of the institution. An initial acceptance check was performed in the mobility survey distributed at the JRC in October 2020. A fraction of the questionnaire was dedicated to the future of mobility at the site, and out of the 25% of staff that filled in the survey, 60% of employees declared willingness to use last mile delivery droids for lunch delivery as well as private or work-related postal services. As the JRC is wheelchair accessible, the droid based system would be able to carry deliveries to all individuals in all buildings located onsite. However, as the last mile delivery droid is not capable of covering the entire shipment demand due to its relatively small cargo space and maximum load capacity, it needed to be coupled with other delivery system. Three types of solutions were considered to assist the droid system, namely:

- eLCV for the majority of deliveries and droid handling special singular requests.
- Euro 4 LCV that currently handles deliveries on the analysed setting only for parcels which do not fit in the droid.
- Depot station, so that the recipients pick up the parcels that cannot be delivered with droids.

The vehicle specific information used for the purpose of the analysis is presented in the following Table 3.

4.2. Development of operational strategies for the analysed options

Currently, the postal services are carried out with an LCV which visits all buildings on site every day to deliver both the external and internal mail as well as potentially pick up the outgoing external and internal deliveries. Furthermore, the LCV makes an additional delivery route, to deliver parcels to their recipients.

The same operational strategy is assumed to remain for all LCVs considered in the analysis. The routes that the LCV follows were assumed to be the shortest (in terms of driving time) possible, found with the traveling salesman optimisation method. The distances and

[1] JRC webpage is available under following address: https://ec.europa.eu/jrc/en

Table 2
Indicator importance weights for each of the analysed scenarios

Dimension	Objective	Indicator	Weight S1	Weight S2	Weight S3	Weight S4
Operational	Quality of service	Time needed for the shipment to reach the final recipient	12,50	10	16,67	8,33
		Share of door-to-door deliveries	12,50	10	16,67	8,33
Economic	Economic productivity	Capital costs	8,33	6,67	11,11	5,56
		Annual operational costs	8,33	6,67	11,11	5,56
		Return of investment after analysed period	8,33	6,67	11,11	5,56
Environmental	Air pollution prevention	Annual CO emissions	2,08	3,33	1,39	2,78
		Annual NOX emissions	2,08	3,33	1,39	2,78
		Annual PM10 emissions	2,08	3,33	1,39	2,78
		Annual SO2 emissions	2,08	3,33	1,39	2,78
	Climate stability	Annual GHG emissions	8,33	13,33	5,56	11,11
	Energy efficiency	Transport annual energy consumption	4,17	6,67	2,78	5,56
		Share of renewable energy in the annual energy consumption	4,17	6,67	2,78	5,56
Social	Community development	Land devoted to transport facilities	6,25	5	4,17	5,56
	Equity	Share of potentially excluded users due to digital exclusion	6,25	5	4,17	11,11
	Noise minimisation	Noise level of a vehicle passing by	6,25	5	4,17	5,56
	Safety and security	Number of accidents and near misses	6,25	5	4,17	11,11

Figure 2. Map of the JRC Ispra site - setting of the analysis

Table 3
Vehicle specific characteristics

VEHICLE	EURO 4 LCV	EURO 6 LCV	ELCV	DELIVERY DROID
Energy source	Gasoline	Gasoline	Electricity	Electricity
Production year	2006	2020	2020	2020
Mass [kg]	2 330	3 000	2 300	40
Cargo space dimensions (L X W X H) [CM]	310 x 142 x 190	305 x 198 x 195	186 x 114 x 113	42 x 38 x 31
Maximum load capacity [kg]	1 500	1 500	715	10
Price (euro per one vehicle)	NA	32 000	38 000	4 550

travel times between each building were obtained using the google distance API and latitude and longitude of each building.

The combination of eLCV with last-mile delivery droid results in a new operational strategy, for which, it is assumed that the eLCV makes two routes. During the first drive, all postal and courier letters are delivered to their recipients, and all parcel deliveries during the second drive. Similarly, to previous operational strategies, it is assumed the driver follows the shortest path between the buildings that have an awaiting shipment. Complementary, the outgoing and internal mail is handled by the last-mile delivery droid. Therefore, the eLCV visits only buildings for which there is an intended delivery on a given day, as it is not required to visit all dwellings, to check if there is a pending internal or outgoing mail to collect. The droid is charged overnight and stored in the post office at the JRC site, from which it starts and in which it ends all its trips. The internal mail is handled with singular trips of the droid upon a request from the sender. The droid makes the trip from the post office to the sender and immediately after to the recipient of the mail and back to the post office. Similarly, the outgoing mail is also handled as singular request with the droid starting the trip in the post office, picking up the mail at the working place of an individual creating the request and coming back to the post office. It is assumed that, for each singular request, the droid chooses to follow the shortest path (in terms of distance), using the walking pathways and accessing buildings. As the exact distance of delivery route was impossible to determine, the distance is assumed to be equal to walking distance from door to door of each building (obtained analogously to driving distance) with additional 100 meters of internal building delivery.

The results, presented further in chapter 5, indicate that one droid is sufficient to account for all daily demand for internal and outgoing mail. While, in the strategies in which the droids are coupled with a Euro 4 LCV or with the depot station the droids also deliver post and courier mail, raising the number of required droids to 3. In said strategies the droids deliver post mail and courier mail separately (due to different timing of deliveries). The route that the droid takes to deliver the post and courier mail is determined using the traveling salesman problem, using the walking distance between buildings. If the route is too long to be handled with one droid on one charge, the delivery is handled by two droids. The parcels to be carried by each droid are determined using the previously encoded clusters of buildings, which allow to direct the parcels with nearby destination together. Moreover, the droids handle the internal and outgoing mail by singular trips upon request, similarly to what was described in the previous operational strategy.

While the droids are coupled with a Euro 4 LCV, the vehicle is used only to handle the incoming parcels, which cannot be delivered by the droid due to cargo space limitation. The LCV delivers the parcels each day, taking the shortest route. Similarly, when the droid is coupled with the depot station the parcels that are not suitable for the droid to deliver are placed in a depot station, located at the post office. It is assumed that the recipients are informed about awaiting parcel and pick it up coming from their main office building, to which they return, once the parcel is picked up.

4.3. Selection of sustainability indicators

This subchapter presents the key assumptions and estimation techniques to obtain the indicator values used in the analysis.

4.3.1. Operational dimension

The time of delivery is estimated based on the operational strategies developed in the previous point. Therefore, for all the LCVs as the operational strategy does not change from the current one, the delivery time remains the same and is equal to 2-3 days. With the introduction of the last mile delivery droids, the delivery time shortens to same or next day delivery, as the droid is able to immediately handle the singular internal and outgoing requests.

Moreover, when the delivery droid is coupled with the depot station, parcels that do not fit into the droid are assumed to be picked up at the depot station. The share of parcels that would not fit into the droid was obtained during interviews with postal services employees and estimated at 5% of the total number of parcel shipments.

4.3.2. Economic dimension

The capital costs of obtaining the last mile delivery solutions, were obtained from their manufacturers. There is no capital cost of obtaining a Euro 4 LCV as it is already available on site.

For the annual operational costs (comprised of maintenance costs, insurance costs and fuel/electricity consumption costs), the electricity/fuel consumption costs for all vehicles are calculated according to the average electricity/fuel price in Italy in 2020. The maintenance as well as insurance costs for the Euro 4 LCV are assumed to be equal to the current costs borne by the JRC for those services. Those costs for Euro 6 and eLCVs are assumed to be equal to maintenance and insurance costs of vehicles of the same class, which are a part of fleet of JRC service vehicles. The maintenance and insurance cost of the last mile drone are assumed to be 5%[2] of the capital costs of the fleet. The same assumption is made for the depot station.

The return of investment indicator was estimated knowing the capital costs and the annual operational costs, after an assumed five-year period. The period was chosen as evaluation period for costs assessment at the analysed institution – the JRC. The return of investment was calculated in the following manner. To obtain the results, the annual savings were discounted over the inflation.

$$\mathrm{ROI} = \frac{Cost\ savings}{Cost\ of\ investment} \cdot 100\% \tag{2}$$

4.3.3. Environmental dimension

To estimate the remaining environmental indicators, first the energy consumption of all last mile delivery solutions needed to be obtained. Total energy consumption of the combustion engine LCVs was calculated as the fuel consumption of everyday drive between all man-present buildings on site, using the green driving tool (European Commission, 2021). Green driving tool is a detailed vehicle simulation platform, developed internally at the EC and made available to the public to support environmentally aware decision making. The tool calculates fuel consumption, cost of journey and GHG emissions of combustion-engine vehicles, based on specific vehicle configuration and journey information.

The fuel consumption of cars, used to pick up parcels at the depot station (used in the strategy of droid system coupled with a depot station) is calculated based on the assumed fleet distribution of the JRC population in a comparable manner, based on expert knowledge of the site's population and launched mobility survey for the site's employees. The fleet was assumed to constitute of Euro 6 vehicles produced between 2017 and 2019. Further information known about the fleet is the distribution to vehicle segments according to green driving tool classification (30% of segment A vehicles, 40% of segment C vehicles and 30% of segment E vehicles) and the engine type of the vehicle (30% of gasoline fuelled vehicles, 65% of diesel combustion engines and 5% of EVs).

The electricity consumption of eLCV and the last mile delivery droid was calculated using vehicle dynamics, according to the following equation (Lebeau et al., 2015):

$$\mathrm{E_{ij}} = \frac{\mathrm{d_{ij}}}{3600 \cdot \eta} \cdot \left(\mathrm{m} \cdot \mathrm{g} \cdot (\omega \cdot \cos\varphi + \sin\varphi) + 0.0386 \cdot \left(\rho \cdot \sigma \cdot \mu \cdot \vartheta_{\mathrm{ij}}^{2}\right) + \mathrm{m} \cdot \frac{\mathrm{d}\vartheta}{\mathrm{dt}} \right) \tag{3}$$

Where:

- E_{ij} is the electricity consumed by the engine (kWh)
- d_{ij} distance of the drive (km)
- η is the efficiency of the vehicle
- m is a mass of the vehicle (kg)
- g is gravitational acceleration
- ω is a vehicle rolling coefficient. Assumed to be the coefficient of car tire on asphalt for LCV and car tire on cobblestone for the last mile delivery droid)
- φ is a road gradient angle (deg)
- ρ is air density
- σ is the drag coefficient of the vehicle (with the delivery droid assumed to be a cuboid)
- μ is the cross section of the vehicle (m^2)

[2] Average vehicle maintenance and insurance cost as a share of vehicle price given by the American Automobile Association (The American Automobile Association, 2019).

- ϑ is the speed of the vehicle ($\frac{km}{h}$) (assumed to be the maximal driving speed allowed onsite for the eLCV and 6 $\frac{km}{h}$ for the delivery droid - a speed of the droid on pavements given by its manufacturer)

The electric solutions could consume energy coming from sustainable renewable sources, which is represented by the share of renewable energy consumed indicator. The indicator is calculated as a share of renewable electricity consumed in total energy consumption, according to the Italian energy mix for 2019 (International Energy Agency, 2021).

The total emissions of the combustion-engine LCVs were obtained using COPERT, a vehicle activity-based emission calculation model developed by the European Environmental Agency (Ntziachristos & Samaras, 2020). Whereas the emissions of eLCV and the last mile delivery droid were calculated according to the emissivity of Italian grid given by the national Italian institute of environmental protection (*Istituto Superiore per la Protezione e la Ricerca Ambientale*) (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2019).

4.3.4. Social dimension

The assessed social indicators include: land devoted to transport facilities, employment turnover, share of potentially excluded users due to digital exclusion, noise level of a vehicle passing by and number of accidents and near misses. To conduct the case study, all of those were thoroughly assessed with all the analysed operational strategies for last mile delivery.

The land currently devoted to last mile delivery services is a parking spot of the LCV. The amount of land dedicated to transport would not change if other LCVs were the prospective solution, whereas in case of delivery droids the vehicle would require a smaller space (operation room for charging and storing). Also, the depot station would require an additional land to stand on. The amount of land required by those solutions was given by their manufacturers.

The employment turnover indicator is omitted in the analysis as it would be constant in all analysed scenarios due to particular characteristics of systematic change. Upon discussing with departments responsible for shipment delivery at the considered setting, it has been agreed that implementation of automated delivery with delivery droid would result neither in additional hires nor in layoffs. The reason being, the wider and diverse responsibilities of staff in charge of delivery services. Additionally, one of the employees could undergo additional training to handle the droid day to day operation and maintenance.

Equity is measured as a share of potentially excluded customers. The LCVs that currently deliver mail on the JRC site do not require an external device to operate, while the last mile delivery droid and the depot station could be more difficult to operate by those digitally excluded. The share of those potentially marginalised is not estimated but, rather acknowledged as an additional difficulty for digitally excluded.

The objective of noise minimisation is measured through a noise pollution indicator as the pass by noise caused by the vehicle. The noise levels of LCVs are obtained from legislative requirements and experimental research (European Parliament, 2014; Miloradović et al., 2017; Ministry of Infrastructure and the Environment, 2015), whereas the noise level of the last mile delivery droid is said to be negligible, as per information obtained from its producer, and is therefore equal to environmental noise.

Safety and security of road traffic is a major concern, especially in presence of delivery droids which would frequent the pavements typically reserved for walkers, and is therefore an important objective. It is measured as the total number of near misses and accidents involving the LCV fleet of the analysed JRC (0) for all LCV vehicles. The safety of the droid is marked as not determined as to lack of available experiment-proven information or conducted risk assessment of the droid.

4.4. Definition of prioritisation scenarios

As discussed in Section 3.4, four scenarios motivated by the stakeholder preferences have been defined. One could argue that the JRC, as a public institution of the EC, is a representation of S1, with all the dimensions equally important. Meaning that a public organisation, contributing to the EC mission, should strive for excellence in all sustainability pillars as well secure a highest quality service.

5. Results

For the sustainability assessment of last mile delivery, the results of each indicator needed to be obtained. The results suggest that droid-based system coupled with a Euro 4 LCV outperforms other solutions on the economic dimensions. While a combination of eLCV with supplementary droid is the most environmentally friendly option. Both of those options also secure the highest quality of delivery, whereas eLCV was found to be the most socially sustainable option.

On the operational dimension, the best results are yielded by the combination of eLCV and delivery droid and the delivery droid-based system coupled with a Euro 4 LCV. As, delivery droid allows for an instant pick up of outgoing mail and delivery of internal shipments, which otherwise would have to wait for the next routine drive of an LCV. Moreover, the supporting LCVs secure the door-to-door delivery of the parcels which do not fulfil criteria of a small delivery droid.

The financial aspects of the analysis are somewhat different. The simulation of weekly delivery of analysed parcel demand with six analysed delivery strategies has allowed to determine the required number of droids needed to cover the demand during the 8 working hours. The assessment was made by plotting the time required for the deliveries and state of charge of the droid. The obtained results suggest that three delivery droids would be needed to handle all delivery services at the JRC, and one droid would be enough to handle outgoing and internal mail as a complement to an eLCV.

The outcomes suggest that with the current market prices, the lower operational costs of delivery droid-based system coupled with the Euro 4 LCV would cover 67% of investment after five years. High return of investment, due to saving in operational costs is also secured with the droid based system combined with a depot station (41%). Additionally, those results indicate that 25% of eLCV investment would be covered after this period and 23% for the best quality of operation system – combination of an eLCV with a delivery droid. Investment in a Euro 6 LCV brings the lowest return, as the fuel costs of this vehicle result in higher operational costs. Which proves that, in presence of developing technology, capital costs should not be a decisive criterion, and in the long run the environmentally unsustainable option could also become a financial anchor.

The environmental dimension is closely related to the total energy consumption of each system, which was obtained because of weekly delivery system simulation. The total energy consumed by the delivery droid is significantly smaller than the consumption of other systems, even though the vehicle covers greater distance. The distance covered by everyday drive and parcel delivery by LCVs is equal to 12 754 km annually, whilst the three delivery droids would have to collectively cover more than twice as much (27 782 km) due to dispersed delivery strategy. Moreover, to deliver the parcels which the droid cannot carry, the Euro 4 LCV would have to drive 1 284 km annually. Interestingly, the number of kilometres covered by cars when recipients pick up their parcels at the depot station is almost three times higher due to disaggregated approach. A combination of both strategies – postal, courier and parcel shipments delivered with eLCV and the internal and outgoing mail handled by the droid, results in a lowering of travelled kilometres to 22 094 km per annum. More importantly, it cuts in half the distance covered with an LCV (6 210 km), significantly contributing to reduction in all emissions while maintaining a full demand coverage.

Annual emissions depend on the type of energy consumed, with cleaner energy source – electricity providing better results. Therefore, investment in delivery droids and the eLCV is the most positive from the environmental standpoint, with singular eLCV being a close second in terms of air quality but lagging in climate neutrality objective due to GHG emissivity of the Italian grid. Moreover, the coupling of delivery droid system with other solution, also yields positive environmental results, decreasing emissions.

Implementation of the droid with the Euro 4 LCV, drastically decreases emissions, and allows to achieve moderately good results in the air quality objective. Coupling the droid with the depot station, results in the final recipient's car usage to pick the parcel from the post office and bring it back to their building. Nevertheless, even with higher millage covered by cars, the GHG emissions are lower than those caused by the Euro 4 LCV. That is because the fleet driven by the JRC employees is newer and subject to higher emission norm standards.

Annual emission of SO_x is the only environmental indicator which gives better results with a fully LCV solution – Euro 6 LCV. It is because of high emissivity of an Italian electricity system, however with a reasonable assumption that Italian energy system will continue the sustainable transformation to renewable energy sources, all the electricity emissions would inevitably decrease.

The results obtained for the social dimension objectives and indicators, point that an eLCV would be the most socially sustainable solution, as per the guaranteed equity of the system, lower harmful noise pollution and proven safety of the LCV based system. Nevertheless, once the delivery droid is tested and established to be safe and with adequate digital education, the droid based solutions could outperform the eLCV, due to the low motor noises and possibly lower spatial demand.

The analysis of results for each indicator did not allow to determine which of the proposed solution is the most optimal, as per contradictory outcomes on the criterion, objective and dimension level. Hence, the need to take the further steps of the assessment support framework. The detailed outcomes of the analysis for each indicator and each delivery solution are presented in Table 4. The table representing the ranking results of each solution (Table 5) is available in Annex 1, along with the detailed explanation of how the ranks were obtained.

The results depicting the performance of the analysed delivery solutions within each prioritisation scenario are obtained using the ranking results presented in Table 5 and chosen weights presented in Table 2 according to the equation 1 given in section 3.4. These results are described in more detail in the following sections, and graphically represented on Figures 3 to 6.

5.1. Scenario 1

S1 reflected a case in which all the dimensions are equally valuable. The results of the analysis indicate that overall, a system using last mile delivery droid supported by the readily available Euro 4 vehicle is the most suitable option in this scenario. While this option is economically and environmentally satisfactory, the further marginalisation of digitally excluded and unknown safety implications are the main drawbacks. Nevertheless, as the JRC population uses digital services in their work, the equity issue would not pose a major constraint.

Secondly, the second-best performing solution could be used – the combination of eLCV with the delivery droid, which while initially cost intensive is more profitable in the long term than a Euro 6 LCV, and less energy-consuming than a singular eLCV. Provided testing and safety assurance of the solution it would further outperform the LCV based options.

The droid-based system coupled with a depot station, is also a well performing option, nevertheless, it would require additional capital costs, and could be troublesome to the population, as the delivered parcels could be too heavy or too difficult to carry by some individuals. Investment in eLCV, either supported by the droid or not, is also preferred to the combustion engine LCVs. There is a clear difference in performance between the combustion engines and electric motor solutions, mostly because of the negative environmental impact but also because of the high operational costs. Pointing, to the fact that investment in the combustion-engine LCVs should not be considered.

The detailed results of S1 performance, with three best preforming scenarios highlighted, are presented hereunder on Figure 3. The horizontal axis on the figure represents the total score obtained by each of the analysed solution, with the highest score, being least favourable according to the sustainability assessment framework.

Table 4
Indicator results for each delivery solution

Dimension	Objective	Indicator	Euro 4 LCV	Euro 6 LCV	eLCV	eLCV + last mile delivery droid	Last mile delivery droid + Euro 4 LCV	Last mile delivery droid + depot station
Operational	Quality of service	Time needed for the shipment to reach the final recipient	2-3 days	2-3 days	2-3 days	0-1 day	0-1 day	0-1 day
		Share of door-to-door deliveries	100%	100%	100%	100%	100%	95%
Economic	Economic productivity	Capital costs [€]	-	32 000	38 000	42 535	13 605	23 605
		First year operational costs [€]	2 834	1 645	822	817	927	834
		Return of investment after analysed period	0%	18%	25%	23%	67%	41%
Environmental	Air pollution prevention	Annual CO emissions [g]	309,50	132,81	0,22	0,12	0,58	0,69
		Annual NOX emissions [g]	419,31	259,43	0,52	0,29	21,62	51
		Annual PM10 emissions [g]	132,09	8,03	0,007	0,004	13,30	42,46
		Annual SO_x emissions [g]	2,06	1,94	48,17	26,88	9,84	10,05
	Climate stability	Annual GHG emissions [g]	2 544 244	2 394 075	1 146 159	639 492	480 975	409 989
	Energy efficiency	Transport annual energy consumption [kWh]	8 604	8 093	2 373	1 324	1 331	1 216
		Share of renewable energy in the annual energy consumption	0%	0%	33%	33%	12%	13%
Social	Community development	Land devoted to transport facilities [m2]	20	20	20	30	30	10
	Equity	Share of potentially excluded users due to technological exclusion	No	No	No	Yes	Yes	Yes
	Noise minimisation	Noise level of a vehicle passing by [db]	74	74	70	66	65	66
	Safety and security	Number of accidents and near misses	0	0	0	ND	ND	ND

Table 5
Ranking results for each delivery solution

Dimension	Objective	Indicator	Euro 4 LCV	Euro 6 LCV	eLCV	eLCV + last mile delivery droid	Last mile delivery droid + Euro 4 LCV	Last mile delivery droid + depot station
Operational	Quality of service	Time needed for the shipment to reach the final recipient	6	6	6	1	1	1
		Share of door-to-door deliveries	1	1	1	1	1	6
Economic	Economic productivity	Capital costs [€]	1	4	5	6	2	3
		First year operational costs [€]	6	5	2	1	4	3
		Return of investment after analysed period	1	6	4	5	2	3
Environmental	Air pollution prevention	Annual CO emissions [g]	5	6	2	1	3	4
		Annual NOX emissions [g]	6	5	2	1	3	4
		Annual PM10 emissions [g]	6	3	2	1	4	5
		Annual SO_x emissions [g]	2	1	6	4	3	5
	Climate stability	Annual GHG emissions [g]	6	5	4	2	3	1
	Energy efficiency	Transport annual energy consumption [kWh]	6	5	4	2	3	1
		Share of renewable energy in the annual energy consumption	6	6	1	1	4	3
Social	Community development	Land devoted to transport facilities [m2]	4	4	4	6	6	1
	Equity	Share of potentially excluded users due to technological exclusion	1	1	1	6	6	6
	Noise minimisation	Noise level of a vehicle passing by [db]	6	6	5	4	1	2
	Safety and security	Number of accidents and near misses	1	1	1	6	6	6

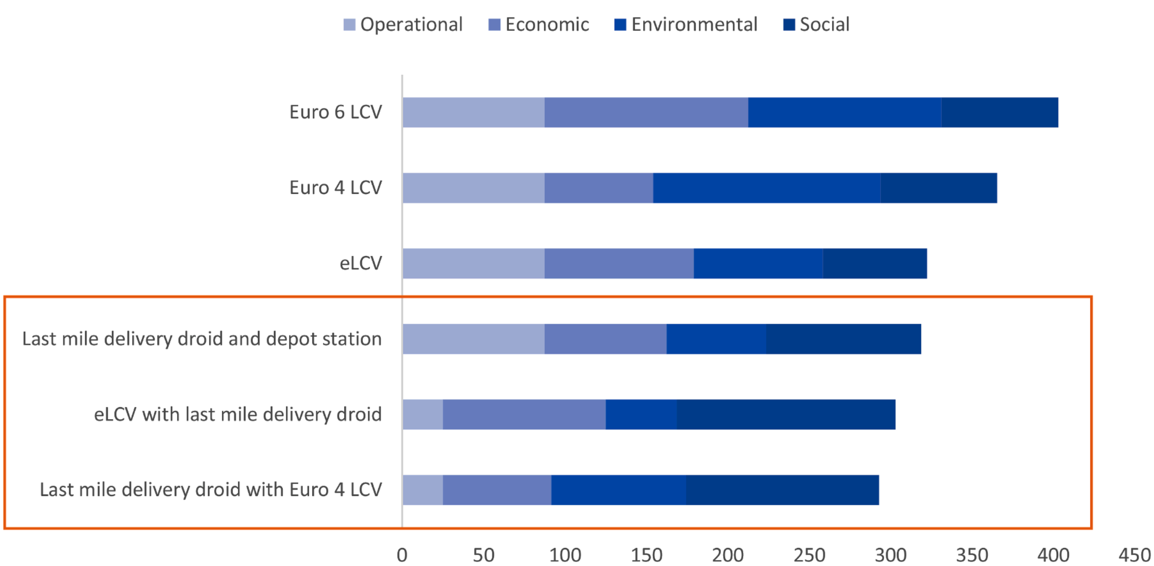

Figure 3. Results of sustainability assessment for scenario 1

5.2. Scenario 2

In S2, emphasis was put on the environmental performance of the solutions, which could reflect the desires of national or multinational governing body, which needs to fulfil the set environmental targets. It is no surprise that the best performing solution in this case is the eLCV coupled with the delivery droid, which is the fully electric solution, resulting in good air quality, low total energy consumption and the highest share of renewable energy. Moreover, the environmental and operational advantage of a droid and eLCV outperforms the economic benefits of singular eLCV investment and the tested safety of the system.

The second best performing solution, is the one with the lowest carbon footprint – the coupling of delivery droids with the depot station. The small and efficient electric motors of the droids result in low electricity consumption, while the new fleet of vehicles used by the JRC employees does not bump the emissivity of the system much higher. The environmental performance of both those strategies would be higher if the vehicles that accompany the droids, would be electric, which was not considered due to high total capital costs of such solution. Nevertheless, with time, the Euro 4 LCV could be substituted with eLCV, and the car fleet of JRC employees would also be transitioning towards a more sustainable one.

Unsurprisingly, the fuel absorbing Euro 4 vehicle is the least desired solution, mostly due to its major negative environmental impact. Nevertheless, the importance of environmental factors does not justify an investment in a Euro 6 LCV, due to the miserable performing economic dimension, and marginal environmental advancement compared to other options. The further support for this scenario could be built with accompanying regional policies restricting the entry of combustion engine vehicles to city centres and residential locations. Such change would result in lower operational performance of combustion engine LCVs, due to inability to deliver the entire shipment demand.

The detailed results of S2 performance are 3 resented hereunder on Figure 4, analogously to S1 representation of Figure 3.

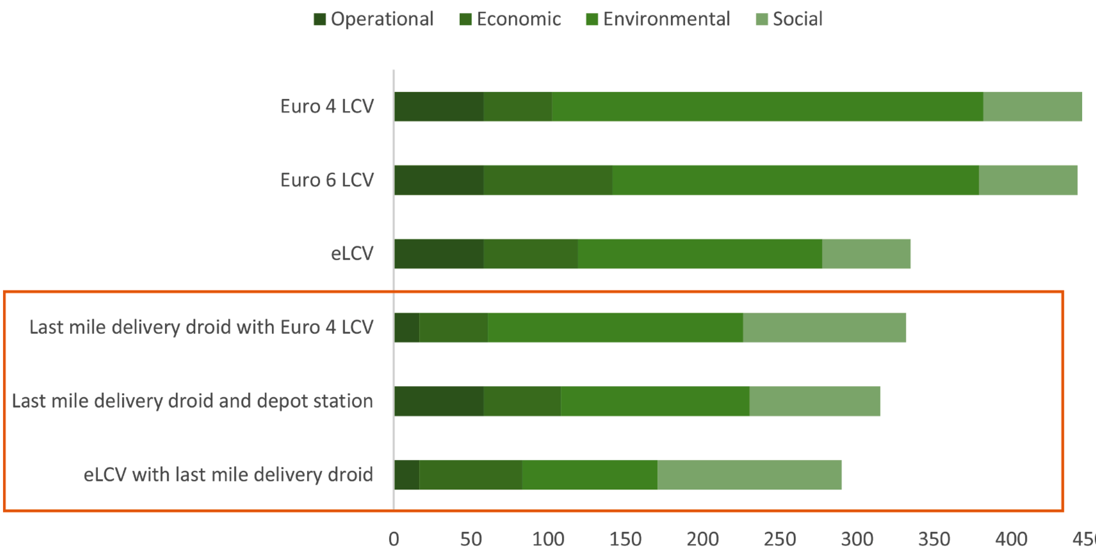

Figure 4. Results of sustainability assessment for scenario 2

5.3. Scenario 3

The S3 reflected the approach of the private last mile delivery service provider. It was assumed that a private body, which is profit oriented would focus on the economic and operational dimensions of the solutions, highlighting the importance of the full delivery coverage.

The last mile delivery droid-based system assisted by Euro 4 LCV for parcel delivery is the preferred option for the last mile delivery provider. Investment in the droids secures better operational performance by shortening the delivery time for the shipments. Moreover, the investment is not capital-consuming compared to the purchase of a new LCV and brings significant savings due to lower operational costs (67% of the investment will be covered by those savings after 5 years).

The second preferred solution is the coupling of eLCV with delivery droid, which, even though cost intensive at the beginning, enhances the operational quality of the service provider by shortening the delivery time, similarly to the best option. This solution also guarantees the lowest operational costs, resulting in significant savings for the investor.

Coupling the droid based system with the depot station is not the preferred option, as it does not provide the door-to-door delivery, which in case of heavy parcels could be problematic for the users, and therefore lowers the quality of the service.

Investment in the eLCV is not considered as preferred solution in this scenario even though it secures annual operational savings, as it is cost intensive and does not secure a better quality of the service for the users. Investment in the Euro 6 vehicle is also not supported, because of similar reasons and further marginalised because of poor environmental performance.

Moreover, keeping only the Euro 4 LCV is also not encouraged, despite the lack of investment. Which proves that, if private companies are even marginally concerned about the societal and environmental implications of their actions, service providers could turn towards innovation. Investments in developing start-ups could prove profitable, while satisfying the growing needs of consumers.

The detailed results of S3 performance are presented hereunder on Figure 5, in an analogical manner to previous results presentation.

5.4. Scenario 4

The S4 underlines the importance of social and environmental sustainability and could reflect the objectives of a regional governing body aiming to enhance the quality of life in its area. The objectives that have

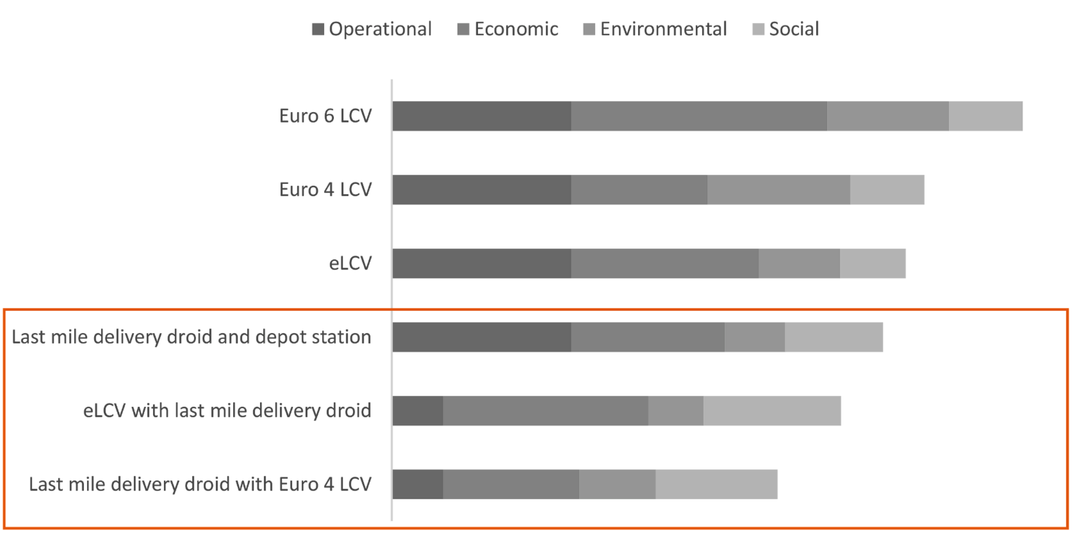

Figure 5. Results of sustainability assessment for scenario 3

the highest impact on the analysis are social equity, safety, air pollution prevention and climate stability.

The results of this scenario highlight the need to investigate and confirm the safety of the last mile delivery droid. As opposed to all previous scenarios, the droid based strategies are not identified as the best solution in this case, because of the lack of risk assessment. Nevertheless, as the last mile delivery droid-based strategies are more environmentally sustainable, once the safety of the droid is assured, those results could change. If so, the second most preferred option is the eLCV coupled with the delivery droids. This option secures the best environmental performance, decreases the traffic noise and provides good quality service to the consumers. The third preferred option of coupling the droid with the depot station, additionally results in lower land demand for transport services which could be preferred in dense urban areas.

Due to their highly negative impact on the environment and low societal added value, the combustion engine LCVs are again the lowest performing solutions, with an increasingly visible difference in the obtained total result.

The detailed results of S4 overall score performance are presented hereunder on Figure 6.

6. Discussion and policy recommendations

With a recent ambitious declaration of EC's objective to cut 90% of transport GHG emissions by 2050 (European Commission, 2019), there is a more pressing need to seek carbon neutral transport solutions also in the last mile delivery systems. Therefore, all stakeholders involved in the system creation should consider the environmental implications of the freight delivery, and transport policies should direct profit seeking companies to consider electric low-carbon technologies. Indeed, this analysis has proved that, even with a marginal consideration of social and environmental factors in S3 and heavy contribution of operational and economic dimensions, the carbon-intensive combustion engine LCVs did not prove to outperform the electric innovations.

Hence the importance of regional, national, and European policymakers to focus on transferring the responsibility for the implications of negative externalities on their creators. For instance, regional policymakers could restrict combustion engine freight vehicles from entering city centres, forcing the companies to invest in or even develop more sustainable alternatives. Furthermore, the European policymakers could opt to subsidise local delivery providers who support sustainable innovation or penalise those with outdated fleets, which contribute to climate crisis and air pollution in urban areas. According to the Green Deal sustainable and smart mobility strategy, fees for road usage could also be implemented (European Commission, 2019). Those types of actions result in further penalisation of combustion engine and preference towards sustainable innovation.

Among the solutions proposed in this analysis, eLCVs are already an established and tested option, yet with a significant potential for further development and implementation by delivery companies. In particular, the high capital costs of the eLCVs at present constitute a barrier for delivery providers. Furthermore, the proposed alternative delivery droid-based systems could further reduce the electricity consumption and following emissions, while lowering the investment cost. Nevertheless, the system that is based on delivery droids also has its shortcomings, namely the limited cargo space and low maximum weight of the parcel, unproven safety record and the plausible marginalisation of digitally excluded.

To secure the full demand coverage, the droid should be coupled with an alternative solution. In this study, we analysed the combination of droid based systems with Euro 4 LCV and the depot station. Both of those solutions provided good results, with cost-efficient droid based system coupled with already available LCV for marginal number of deliveries preferred. That is because of guaranteed full door to door service, and significant emissions and energy consumption reduction. Nevertheless, Euro 4 LCV in time should be decommissioned and replaced by a more sustainable solution.

Alternatively, the delivery droid could be coupled with depot stations, at which the packages which do not fulfil the droid criteria could be stored waiting for the pick up by their final recipient. It is crucial to highlight the importance of land needed for transport services indicator. The reduction of land dedicated for transport services is a desirable outcome for cities as the reclaimed land could be used for community development, enhancing the quality of life of the citizens and proposing new social activities. Moreover, where possible, the land could be used for residential purposes, possibly reducing the urban sprawl, further contributing to the air quality improvements. This solution, however, could prove to be unsustainable if individuals coming to collect the shipment would use unsustainable transport solutions. Therefore, droid based delivery systems coupled with depot stations could be implemented in dense urban areas in which there is a pressing need to reduce land devoted to transport. In those types of spaces, provided that the depot station is nearby, it is also more likely that individuals would opt

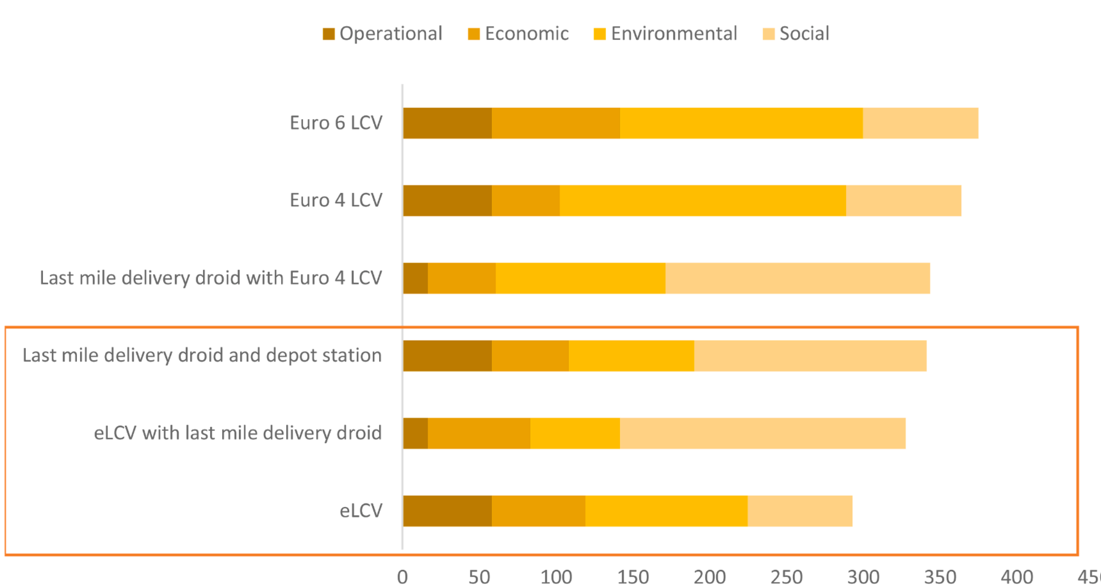

Figure 6. Results of sustainability assessment for scenario 4

to walk to pick up shipments.

Nevertheless, before those vehicles are allowed to roam on our pavements, the safety of those solutions needs to be established. For that purpose, the droid should firstly be implemented on testing grounds, preferably within living labs, in which participants are already using innovation. Guaranteed safety of the droid would significantly improve the scores it obtained in this analysis, confirming its sustainable status.

Moreover, the implementation of droid-based services could result in further exclusion of those digitally impaired. As an advanced society, we should not aim for further marginalisation of those digitally excluded, either by change or by choice, and, while implementing the solution of tomorrow, always consider the digital capabilities of the entire population. Therefore, whilst implementing the droid delivery systems, some form of analogue delivery should always be possible. The living labs could be used to co-create the delivery droid application and booking system with digitally excluded. Such activity could result in provision of a solution more accessible to all.

7. Conclusions

This work followed an MCDA framework for the sustainability assessment of innovation in last mile delivery. The framework was applied to the mail and parcel delivery system of the JRC Ispra site (Italy), due to relatively small size of the delivery system and therefore an adequate complexity of the associated optimisation problems. Modelling of the operational scenarios for a larger problem could prove to be impractical, therefore the outputs of this study could serve to lower the complexity of the problem. Whereas, the proposed sustainability assessment framework is considered a suitable decision-making support tool for the deployment of future, carbon neutral transport systems.

The obtained results illustrate the complexity and challenges faced by the planners and policymakers designing future transportation, in which multiple stakeholders with various preferences and priorities intertwine with significant externalities that the system is responsible for. The results point out that there is no fit for all solution, but a string of conflicting needs and criteria, hence trade-offs and compromises are necessary.

It has been demonstrated that, for a stakeholder valuing all sustainability and operational dimensions equally, the implementation of last mile delivery droids coupled with currently available LCV would be the preferred system. It is also a very cost-efficient system, resulting in fast return of investment due to operational savings, and would be therefore the preferred option for delivery service providers, who value the economic and operational dimensions.

Moreover, the eLCV assisted by a delivery droid was the preferred option for all environmentally concerned, because of the efficient electric motors and clean energy source. When considering social criteria, the marginalisation of digitally excluded coupled with safety uncertainties related to untested delivery droids, point to a different implementation direction, identifying the eLCV again as the most sustainable option.

The results indicate that the implementation of the delivery droid system can have a positive impact on the environment, whilst improving the quality of services by shortening the delivery times. Nevertheless, due to compact size of those solutions, they should always be implemented with utmost caution for the type of delivered shipments. The limited cargo space of the droid often indicated the need to couple the system with an assisting technology for larger parcels and for those not willing or not capable of using the droids.

Nevertheless, it is important to investigate whether the usage of delivery droids would be sustainable throughout the entire lifecycle, using the cradle to grave approach. Therefore, as a next step complementing this research, a thorough LCA of the solution would be needed. In particular LCA could be applied to understand the number of droids which could be sustainably replaced by an electric LCV. This would considerably strengthen the sustainability assessment of last-mile delivery services, especially when several droids would be needed. Moreover, before the delivery droids are allowed to freely roam on pavements of our cities, viable safety tests must be performed along with digital education and co-creation with those users unwillingly excluded by technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1 Ranking of the delivery solutions

For the ranking, the smallest value is assigned to the most desirable outcome whereas the highest value is assigned to the solution that performs the worst in each indicator. Moreover, to penalize the worst performing delivery solutions and reward the best performing ones, the ranking is kept always between 1 and 6 (e.g. if there is just one differentiative result, as in the share of door-to-door deliveries, the best performing solutions will all be ranked as 1 while the worst performing ones will be ranked 6). The results of the ranking are presented hereunder in Table 5.

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