



Research paper

Operational cost analysis for e-commerce deliveries using agent-based modeling and simulation

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ABSTRACT

The COVID-19 pandemic has highlighted the growth of e-commerce around the world. Especially in developing countries, assisted home delivery (AHD) is the main way for people to receive their goods purchased online. This delivery policy can result in delivery failure when the consumer is not at home and, consequently, in greater externalities that impact all stakeholders in last mile logistics. This paper aims to evaluate the operating costs of delivery lockers (DLs) through agent-based modeling and simulation. A total of 84 scenarios were simulated alternating the DLs usage rate and different delivery attempt policies. The results show that the most impacting system costs are time, external and re-delivery costs. The implementation of DLs and the exclusion of the three-attempt delivery together can reduce these costs and increase net profit by up to 79.1%. Therefore, DLs have economic potential for last mile logistics operations. However, this solution must be accompanied by incentive policies resulting from stakeholder engagement. We hope that this study contributes to a greater understanding of DLs as a sustainable solution for last mile e-commerce deliveries, helping decision makers in urban freight transport.

1. Introduction

The growth of e-commerce is a worldwide trend and was even more accentuated during the COVID-19 pandemic, something that tends to continue, although not with the same intensity (Maltese et al., 2021). In Brazil, this growth is evidenced by the nominal increase of 27% and 10% in revenue and in the number of new consumers, respectively, in 2021 compared to the previous year (NielsenIQ Ebit, 2022). However, along with the e-commerce growth, there is a greater demand for individual deliveries, resulting in an increase in the circulation of cargo vehicles in cities (Cardenas et al., 2017) and, consequently, causing problems in urban freight transport (UFT) activities in the last mile (Holguín-Veras et al., 2020). The majority use of motor vehicles to meet this demand is one of the biggest contributors to CO₂ emissions, in addition to decreasing the accessibility of urban roads and increasing the rate of noise pollution and congestion in cities (Enomoto & Lima, 2007; Zissis et al., 2018).

These problems are even more intensified by consumers' preference for Assisted Home Deliveries (AHD), which, in Brazil, follows the three-attempt delivery policy. This type of delivery requires a person to

receive the package. However, the consumers may not be at home to receive their order, which results in a "failed delivery". When the delivery does not occur on the first attempt, other two attempts may occur in the following days. The item is usually returned to the sender if the delivery cannot be completed after the third attempt. It results in high costs that must be afforded by the carrier, online retailer, or consumer (Gevaers et al., 2014). Therefore, it is important to rationalize e-commerce deliveries due to the high rates of delivery failures, as well as the high cost and environmental impact of AHD (Iwan et al., 2016).

In this sense, City Logistics becomes an ally for business to consumer (B2C) deliveries, promoting the optimization of activities related to the distribution of goods in urban centers carried out by public or private entities and considering factors such as traffic, congestion, and energy consumption. This concept is based on the understanding of the problems that include distribution costs, seen from the private perspective, and social and environmental costs, observed by public entities (Taniguchi et al., 2001). One of City Logistics' main initiatives for AHD is the use of delivery lockers (DL) which are automated lockers that consumers can pick up and/or return their goods purchased online (Alves et al., 2019). This study focuses on DLs due to their potential demand in Brazil

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and because they operate 24 h a day (Oliveira, Morganti, et al., 2017).

Given the above, this study aims to evaluate the operational costs of delivery lockers, considering the behavior and interaction between stakeholders in urban freight transport through agent-based modeling and simulation (ABMS). The analyses are presented in terms of operational costs, external costs, and earnings obtained in scenarios that alternate the use of DLs and different delivery attempt policies. Therefore, this paper makes a major contribution to research on last mile logistics by investigating the operational feasibility of a city logistics solution with great potential to be inclusive, resilient, and sustainable. This paper is organized as follows: Following this introduction, Section 2 presents a literature review; Section 3 describes the research method adopted; Section 4 provides the results; Section 5 presents a discussion of the results and; finally, the concluding remarks are in Section 6.

2. Background

2.1. Delivery lockers

Collection-and-delivery points (CDP) encompass the principle of self-collection, involving the customer in the delivery process. In this system, the parcels are delivered to a delivery point chosen by the customer who must go to this place to pick up the order (Arnold et al., 2018). The most well-known CDPs' configurations are (1) automatic delivery stations, also known as delivery lockers, which operate without supervision, and (2) collection points (CP) which require supervision (Morganti et al., 2014; Weltevreden & Rotem-Mindali, 2009). DLs are automated lockers operated from an electronic code, which carriers use this code to inform customers about their orders status (Twan et al., 2016). In CPs, on the other hand, orders are delivered to a store that manages, receives, and delivers the goods, such as laundry, gas station, or post office (Dell'amico & Hadjidimitriou, 2012).

Among the advantages of a CDP, whether DL or CP, there are: (1) the customer does not have to stay at home all day waiting for their delivery; (2) a high customer satisfaction rate; (3) high level of service security; (4) reduces extra distances traveled due to re-deliveries; (5) enable optimization of routes; (6) enable delivery tracking; (7) enable better use of vehicles; (8) 100% of deliveries are successful (Dell'amico & Hadjidimitriou, 2012; McLeod et al., 2006; Morganti et al., 2014; Wang et al., 2014; Friend & Lima, 2011; Weltevreden, 2008). In addition, CDPs also apply to reverse logistics which plays an important role in some segments of e-commerce (Iannaccone et al., 2021).

Suwatcharachaitiwong et al. (2020) investigated the use of DLs in medication distribution through convenience stores to minimize operating costs. Using a genetic algorithm, the authors concluded that the distribution cost was mostly influenced by the location and coverage of the DLs when compared to the number of lockers available. González-Varona et al. (2020) proposed a B2C delivery model that reuses old newspaper kiosks as CDPs in Valladolid, Spain. The results obtained showed that the proposed model can present reductions of about 90% of the distance traveled and CO₂ emission associated with last mile deliveries. Similar results were obtained by Milewski and Milewska (2021) that simulated AHD and DLs during the COVID-19 pandemic in Poland and identified reductions between 74% and 87% in fuel consumption per order in scenarios where the use of DLs was considered.

Like this paper, other authors also evaluated the costs of B2C deliveries considering the use of CDPs. Cardenas et al. (2017) compared the cost of this initiative with AHD deliveries. The authors concluded that the benefits of pick-up points can be obtained with a minimum number of CDPs. Melkonyan et al. (2020) explored the sustainability potential of CDPs through dynamic system simulation and multicriteria decision applied in a food network in Austria, identifying economic viability in the results. Recently, Masteguim and Cunha (2022) evaluated the use of pick-up points in São Paulo city and found that it is possible to achieve an average cost reduction of up to 53.3% in

operations that consider this type of delivery.

There is a growing interest in issues related to CDPs in the literature. However, it is not known what implications the implementation of this initiative can bring to each stakeholder because, although successfully installed in several cities, local public policies can influence the success of this system. Thus, this article aims to investigate the operational costs of DLs in Belo Horizonte, considering ABMS as a technique to support the analysis.

2.2. Agent-based modeling and simulation

Simulation models commonly used to assist decision-making in urban freight are concerned with estimating the points of origin and destination of goods and calculating the optimal route, considering traffic conditions, and, finally, generating the output parameters (Arnold et al., 2018; Durand et al., 2013). Such an analysis is static since it presents an overall optimal value for cost, demand, and traffic flow constants. Thus, the impacts of UFT are not estimated considering the different stakeholders involved in this activity. In this case, ABMS presents important advantages for analyzing urban transport as it allows incorporating the behavior of stakeholders and their reactions to the implementation of initiatives and policies, enabling the analysis of effects related to sustainability and economic and social aspects (Maggi & Vallino, 2016; Van Kolck, 2010).

In the literature, Vallino et al. (2018) used ABMS to evaluate policies promoted by Turin's municipality within the European NOVELOG (New Cooperative Business Models and Guidance for Sustainable City Logistics) project. This project deals with policies that aim to trigger more ecological behavior in retailers during the supply process. The model is based on the idea that ecological behavior depends on economic and social characteristics and individual environmental sensitivity. The authors concluded that the most effective results are obtained from monetary incentives for the purchase of an eco-friendly vehicle or by combining pricing policies. Marcucci et al. (2017) developed a multi-agent model to support UFT decisions in a low-emission zone environment in Rome. In this model, stakeholders cooperate in a participatory decision-making process aimed at building consensus through a cycle of meetings in which policy measures are discussed and collectively deliberated to balance the conflict of interests. Each simulation of the model reproduced the decision between the current situation and a certain urban freight policy.

Elbert and Friedrich (2018), Firdausiyah et al. (2019), and Van Heeswijk et al. (2019) used the ABMS to evaluate deliveries in urban consolidation centers (UCC) from different perspectives. Elbert and Friedrich (2018) evaluated the implementation of UCCs in scenarios that alternate commercial vehicle restriction policies and concluded that the more restrictive the scenarios are, the more attractive the UCC becomes. Van Heeswijk et al. (2019) tested various measures combinations, through ABMS applied to the city of Copenhagen, and presented which ones provide favorable conditions to improve the chances of long-term success for the studied UCC. Firdausiyah et al. (2019) used UCC as an initiative for their study, but the aim was to use reinforcement-based learning in dynamic programming adaptable to multi-agent simulation. The authors showed that this technique outperforms Q-learning in terms of modeling agents' behavior.

Recently, the number of studies that use ABMS applied to CDPs has increased. Reiffer et al. (2021) used this tool to model the demand for trips generated by e-commerce last mile deliveries in the city of Karlsruhe, Germany. The authors considered three options for delivery locations: work, parcel lockers or home. The results showed that the delivery success rate is higher on Saturdays and lower during working hours. Calabrò et al. (2022) presented an ABMS to compare the performance of home deliveries and CDPs in terms of consumer demand, vehicle fleet capacity and the spatial density of CDPs. The results showed that there is a trade-off between freight vehicle traveled distance, customer satisfaction and logistics costs, being possible to find an

optimal configuration that would result in the best results.

Some of these studies looked at the costs of CDPs. [Sawik et al. \(2022\)](#) applied ABMS with a multicriteria analysis to define and validate a CDPs network in the city of Poznan, Poland. The results indicated a predicted increase in population, e-shoppers, CDPs' users, parcel demands and number of CDPs in the coming years. In addition, the authors concluded that the most expressive costs are related to the service and maintenance of the CDPs. Finally, [Alves et al. \(2019\)](#) evaluated delivery lockers as a solution to reduce unsuccessful last-mile deliveries through ABMS, identifying the potential of CDPs as an environmentally and economically favorable solution for this context. In their most recent study, [Alves et al. \(2022\)](#) also identified the variables that most influence the costs of a CDP network through ABMS and Design of Experiments (DoE).

However, CDPs are not fully understood in terms of operational costs, especially when compared to AHD. As far as we know no similar studies have been conducted to calculate these costs considering the most influential variables for e-commerce last mile logistics. Furthermore, except for [Alves et al. \(2019\)](#), most current studies focus only on costs that can be objectively quantified, excluding time and externalities costs, for instance. This article fills these gaps in the literature and presents an innovative aspect by using a model with 84 scenarios that considers multi-agents with conflicting objectives to calculate the operational costs of CDPs and compare them with those of AHD.

3. Methodology

This study uses a method of modeling and simulation in a computational environment. This method is the most appropriate considering the objective proposed in this paper, as it allows the analysis of the implementation of DLs for e-commerce deliveries through comparative scenarios, without the need for intervention in the real system ([Bertrand & Fransoo, 2002](#)).

Among other types of simulation, our study uses agent-based modeling and simulation due to its ability to capture the heterogeneity and interaction between the different stakeholders of urban freight transport ([Sopha et al., 2016](#)). Therefore, these stakeholders can be modeled as agents capable of making decisions and interacting with each other and with the environment according to a predetermined situation in the model ([Taniguchi et al., 2016](#)). Their actions are decided based on their respective goals and behaviors ([Firdausiyah et al., 2019](#)).

The ABMS of this study follow an adaptation of the frameworks proposed by [Banks et al. \(2010\)](#), [Bertrand and Fransoo \(2002\)](#) and [Chwif and Medina \(2015\)](#) due to their wide applications regardless of the type of simulation. These frameworks comprise three main stages. They are (1) design of the model which allows understanding of the system to be simulated and its objectives, as well to encompassing the construction of

the conceptual model and its validation, documentation, and modeling of input data; (2) implementation of the model that consists of the construction, implementation, and validation of the computational model and; (3) analysis of the results in which the computational model is ready for experiments and execution of runs so that the simulation results are analyzed and documented. The conceptual model, including the interactions between the agents, was built based on [Grimm et al. \(2020\)](#), as detailed in [Appendix 1](#) and summarized in [Fig. 1](#).

As we can see in [Fig. 1\(a\)](#), the E-Store Agent manages the orders and sends the goods to the carrier. This agent uses heuristics to organize the load. Undelivered orders take priority over other orders and are allocated in the next day's load for resending, as they follow the three-attempt policy. If there is an order, the E-Store Agent sends the message "Start delivery" to the Truck Agent. In [Fig. 2\(b\)](#), the carrier has a distribution center (DC) near the delivery region and coordinates a specific number of "truck agents" to carry out the delivery from the store. The truck route follows the principle of the nearest neighbor algorithm. This agent sends an "Order Delivered" message to the Customer Agent so that they can collect their order on the DC or DL. When the destination is the Customer Agent's house, the order is delivered if the customer is at home; if the customer is absent, the simulated policy is applied. Thus, as shown in [Fig. 2\(c\)](#), the model classifies customers into AHD customers and DL customers. After making this choice, the Customer Agent waits for the delivery of the order, and when the order is delivered, this agent receives a message from the Truck Agent. When the order of the Customer Agent who chooses to receive it at home is not delivered, there are situations in which he can pick up the order at the nearest DC or DL. The Delivery Locker agent interacts with the Truck Agent and the Customer Agent in the model, who deliver and receive orders at these locations. DLs are a type of inanimate agent with only one location. The goal of this agent is to host as many orders as possible and increase earnings. Finally, face-to-face validations were performed for both conceptual and computational models according to [Sargent \(2013\)](#).

It is important to mention that the volume and weight of orders delivered in the model follow Triangular (0.1, 1, 0.6) m³ and Triangular (5, 20, 15) kg distribution, respectively. This implies that the type of products considered in the model can be varied, such as some telephony, electronics, clothing and footwear, cosmetics, books, among other products. According to [NielsenIQ Ebit \(2022\)](#), these types of products can represent up to about 60% of the Gross Merchandise Volume (GMV) of e-commerce in Brazil. Perishable products were excluded from the proposed model.

This paper focuses only on the analysis stage of the methodology framework. The previous steps, i.e. the construction of the conceptual and computational model, can be consulted in detail in [Alves et al. \(2019\)](#).

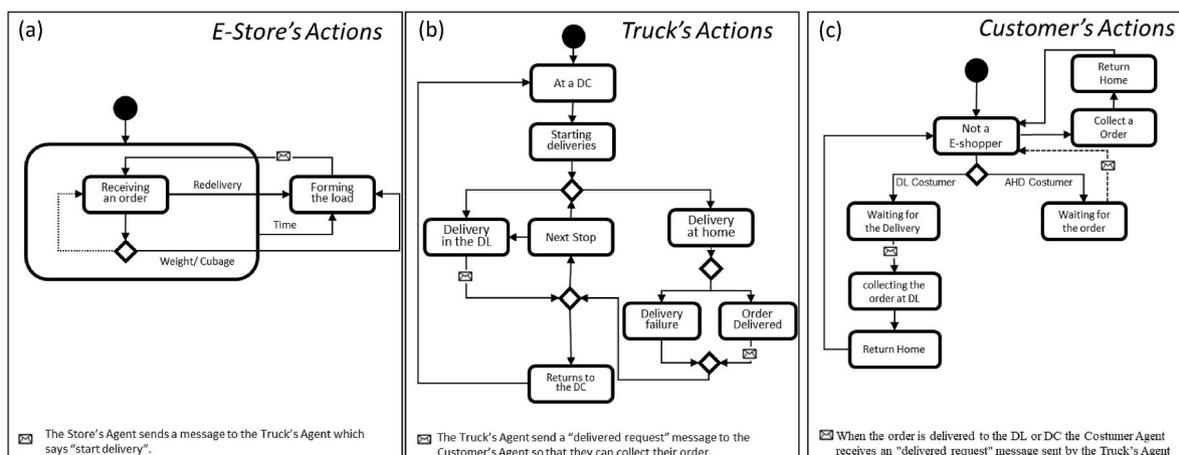


Fig. 1. Actions and interactions of agents.

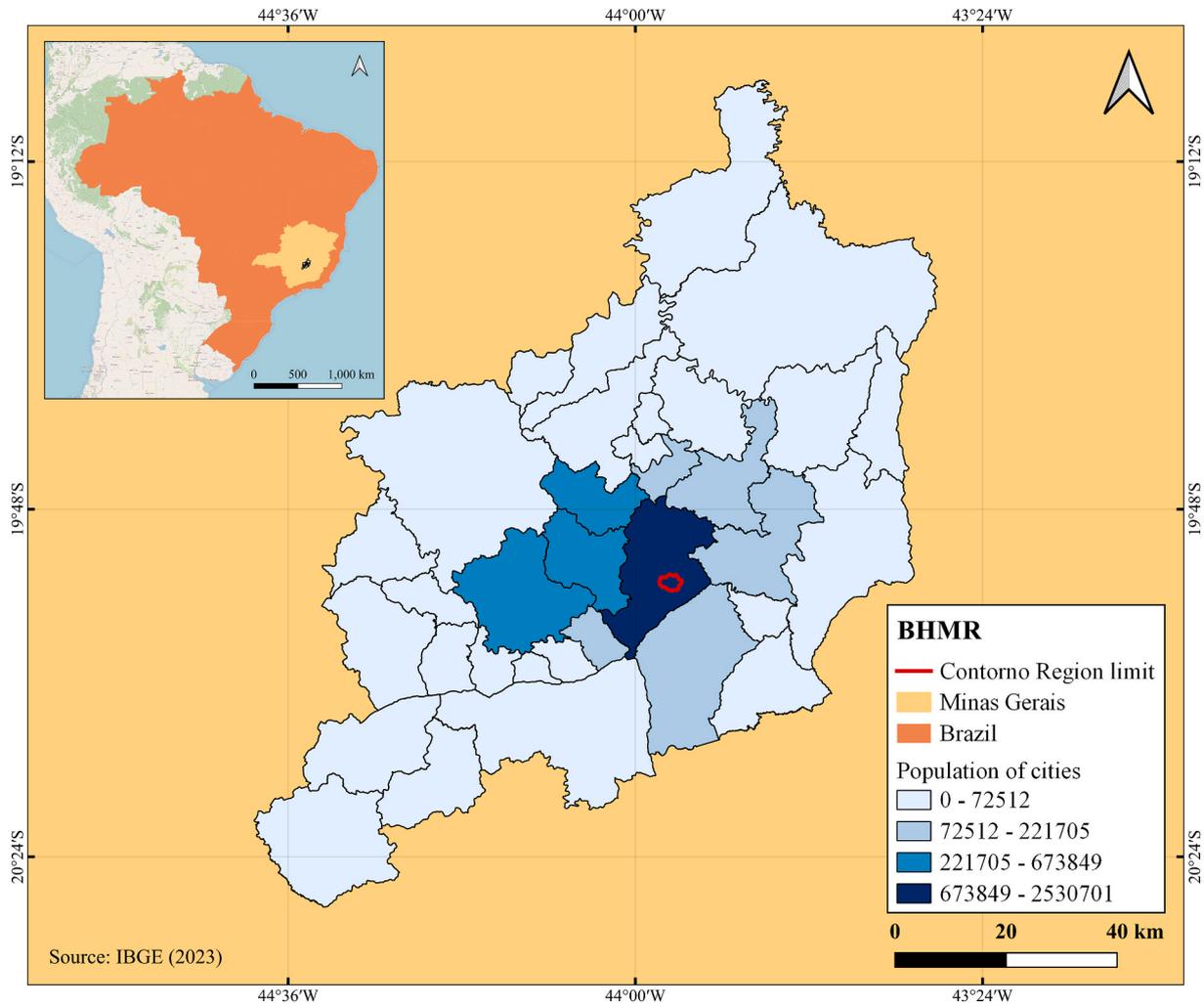


Fig. 2. Map of the study region. Source: IBGE (2023).

3.1. Costs basis of calculation

In order to compare overall results for each simulated scenario, a cost analysis was performed based on operational costs previously mentioned in the literature and on our conceptual model. Thus, the results found for each agent will be calculated in terms of costs and earnings obtained. Table 1 shows each cost considered in the analysis and its corresponding equation.

The cost of fuel was obtained for both carriers (C_{TF}) and consumers (C_{CF}) based on fuel consumption per vehicle, fuel price per liter and distance traveled. The calculation of the re-delivery cost (C_{re}) is important due to the three-attempt delivery policy that currently occurs in the study region. This cost refers to situations in which the customer does not receive their orders in the first attempt, making re-deliveries necessary. It is calculated based on the number of re-deliveries and the cost associated with each order in these situations.

Parameters not commonly monetized in previous studies were also considered. The cost related to the carrier’s delivery operating time (C_T) followed the methodology proposed by the Brazilian entities Institute of Applied Economic Research (Ipea) and National Association of Public Transport (ANTP). The calculation of external costs was based on the externalities that receive the most attention in the literature, such as the emission of pollutants, noise, and congestion. This last cost was calculated for both freight vehicle trips (C_{ET}) and consumer trips (C_{EC}).

The sum of these costs represents the total cost (C_{TOTAL}). Finally, the

Table 1

Equations used to calculate costs and gains.

Type	Equation	Description
Fuel Cost (C_F)	$C_F = C \times p \times D$	C : Fuel consumption per vehicle; p : Fuel price; D : Distance traveled (km).
Re-delivery cost (C_{re})	$C_{re} = C_r \times P_{ne}$	C_r : Re-delivery cost; P_{ne} : Not delivered orders.
Total cost of travel time (C_T)	$C_T = \frac{w \times ES \times FA \times HP}{y_w} \times t_v \times n_v$	w : Average monthly income of carriers; ES : Social charges of 95.02% (1.9502); FA : Possibility of alternative use of time; HP : % of productive use of conveyor time; y_w : Working time per month (min); t_v : Conveyor travel time (min); n_v : Number of trips taken.
External costs (C_E)	$C_E = k \times D$	k : Emission coefficient; D : Distance traveled (km).
Earnings on hosting (E_h)	$E_h = k_h \times Q_h$	k_h : Hosting order earning; Q_h : Hosted quantity.

Table 2
Parameters used to calculate costs and gains.

Parameters	Quantity	References
Fuel consumption truck (diesel)	0.13 L/km	
Fuel consumption car (petrol)	0.11 L/km	
Diesel cost	US\$0.68/L	
Petrol cost	US\$0.89/L	
Average monthly income of carriers (w)	US\$866.47	NTC & Logística (2018)
Possibility of alternative use of time (FA)	0.3	Ipea and ANTP (1999)
Percentage of productive use of time (HP)	0.5	Ipea and ANTP (1999)
Working time (y_w)	13,200 min/month	NTC & Logística (2018)
External Cost Factor Truck (k)	US\$617.91/km	Cardenas et al. (2017)
External Cost Factor Car (k)	US\$0.48/km	European Commission (2014)
Hosting order earning (k_h)	US\$0.97/order	
Re-delivery cost (C_r)	US\$3.87/order	NielsenIQ Ebit (2018)

net profit (N_p) is obtained by subtracting DLs' earnings when hosting an order (E_h) and the total cost. Finally, Table 2 presents the parameters used to calculate all costs and earnings. The other parameters necessary for the analysis, but not included in Table 2, were obtained through the performed simulation in this study.

4. Results

The computational model was implemented in Anylogic® software. This software presents an integration of ABMS with Geographic Information System (GIS), which allows the georeferencing of data and agents in the simulation environment. The computational model of this study defined that both the DLs and the DC have a fixed location on the map. The Customer and Trucks Agents are randomly allocated and can choose a route and move around.

4.1. Case study

The computational model was implemented for the Contorno Region of Belo Horizonte, the capital city of Minas Gerais, Brazil. This region is limited by an avenue that receives the same name and surrounds the central region of the city. Originally, the Contorno Region was designed so that urbanization would only occur in its interior. However, the city has already exceeded this limit and is currently the seat of the third most populous metropolitan region in Brazil. Fig. 2 shows the Belo Horizonte Metropolitan Region (BHMR) and the study region highlighted in red.

Belo Horizonte has the fifth largest GDP of Brazilian cities. There are 1,783,961 vehicles in the city (68% cars, 16% light cargo, 12% motorcycles, 3% heavy vehicles, and 1% buses), an average of 1.4 inhabitants per vehicle (IBGE, 2011). The biggest transport problems in the city are related to the high travel time, the high use of private vehicles and the low use of public transport (Kijewska et al., 2021). Since 2009, there are municipal laws in Belo Horizonte (BHTRANS DPR No. 138/2009, BHTRANS DPR No. 077/2014 and BHTRANS DPR No. 004/2019) that address restrictions on the capacity and size of freight vehicles, especially those circulating in the Contorno Region. This resulted in an increase in the number of freight vehicles in the city (Oliveira, Abreu, et al., 2017).

The Belo Horizonte Mobility Plan pointed that generation of trips is greater in the study region, affecting the transport of people and cargo due to the currently low efficiency of road circulation there, which is also one of the biggest problems according to the residents (Kijewska et al., 2022). Regarding last mile logistics, most deliveries are AHD and follow the three-attempt policy in Belo Horizonte. Thus, it is evident that this policy increases freight costs due to the incidence of re-deliveries and, consequently, generates more externalities in the city. The

Contorno region was chosen due to the greater availability of data and economic relevance for Belo Horizonte. In addition, the region has a high population density, mainly of people with higher incomes, and concentrates a significant number of potential consumers of e-commerce, whether residents or workers (Oliveira, Morganti, et al., 2017).

4.2. Comparative scenarios

In order to investigate more effective and efficient alternatives for re-deliveries in the study region, comparative scenarios were developed considering different delivery attempt policies and DLs implementation, as detailed below:

- **Scenario 1 or base scenario - AHD deliveries and three-delivery attempts:** The first scenario is taken as the base scenario because it resembles reality. In this scenario, all deliveries must be AHD and respect the three-delivery attempts policy. This scenario is expected to be the "worst" because it requires many delivery attempts.
- **Scenario 2 - DLs implementation and three-delivery attempts:** In this scenario, some customers choose to receive their deliveries in DLs. The AHD deliveries remain and, for this case, the three-delivery attempts. It is expected to obtain gains both in the reduction of failed deliveries and in kilometers traveled.
- **Scenario 3 - DLs implementation, without three attempts and with re-delivery to the DC:** Customers continue to choose if they prefer AHD or DLs. However, if an AHD is not made on the first attempt, the carrier transports the package to the DC which will inform customers to pick up their orders there. It is expected that the truck route and the number of trips will decrease as they have fewer orders to be transported since it is no longer necessary to include re-delivery orders in the load.
- **Scenario 4 - DLs implementation, without three attempts and with re-delivery to DLs:** Customers can still choose between AHD and DLs. However, if the AHD is not received on the first attempt, the carrier leaves the order in the closest DL to the customer's house and informs them where their order is waiting to be picked up. It is expected that this scenario will bring greater gains for all stakeholders and that the truck will reduce its route, as well as the number of trips as a result of lower load. In addition, it is expected that DLs will host more orders and the average distance traveled by customers may be less than that obtained in Scenario 3, due to the use of DLs.

In the development of the scenarios, variations of the input parameters that presented significance according to a study carried out by Alves et al. (2022) were added, and they are: (1) the DLs use rate; (2) the first attempt delivery failure rate and; (3) the truck stoppage time. Also, the number of orders placed by customers in a year varied into 1, 3, and 6. According to Oliveira, Morganti, et al. (2017), if each customer places 1 order per year in the studied region, there is an average of 80 orders per day. Similarly, demand variations were calculated for 3 orders per year (240 orders per day) and 6 orders per year (480 orders per day).

The choice to simulate different order demands was based on the assumption that there is a greater number of orders placed in areas with higher population density. Thus, assumptions about e-commerce deliveries in cities of small, medium, and large population density can be made by varying the demand. In addition, these values can represent the difference between the performance of a carrier with low, medium, and high market share.

Fig. 3 shows the groups of scenarios that represent each combination of input parameter variations as detailed. For instance, groups A and B represent scenarios that simulate a demand of 80 orders/day with a truck stoppage time of 5 min and a failure rate on the first attempt of 5%. Group A differs from Group B in terms of the DLs use rate, being 22.5% and 45%, respectively. Groups A* and B* differ from groups A and B only in relation to the truck stoppage time parameter, which becomes 10 min. All other constructions followed the same logic and were combined with

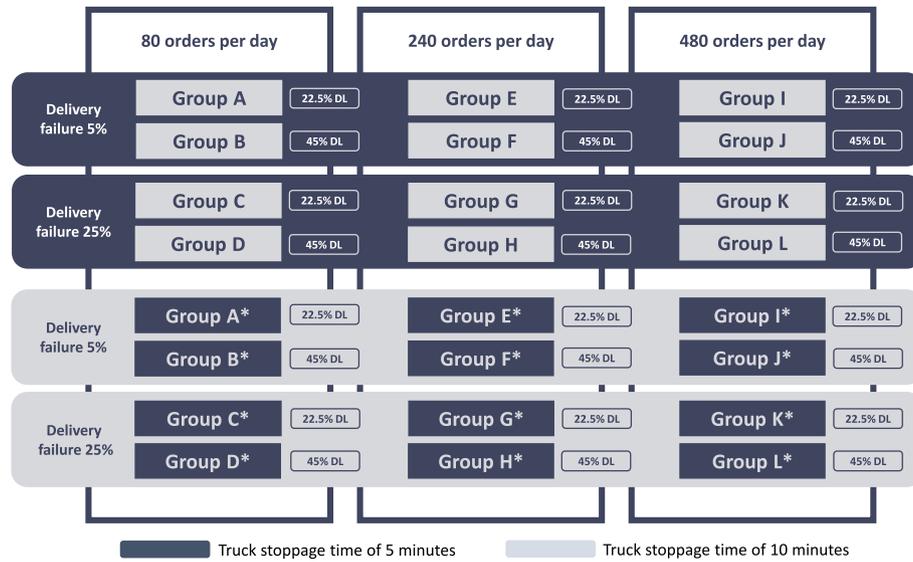


Fig. 3. Scenarios design logic.

each other.

4.3. Cost analysis

All results were calculated from the mean of 3 replications of each scenario. Table 3 presents the costs, earnings, and profits of the simulated scenarios. It is observed that the base scenarios have lower total costs in most configurations. This is explained because there is no customer travel in these scenarios and, consequently, the costs related to customers (C_{CF} and C_{EC}) are zero. However, when considering the host earnings obtained with the use of the DLs (E_h), the net profit in the group of scenarios 2 exceeds that obtained in the base scenarios hence the worst net profit.

The scenarios that simulate the highest failure rate in the first delivery attempt (C, D, G, H, K, L) presents higher total costs when compared to those of the same configuration, but with a lower failure rate in the first delivery attempt. This is because the costs related to the truck (C_{TF} , C_{ET} , C_T) and the cost of re-delivery (C_{re}) are higher in the scenarios with the highest failure rate, except for groups of scenarios 3 in which the cost with trucks does not change regardless of the failure rate. This result can be explained by the fact that there are no re-deliveries in Scenarios 3 and the truck takes undelivered orders to the DC at the end of the day, which does not add extra stops to its route unlike Scenarios 2 and 4. On the other hand, in relation to customer costs in Scenarios 3, external and fuel costs (C_{CF} , C_{EC}) increased between 36% and 59% in scenarios that simulate a higher failure rate on the first attempt when

Table 3
Costs in thousands of US\$ of each scenario.

Scenario	C_{TOTAL}	E_h	N_p	Scenario	C_{TOTAL}	E_h	N_p	Scenario	C_{TOTAL}	E_h	N_p
Base(AB)	- 24.56	-	- 24.56	Base(EF)	- 37.55	-	- 37.55	Base(IJ)	- 53.46	-	- 53.46
2A	- 28.12	6.34	- 21.77	2E	- 53.63	19.08	- 34.54	2I	- 85.24	37.99	- 47.25
2B	- 28.83	12.72	- 16.11	2F	- 66.12	38.08	- 28.04	2J	- 106.10	75.99	- 30.11
3A	- 27.96	6.40	- 21.56	3E	- 53.90	18.97	- 34.93	3I	- 83.91	38.11	- 45.81
3B	- 29.68	12.71	- 16.96	3F	- 64.00	38.31	- 25.69	3J	- 108.79	76.15	- 32.64
4A	- 27.08	7.47	- 19.61	4E	- 48.20	22.35	- 25.85	4I	- 77.43	44.61	- 32.82
4B	- 27.55	13.43	- 14.12	4F	- 59.09	40.37	- 18.72	4J	- 103.59	80.83	- 22.77
Base(CD)	- 32.72	-	- 32.72	Base(GH)	- 65.68	-	- 65.68	Base(KL)	- 107.29	-	- 107.29
2C	- 34.61	6.36	- 28.25	2G	- 77.24	19.05	- 58.19	2K	- 125.22	38.11	- 87.11
2D	- 34.13	12.74	- 21.39	2H	- 80.65	38.25	- 42.40	2L	- 137.80	76.12	- 61.67
3C	- 38.32	6.39	- 31.93	3G	- 80.33	19.14	- 61.19	3K	- 143.56	38.08	- 105.48
3D	- 36.02	12.70	- 23.33	3H	- 84.99	38.03	- 46.96	3L	- 147.65	76.26	- 71.39
4C	- 33.08	11.83	- 21.26	4G	- 59.16	35.54	- 23.61	4K	- 103.43	70.96	- 32.47
4D	- 31.67	16.68	- 14.99	4H	- 69.02	49.79	- 19.23	4L	- 121.58	99.52	- 22.06
Base(AB)*	- 26.20	-	- 26.20	Base(EF)*	- 45.87	-	- 45.87	Base(IJ)*	- 61.77	-	- 61.77
2A*	- 29.35	6.33	- 23.02	2E*	- 62.20	19.16	- 43.04	2I*	- 91.85	38.22	- 53.63
2B*	- 28.89	12.74	- 16.15	2F*	- 74.60	38.17	- 36.44	2J*	- 115.64	76.22	- 39.42
3A*	- 28.33	6.31	- 22.02	3E*	- 60.46	19.03	- 41.43	3I*	- 90.13	38.23	- 51.90
3B*	- 29.23	12.69	- 16.54	3F*	- 73.03	38.11	- 34.92	3J*	- 117.17	76.29	- 40.87
4A*	- 28.20	7.39	- 20.81	4E*	- 58.55	22.49	- 36.06	4I*	- 86.80	44.69	- 42.11
4B*	- 29.29	13.51	- 15.79	4F*	- 69.18	40.38	- 28.80	4J*	- 112.15	80.94	- 31.21
Base(CD)*	- 37.25	-	- 37.25	Base(GH)*	- 68.52	-	- 68.52	Base(KL)*	- 112.20	-	- 112.20
2C*	- 37.25	6.35	- 30.90	2G*	- 79.02	17.80	- 61.22	2K*	- 125.36	35.93	- 89.43
2D*	- 35.25	12.76	- 22.49	2H*	- 90.07	38.12	- 51.94	2L*	- 148.37	76.22	- 72.15
3C*	- 38.74	6.32	- 32.42	3G*	- 88.98	19.04	- 69.94	3K*	- 148.73	38.09	- 110.65
3D*	- 37.40	12.71	- 24.69	3H*	- 90.92	38.19	- 52.72	3L*	- 157.02	76.40	- 80.62
4C*	- 33.66	11.78	- 21.88	4G*	- 71.26	35.58	- 35.68	4K*	- 109.82	70.71	- 39.11
4D*	- 32.87	16.57	- 16.31	4H*	- 78.01	49.81	- 28.20	4L*	- 126.07	99.48	- 26.59

compared to those with a lower failure rate. The greater failure leads to a greater number of customers picking up their orders at the DC, increasing their costs.

The costs related to trucks are higher in Scenarios 4 when compared to Scenarios 3. Still, the total cost is lower in Scenarios 4, as the lower customer costs outweigh the truck costs. This is because there is a reduction in customers' external and fuel costs in these scenarios, and the average distance to pick up an order in the DL (Scenarios 4) is up to 60% shorter than going to the DC (Scenarios 3). In addition, Scenarios 4 show the highest hosting earnings and the highest net profit in all settings.

When compared to each other, there is a small difference in net profit by changing the failure rate in Scenarios 4. As the number of orders/day increases, it is possible to observe that the net profit becomes greater in the scenarios with the highest failure rate, due to the greater hosting earnings in these scenarios. In this way, DLs can help reduce costs when there are higher failure rates on the first delivery attempt. In general, the scenarios that have in their configuration a percentage of 45% of DL use (B, D, F, H, J, L) presents a higher net profit that varies between 17% and 36% when compared to those of the same configuration but with 22.5% of DL use (A, C, E, G, I, K).

Regarding the influence of the truck stoppage time, the biggest difference in terms of cost in the simulated scenarios with a stoppage of 10 min is about the costs of the truck, with emphasis on the cost over time (C_T), reaching up 39.2% higher than in scenarios with a stoppage of 5 min. This is because, in general, scenarios with higher stoppage time require a greater number and travel time to meet daily demand. The other costs show a considerably small variation but are not proportional.

Fig. 4 presents the average total cost per order for each simulated demand, in addition to how much the external costs represent these values. It is observed that the scenarios of 480 orders/day (I, J, K, L, I*, J*, K*, L*), which can characterize a city with a high population density or a carrier with a high market share, provided a cost reduction per delivery that can reach up to 56.7% (US\$0.84 versus US\$1.95) when compared to scenarios of 80 orders/day (A, B, C, D, A*, B*, C*, D*) that characterize a sparsely populated area or a small carrier. When comparing a densely populated urban area (480 orders/day) with an average density (E, F, G, H, E*, F*, G*, H*) (240 orders/day), this reduction is only 13.7% (US\$0.84 versus US\$0.98).

The analysis of external costs (Fig. 4) was performed to analyze the main externalities of deliveries, such as emission, noise, and congestion. The external cost of the customer varies similarly regardless of the simulated demand, having its peak in Scenarios 3, which can be explained by the greater distance between the DC and the customers'

homes. In addition, it is noted that the external cost of customers represents larger portions of the total cost as demand increases, although there are no significant changes in absolute values. The external cost of the truck represents a considerable portion of the total cost per order in low-demand scenarios (80 orders/day), representing an average of 38.6% of the total cost per order. However, whereas a higher demand is simulated, the external cost of the truck decreases, representing on average only 21.9% of the total cost per order.

In short, scenarios with higher demand generate higher total costs. However, the cost per order is lower in these scenarios, due to the lower number of stops made and greater consolidation of deliveries. This result may be even lower in scenarios that consider the use of DLs. Furthermore, it can be said that DLs benefit both urban centers with higher population density and those with lower population density.

5. Discussion

According to the results obtained, it is observed that the costs that most impact the total cost of e-commerce deliveries are: time and external costs and, for scenarios that have re-delivery (Scenarios 1 and 2), the cost of re-delivery. External costs tend to be higher when customers must move either to DC (Scenarios 3) or DLs (Scenarios 4). On the one hand, if it is to DC (Scenarios 3), which is usually located in regions far from residential areas, customers tend to use more motor vehicles. On the other hand, if it is to DLs (Scenarios 4), there is a reduction in these costs when compared to Scenarios 3, as the consumer travels on average shorter distances to collect failed deliveries in the DLs, as opposed to traveling to the CD. Cardenas et al. (2017) and Iannaccone et al. (2021) also found that the consolidation promoted by the greater use of DLs is beneficial for external costs.

Associated with this, if the DL is within a walking distance, it is more likely that people will not use their private vehicles to pick up their orders, which makes customers feel more likely to accept this delivery option (Arnold et al., 2018; Cardenas et al., 2016; Iannaccone et al., 2021; Iwan et al., 2016). The simulation results show us that customer trips to DLs have an average round trip distance of 2.1 km. Thus, Morganti et al. (2014) and Kedia et al. (2017) highlighted the importance of understanding the distance that the consumer considers acceptable to walk or cycle, as this information will help determine which size and location the DLs network should be installed. In this sense, Oliveira, Morganti, et al. (2017) highlighted the importance of studies that show consumers' behavior. Actionable data will allow us to assess which distance would encourage customers to use non-motorized vehicles to pick up their orders and even which location would be more conducive

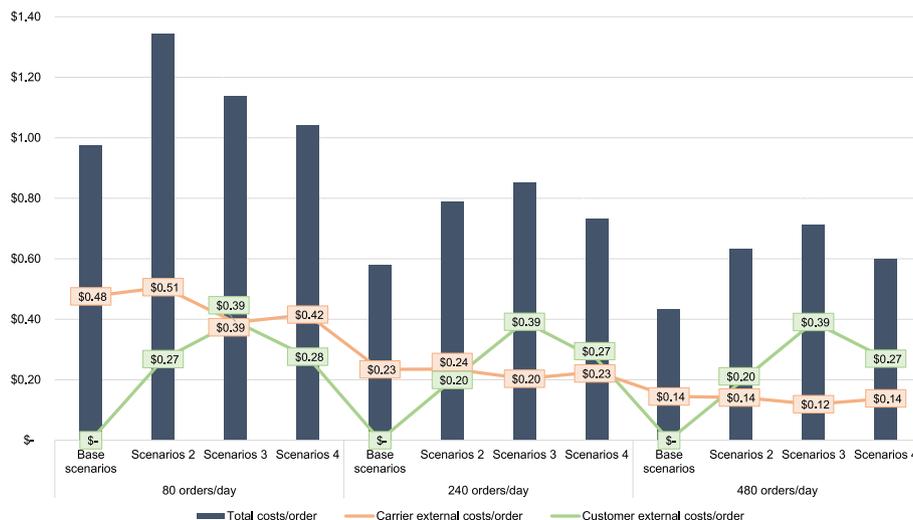


Fig. 4. Average costs per order.

to chaining trips.

Morganti et al. (2014) attested in their study that strategies to reduce delivery failures, such as calling the absent customer, and delivering to the concierge or a neighbor, have been increasingly used to reduce the costs of last mile operations. The results presented here indicate that the scenarios with the highest net profit are those with the lowest failure rate in the first attempt combined with the highest use of DLs. Thus, using DLs associated with delivery failure reduction strategies can represent a significant increase in system profits.

These results highlight that more active customer participation in B2C deliveries is highly cost-efficient for carriers. However, promoting this can be difficult, as most customers are used to the comfort of AHD. In addition, this preference tends to intensify in the face of post-COVID-19 pandemic changes, which make people spend more time at home and adhere to remote work and distance learning. Therefore, one idea to promote this change is to offer financial discounts on their deliveries. The results of this paper suggest that, with the savings achieved by cargo consolidation in the scenarios with DLs, companies could offer discounts of up to US\$3.68 per order to customers who choose to pick up their order, without changing the profit of the carriers. A similar result was found by Arnold et al. (2018). The authors also suggested that the authorities assist in promoting the use of DLs if carriers reduce external costs. This can be done by using bicycles, alternative fuel vehicles, and electric vehicles to deliver (Ehrler et al., 2021; Teoh et al., 2018).

As seen in the results of Scenarios 4, the high external cost generated by consumers when picking up their orders in the DLs may make this initiative unattractive and difficult for the local government to support it. Thus, the importance of the proper location of the DLs is emphasized because the strategic location can facilitate non-motorized access. Once again, less polluting vehicles can be allies to balance these external costs. These combinations of initiatives may be encouraged by public authorities.

Regarding managerial implications, some previous studies also highlighted that DLs require greater stakeholder collaboration and engagement in last mile logistics planning (Alves et al., 2022; Wang et al., 2021). This implies that each of these companies, whether they are retailers or carriers and public or private, must reformulate their managerial values. On the one hand, this is a difficult decision to plan and execute. On the other hand, greater collaboration also provides greater resilience in multi-level supply chains, which has been encouraged to guarantee basic supplies to people in recent years, mainly after the COVID-19 pandemic (Boyaci-Gunduz, Ibrahim, Wei, & Galanakis, 2021).

CDPs, whether automatic or not, are usually located in different types of commercial establishments, such as supermarkets, pharmacies, public transport stations, among others. Consequently, this city logistics initiative increases the flow of people visiting these places. In Poland, 52% of CDP users also make purchases at these establishments (Iwan et al., 2016). Therefore, although many managers classify them as one more activity to be managed, CDPs promote potential extra income earnings for the establishments that host them. This can be used as an incentive to maintain CDP operations.

In Brazil, the gains of DLs are not yet observed, due to their small and recent use, especially in Distrito Federal, Rio de Janeiro, and São Paulo. The findings of this study can be observed in large Brazilian and Latin American cities where deliveries are not left unattended on the street due to the risk of theft. As this is a developing e-commerce market, stores are unable to offer different delivery options to their customers, for instance, with a time window service that is acceptable with the consumers' needs. This implies that re-delivery occurs in most cases, as the carriers' delivery time window usually coincides with the time that customers are at work. Thus, the use of DLs is a viable delivery option for customers seeking greater flexibility to receive their goods, reducing the number of re-deliveries to carriers.

6. Conclusions

This paper aims to analyze the operational costs of DLs as a last mile solution for e-commerce deliveries based on scenarios implemented through ABMS. This analysis was based on the simulation of 84 scenarios. In addition to the base scenarios, similar to the real situation, without DLs and with three-attempt delivery, three other groups of scenarios were constructed considering the deployment of DLs and the exclusion of the policy of the three-attempt delivery. Also, different demands and variations in the input parameters were considered for each of the four situations.

As expected, the base scenarios showed the worst net profit. The implementation of DLs (Scenarios 2) brings improvements in terms of reducing re-deliveries and earnings obtained, increasing net profit. In addition, the benefits are even greater when the possibility of the three-attempt delivery is excluded. However, an unintended effect of DLs is increasing the number of private trips customers make to pick up their goods. The ABMS showed that customers travel long distances when they must pick up their failed deliveries at the DC (Scenarios 3), which could increase vehicle traffic in the region. When DLs are used to receive failed deliveries (Scenarios 4), the distances traveled by customers can be reduced by up to 60% when compared to Scenarios 3 and can be traveled by bicycle or on foot in many cases. The same goes for customers who initially choose DLs to receive their orders.

Thus, when combined, the implementation of DLs and the exclusion of the three-attempt policy represent an attractive delivery system, which can increase the number of orders delivered by 16.7% and net profit by up to 79.1%, when compared to the base scenarios. The efficiency of this system can be further enhanced by encouraging customers to use DLs, as AHD is still their preferred way to receive their orders. Therefore, the implementation of DLs must be accompanied by incentive policies for customers to use the DL through, for example, a discount on delivery or another type of bonus, monetary or not. Furthermore, security policies must be considered in DL projects in Brazil to offer less risk for the users and their goods. That is why both public and private institutions must be involved and promote DLs as a solution to avoid the externalities caused by last mile deliveries.

These findings are subject to certain limitations. The study is limited by the lack of information in the calculation to monetize the externalities, which we consider emissions, noise, and congestion as the main ones. However, we acknowledge that there may be other influential externalities as this is still under discussion in the literature. Furthermore, data collection is crucial in modeling and simulation studies. We identified a great difficulty in this step due to the complexity of last mile logistics involving several stakeholders. However, we were able to obtain the missing data based on previous research.

These limitations do not invalidate the gain achieved in this study but provide some insights for future research. A greater focus on calculating costs, especially on external costs, could be improved considering the costs of searching for parking spaces and even possible penalties with fines, for example. Further research into combining DLs and other City Logistics initiatives is also strongly recommended, such as off-peak and eco-vehicles deliveries. Finally, this study can also be expanded by other areas of knowledge, such as sciences that study consumer behavior, which could provide a greater understanding of the decision-making of future users of DLs.

Finally, the analysis of DLs undertaken here has extended our knowledge of this initiative as a solution to reduce the externalities of AHD. Therefore, this study brings several contributions to the current literature. First, this paper also contributes to the recent context of the COVID-19 pandemic, which has promoted greater attention to online shopping. Second, it provides meaningful insights into an innovative e-commerce last mile delivery solution for a country where AHDs are still most widely used. Third, it highlights DLs as a sustainable city logistics policy, both in economic, environmental, and social terms. Fourth, it also underlines the active participation of the population in last mile

delivery operations, which can make supply chains more inclusive and resilient. Fifth, it uses modeling and simulation as a technique to encourage the engagement of stakeholders who often have conflicting goals. Last, but not least, it presents a model with high replicability in other regions and for other last mile logistics solutions.

CRedit authorship contribution statement

Roberta Alves: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Cecília Aparecida Pereira:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Renato da Silva Lima:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.retrec.2023.101348>.

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