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Assessing the Impact of Time Windows on Last-Mile Sustainability: A Scoreboard-Based Approach and Case Study Analysis

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Abstract:

Purpose: To ensure customer satisfaction, e-retailers have focused on providing a last-mile service that includes time windows. Due to the sustainable challenge this posed, the purpose of this article is to define a method that can be used to evaluate the impact of time windows on sustainability and to apply this method to a particular case study.

Design/methodology/approach: Desk research allows us to identify and define this method (based on a scoreboard). Then, a case study is conducted to evaluate the applicability of the scoreboard and analyse the impact of time windows on sustainability.

Findings: A method to evaluate the impact of time windows on the three pillars of sustainability is defined and implemented. Through this implementation, the negative impact time windows have on the last-mile sustainability is identified and defined. Thus, the use of time windows leads to a greater impact on the environmental and social pillars. Regarding the economic pillar, the impact is ambiguous. Time windows have a negative impact on delivery costs and vehicle utilisation, but a positive impact on service levels and customer satisfaction. In this sense, intermediate alternatives can largely maintain the benefits of time windows elimination without significantly affecting the service level.

Originality/value: Retailers can use the findings as a guide to evaluate and set up sustainable last-mile strategies, deciding whether the use of time windows is necessary and sustainable. In contrast to previous research, this study integrates the three pillars of sustainability. With this integration, it is concluded that intermediate alternatives, such as offering a limited time window system based on historical data, could be the most sustainable solution.

Keywords: last mile, e-commerce, sustainability, time windows

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1. Introduction

With the disproportionate increase in online sales, the last mile has become a critical factor in the online channel (Buldeo-Rai, 2019). Thus, being the transport of online orders from the last point of transit from the retailer to the point of consumption (Halldorsson & Wehner, 2020), it is the only point of physical contact between the online retailer and the consumer (González-Romero & Prado-Prado, 2023).

Given its importance, efforts to enhance customer satisfaction have driven the development of last-mile strategies that equal or even surpass the service experience offered in-store (Buldeo-Rai, 2019). In this context, online retailers have aimed to differentiate themselves through comprehensive value propositions, including faster deliveries, multiple delivery points, and free returns (Dumez, Tilk, Irnich, Lehuédé & Péton, 2021; Xu, Jiang & Li, 2013). Additionally, retailers are increasingly focused on offering competitive prices alongside more sustainable services. This approach allows e-retailers to synchronize optimally with customers and encourages customer involvement, such as allowing consumers to provide additional instructions or delivery preferences (De-Kervenoael, Schwob & Chandra, 2020). Moreover, this range of value propositions has also been shaped by consumers' demand for improved services, including faster, reliable, and convenient deliveries (Allen, Piecyk, Piotrowska, McLeod, Cherrett, Ghali et al., 2018).

Among these alternatives, some retailers and sectors (in particular, e-grocery) have focused on offering very narrow delivery time windows. In this sense, time windows are understood as a marketing promise tied on delivery time. Thus, time windows provide consumers with certainty about the arrival time of their orders, which can be as limited as 30 minutes or 1 hour, or non-existent. In this way, considering time as one of the key aspects of online delivery, the aim of time windows is to give customers more choice and flexibility (De-Kervenoael et al., 2020).

However, these efforts to provide a higher level of service to online customers have made the last mile an unsustainable process (Halldorsson & Wehner, 2020). Thus, this process impacts all three pillars of sustainability (economic, environmental, and social). Last mile is disproportionately responsible for the costs of online logistics, as well as the environmental and social impacts of transport (Brown & Guiffrida, 2014). Thus, this impact has triggered an increase in research about sustainable last mile in e-commerce. In this sense, previous literature has focused on reducing the last-mile impact on sustainability through innovative alternatives such as crowdsourcing or drones (e.g., Seghezzi, Mangiaracina, Tumino & Perego, 2021). Furthermore, research has also aimed to analyse, estimate and quantify the last-mile impact on sustainability, comparing different situations and innovative alternatives (e.g., Buldeo-Rai, Verlinde & Macharis, 2021; Caspersen & Navrud, 2021). In particular, some authors have focused on the analysis and redesign of vehicle routing problems with time windows, trying to reduce the economic or environmental impact of such routes (e.g., Dumez et al., 2021). In this sense, these studies have mentioned that the use of these time windows puts greater pressure on drivers by reducing flexibility and requiring more deliveries to be made in a shorter time frame (De-Kervenoael et al., 2020). This strain leads to inefficient management of logistics resources (Allen et al., 2018). However, despite these works, research has not yet provided a detailed analysis of how these time windows affect the three pillars of sustainability (economic, environmental and social).

To tackle this gap, this paper has a double objective. First, to define a method that can be used to evaluate the impact of time windows on last-mile sustainability. Second, applying this method, to provide a comprehensive analysis of the impact of time windows on sustainability. To this end, the following research question is defined:

RQ1. How should the impact of time windows on the sustainability of the last mile be measured?

To do so, desk research (based on archival data collection and a literature review) allowed us to identify and define a method that can be used to measure the impact of time windows on last-mile sustainability. Then, a case study was conducted, where this method was implemented to evaluate its applicability and analyse the impact of time windows on sustainability.

The article is structured as follows. The second section presents a research background on time windows and sustainable last mile. Section three introduces the methodology followed in the article. The fourth section presents the scoreboard, and the fifth section introduces de results of its application. Section five presents the discussion of the results, and the final section provides the conclusions and the limitations of this study.

2. Research Background

As e-commerce has grown strongly over the last decade, consumer habits have been changing, affecting last-mile deliveries and generating more vehicles on the road. Consequently, this has triggered a greater sustainable impact (Tebaldi, Murino & Bottani, 2020). In this regard, De-Kervenoael et al. (2020) referred to failed deliveries as one of the main problems of last mile, being detrimental to sustainability. Thus, failed deliveries are all those deliveries that are not completed because the customer is not at the delivery point (De-Kervenoael et al., 2020). These failed deliveries, often caused by poor information to consumers or by their carelessness, contribute significantly to sustainable impact (De-Kervenoael et al., 2020). In this sense, these delivery failures force the management of reverse logistics and a new delivery attempt (De-Kervenoael et al., 2020).

To mitigate delivery failures, both researchers and e-retailers have explored the potential of implementing specified delivery times to ensure that customers receive deliveries within certain days and specific times (Allen et al., 2018). When the delivery period is limited to a slot between two predetermined times, it is termed as time window (De-Kervenoael et al., 2020).

However, demand for time windows introduces considerable logistical challenges, which can adversely impact all three pillars of sustainability (Tebaldi et al., 2020). For instance, in low-demand areas with multiple time windows available, managing the last mile becomes complex and often inefficient.

In response to this situation, the literature has begun to address and analyse the sustainability implications of time windows (e.g., Bányai, 2018; Tebaldi et al., 2020). Mainly, research has focused on optimising the use of time windows from the perspective of one of the pillars of sustainability. For example, Tebaldi et al. (2020) proposed an optimisation algorithm for the vehicle routing problem with capacity constraint and time windows, focused on reducing travel times. Dumez et al. (2021) focused on reducing the delivery cost by solving the vehicle routing problem with time windows and delivery options with a metaheuristic that relies on a large neighbourhood search employing several problem-tailored destruction operators.

To a lesser extent, some studies have also quantified the sustainability impact of time windows. De-Kervenoael et al. (2020) analysed the impact of time windows on the working conditions of independent delivery drivers. Arévalo-Ascanio, López, García and Fernández (2023) created a strategic model for the calculation of CO_2 emissions in the distribution of parcels. More recently, González-Romero and Prado-Prado (2024) conducted a case study comparing last-mile sustainability with and without time windows. Although this comparison offers valuable insights, it lacks a comprehensive analysis method, is based on a single day's data, and compares only two scenarios.

Despite this previous research, the literature has not provided a comprehensive analysis of the real impact of time windows on sustainability. Furthermore, no tool has been provided to measure the overall impact of time windows on the sustainability of the last mile.

3. Methodology

The aim of this study is to define a method to evaluate the impact of time windows on the three pillars of sustainability. As this research responds to an open and underexplored topic, we analyse it empirically through a case study (Eisenhardt, 1989; Yin, 1984), following the example of previous literature (e.g., Medina-Serrano, González-Ramírez, Gascó & Llopis, 2021; Orue, Lizarralde, Amorrotu & Apaolaza, 2021). In this sense, according to Hartley (1994), case studies are tailormade for exploring processes that are little understood.

3.1. Case Selection, Sampling Time, Data Collection and Data Analysis

Case selection, sampling time, and data collection procedures are important when designing the case study (Meyer, 2001). In this study, case selection was based on theoretical sampling. This means that the case study was chosen purposefully rather than randomly. As geographical scope, Spain was selected as the case of interest. This selection was based on the constant growth that e-commerce has experienced in this area and, in particular, the importance of e-grocery as one of the fastest growing sectors in recent years (Kantar, 2022). Furthermore, the e-grocery sector is the pioneer in the introduction of time windows and the most complex channel to establish (Kantar, 2022). Thus, in this sense, the leader of the Spanish market, a mature e-grocer (more than 20 years selling online), was selected as case study.

The sampling time was three months. The first two were dedicated to desk research, context comprehension, and data collection. The rest of the time was spent on data analysis.

Data collection procedures that allow for triangulation were selected for this case study (Yin, 1984), combining three methodologies: (1) desk research, (2) two semi-structured interviews with the case study and (3) archives from the e-grocer database.

During the desk research stage, researchers made a detailed analysis of various data sources (reports, websites, etc.) to establish the context for the Spanish e-grocery market and the selected case study. Furthermore, as a basis for the next stage, a literature review was conducted on the quantification of last mile sustainability and time windows in e-commerce (presented in Section 4.1). To develop this literature review, a method implemented in previous literature was followed (e.g., Bayonne, Marin-Garcia & Alfalla-Luque, 2020). This review identified the key metrics that should be used to estimate the impact of time windows on sustainability. To do that, a search on Web of Science and Scopus, using keywords, was developed. Thus, scientific articles addressing the quantification of the impact of the last mile and time windows on sustainability were selected and analysed. Through this analysis, indicators were selected to integrate the scoreboard to be presented in Section 4.

The second stage included two semi-structured interviews with the Transport Manager and the Logistics Manager of the case study. The interviews lasted on average an hour and a half and were structured along three different topics: (1) e-commerce logistics strategy, (2) last-mile strategies, and (3) time windows and sustainability.

The third stage consisted of obtaining the data about last-mile deliveries and time windows needed to calculate the impact of these deliveries on sustainability. This data was structured along three axes: (1) online orders (number of orders, number of boxes per order, time windows requested), (2) routes (number of orders per route, number and location of the stops in each route), and (3) vehicles used (type of fuel, consumption, capacity and emissions). Historical data for the last year (between September 2023 and August 2024) were collected and analysed.

For the data analysis stage, spreadsheet files were used to manage, store, and organise the data. Then, the impact of time windows in last-mile sustainability for different scenarios was assessed. In this assessment, the economic, environmental, and social pillars of sustainability were considered. After that, the results were analysed and compared.

To develop this assessment, secondary information was collected and used. For the specific case study analysed in this article, Table 1 shows the secondary information used related to external costs (Van-Essen, Van-Wijngaarden, Schroten, Sutter, Bieler, Maffii et al., 2019).

External cost element	Factor	Source
Air pollution cost	0,0272 €/km	Van-Essen et al. (2019)
Congestion cost	0,1961 €/km	Van-Essen et al. (2019)
Climate change cost	0,0282 €/km	Van-Essen et al. (2019)
Noise cost	0,0214 €/km	Van-Essen et al. (2019)
Accidents cost	0,0970 €/km	Van-Essen et al. (2019)

Table 1. Secondary information related to external costs

Different scenarios were analysed for home deliveries. In this sense, the sustainable impact was analysed based on the routes developed and the type of vehicle used to develop them. Thus, we evaluated the current situation (with the time windows selected by customers), a possible variant without time windows, an alternative based on only two time windows (morning and afternoon deliveries), and an alternative based on historical demand for time windows (enabling the 3 most demanded 2-hour time windows, together with the morning and evening windows). These scenarios were analysed through a scoreboard that will be presented in Section 3.3 and Section 4.

3.2. Case-Study Presentation

The selected case study is a leading e-grocer in the Spanish market. The company was the market leader within the defined area of activity at the end of 2022, obtaining a 16.2% market share. In the online channel, it is the market leader with a share of close to 30%. This e-grocer has a network of 270 supermarkets, where online orders are prepared at and shipped from. This network is in a geographical area of around 30,000 km^2, serving both urban and rural areas. They have a multichannel model in which stores have been used for both channels. Customers can choose between collecting their order at the picking store (Click & Collect) or waiting for their orders at home (Home Delivery). When customers select "Home Delivery", online orders are transported by the company's transport fleet, based on diesel vans with an average capacity of 30 boxes. In these deliveries, customers can select delivery time windows with a duration of 2, 4, 6 and 8 hours.

To analyse the sustainability of the last mile with time windows, we used data between September 2023 and August 2024, focusing on a specific picking store. This store was selected for two reasons: it is the most mature picking store in the network, and access to data was adequate.

3.3. Case-Study Analysis

The collected information was analysed through a scoreboard that will be presented in Section 4. Thus, this scoreboard was used to quantify the impact of time windows on last-mile sustainability.

To implement this scoreboard, first, a method of analysis of the delivery routes for each scenario was implemented. In this sense, this method was created based on the solution of the vehicle routing problem with capacity constraints provided by OR-Tools (Laurent & Vincent, 2023). This solution minimises the kilometres needed to deliver the stipulated orders and includes capacity restrictions for delivery vehicles. However, as this solution provided by OR-Tools (Laurent & Vincent, 2023) did not consider time windows, an adaptation was necessary.

Thus, an algorithm was created that, to each analysed scenario (except the current situation, where the delivery routes were already defined), through the coordinates of the delivery point and the selected time window for each order, calculates the distance matrix. In this matrix, the distance between each delivery point is established. A different distance matrix was created for each time window. In this sense, for the first scenario (without time windows) only a distance matrix that integrated all delivery points was created. For the second scenario (two time windows), two distance matrix were created. Here, each matrix represented a different time window (morning or afternoon deliveries). Finally, for the third scenario (time windows based on historical data), two distance matrix were created. Here, each matrix represented a different time window (morning or afternoon deliveries), integrating, at the same time, the 3 most demanded 2-hour time windows.

Through this method of analysis, the routes for each scenario (except the current situation) were redesigned, providing as results the number of routes to be developed, the number of orders per route and the kilometres per route for each scenario. To determine the impact of each scenario on sustainability, these results were analysed through the scoreboard presented in Section 4. Thus, through a literature review, the most appropriate indicators to measure the impact of time windows on last-mile sustainability were identified. These indicators were structured in a scoreboard that was employed to compare the four scenarios.

4. The Scoreboard

4.1. Selection of Sustainable Indicators for the Last Mile. A Literature Review

In order to evaluate the level of sustainability of last mile and time windows, previous literature has mentioned and implemented different indicators related to the three pillars of sustainability (e.g., Momments, Buldeo-Rai, Van-Lier & Macharis, 2021). In this sense, these indicators would be adequate to evaluate the impact of time windows on last-mile sustainability.

4.1.1. Economic Pillar

First, regarding the economic pillar, Edwards, McKinnon and Cullinane (2010) used the percentage of failed deliveries in their comparative analysis of the carbon footprint between a conventional and an online retailer. Wang, Dang and Hsu (2021), in their evaluation of sustainable last-mile delivery in B2C e-commerce, calculated customer satisfaction (out of 5) by assessing the customer experience. Furthermore, like Alvarez-Palau, Calvet-Liñán, Viu-Roig, Gandouz and Juan (2021), when assessing the economic profitability of home delivery, they used cost per delivery as an indicator. Finally, in relation to the operational management of the last mile, Milewski & Milewska (2021) calculated the vehicle occupancy rate.

4.1.2. Environmental Pillar

Concerning the environmental pillar, Tsakalidis, Krause, Julea, Peduzzi, Pisoni and Thiel (2020) measured pollutant emissions per delivery in their research on electric light commercial vehicles in the last mile. In the same vein, Edwards et al. (2010), in their comparative study of the carbon footprint between conventional and online retailing, measured CO_2 emissions per delivery.

Secondly, Milewski & Milewska (2021) used fuel consumption per delivery to determine the energy efficiency of the last mile in e-commerce. Mommens et al. (2021) calculated the air pollution cost per delivery in their analysis on the sustainability of urban, urbanised and rural areas in Belgium. Furthermore, Mommens et al. (2021), like Cardenas, Beckers and Vanelslander (2017) in their development of an index of external costs of last-mile delivery in Belgian e-commerce, calculated the cost of congestion, climate change and noise per delivery. These costs were developed based on the study by Van-Essen et al. (2019).

4.1.3. Social Pillar

Regarding the social pillar, Mommens et al. (2021) and Cárdenas et al. (2017) calculated the accident cost per delivery, following the work of Van-Essen et al. (2019). Also related to working conditions, Alves, da-Silva-Lima, Custódio-de-Sena, Ferreira-de-Pinho and Holguín-Veras (2019), in their agent-based simulation model to evaluate e-commerce urban transport policy, used as social indicators the number of routes per driver per day, the number of routes per day and the number of deliveries per day.

Finally, De-Mello-Bandeira, Goes, Gonçalves, Márcio-de-Almeida and Oliveira (2019), in their analysis of electric vehicles for urban transport in the last mile of Rio de Janeiro, as well as Alves et al. (2019) and Mommens et al. (2021), calculated loading time, driving time and delivery time as key indicators related to drivers' working conditions.

In this sense, through previous research, this section identifies the indicators of interest for the sustainability assessment of the last mile and time windows. Thus, Table 2 presents a summary of all indicators used in previous literature to evaluate the sustainability of last mile and time windows.

Sustainability pillar	Indicator	Author
Economic pillar	Cost (€/delivery)	Alvarez-Palau et al. (2022); Wang et al. (2021)
	% of failed deliveries	Edwards et al. (2010)
	Customer satisfaction (out of 5)	Wang et al. (2021)
	% occupancy	Milewski & Milewska (2021)
Environmental pillar	Pollutant emissions (kg/delivery)	Tsakalidis et al. (2020)
	CO_2 emissions (kg CO_2 /delivery)	Edwards et al. (2010)
	Fuel consumption (l/100km)	Milewski & Milewska (2021)
	Air pollution cost (€/delivery)	Cárdenas et al. (2017); Mommens et al. (2021)
	Congestion cost (€/delivery)	Cárdenas et al. (2017); Mommens et al. (2021)
	Climate change cost (€/delivery)	Cárdenas et al. (2017); Mommens et al. (2021)
	Noise costs (€/delivery)	Cárdenas et al. (2017); Mommens et al. (2021)

Sustainability pillar	Indicator	Author
Social pillar	Accident costs (€/delivery)	Cárdenas et al. (2017); Mommens et al. (2021)
	Number of routes per day	Alves et al. (2019)
	Number of orders per route	Alves et al. (2019)
	Number of routes per driver	Alves et al. (2019)
	Loading time (min/delivery)	Alves et al. (2019); De-Mello-Bandeira et al. (2019); Mommens et al. (2021)
	Driving time (min/delivery)	Alves et al. (2019); De-Mello-Bandeira et al. (2019); Mommens et al. (2021)
	Delivery time (min/delivery)	Alves et al. (2019); De Mello Bandeira et al. (2019); Mommens et al. (2021)

Table 2. Summary of identified indicators through the literature review

4.2. Construction of the Scoreboard

Through this literature review, a scoreboard is created that can be used to measure the impact of time windows on last-mile sustainability. This scoreboard is based on the three pillars of sustainability (economic, environmental and social pillar). Table 3 represents this scoreboard.

Sustainability pillar	Indicator	Calculation method
Economic pillar	Cost (€/delivery)	Total costs / Number of deliveries
	% of failed deliveries	(Number of failed deliveries / Number of deliveries per order) ·100
	Customer satisfaction (out of 5)	Out of 5
	% occupancy	(Number of boxes transported / Maximum vehicle capacity) ·100
Environmental pillar	Pollutant emissions (kg/delivery)	Vehicle emissions (kg/km) ·Distance (km) / Number of deliveries
	CO_2 emissions (kg CO_2 /delivery)	Vehicle CO_2 emissions (kg/km) ·Distance (km) / Number of deliveries
	Fuel consumption (l/100km)	Vehicle consumption (l/km) ·Distance (km) / Number of deliveries
	Air pollution cost (€/delivery)	Air pollution external cost (€/km) ·Distance (km) / Number of deliveries
	Congestion cost (€/delivery)	Congestion external cost (€/km) ·Distance (km) / Number of deliveries
	Climate change cost (€/delivery)	Climate change external cost (€/km) ·Distance (km) / Number of deliveries
	Noise costs (€/delivery)	Noise external cost (€/km) ·Distance (km) / Number of deliveries
Social pillar	Accident costs (€/delivery)	Accidents external cost (€/km) ·Distance (km) / Number of deliveries
	Number of routes per day	Number of routes / Number of days
	Number of orders per route	Number of deliveries per order / Number of routes
	Number of routes per driver	Number of routes / Number of drivers
	Loading time (min/delivery)	Total loading time / Number of deliveries
	Driving time (min/delivery)	Total driving time / Number of deliveries
	Delivery time (min/delivery)	Total delivery time / Number of deliveries

Table 3. Scoreboard to evaluate the impact of time windows on last-mile sustainability

Regarding the economic pillar, as mentioned in Section 4.1, costs per delivery, percentage of failed deliveries, customer satisfaction and vehicle occupancy rate are included.

Regarding the environmental pillar, Table 3 shows the environmental indicators of the scoreboard. For this pillar, the indicators are pollutant emissions per delivery, CO_2 emissions per delivery, air pollution cost per delivery, fuel consumption per delivery, congestion cost per delivery, climate change cost per delivery and noise cost per delivery.

Finally, Table 3 shows the social indicators of the scoreboard. For this pillar, the indicators are accident cost per delivery, number of routes per driver per day, number of routes per day, number of deliveries per day, loading time, driving time and delivery time.

For the implementation of this scoreboard, it would be necessary to collect and analyse operational information on the last-mile strategy and time windows used. In this sense, it would be required to have data regarding delivery routes (as mentioned in Section 3). Furthermore, secondary data should be collected and used to calculate some of the indicators mentioned in Table 3. In this sense, in addition to information about the vehicle used (already mentioned in Section 3.1), it is necessary to select the appropriate factor for each external cost (air pollution, congestion, climate change, noise, and accidents) according to the characteristics of the delivery (type of vehicle, type of road, delivery area, traffic situation, time of the day). The factors used for the case study analysis can be found in Section 3.1 (Table 1).

5. Applying The Scoreboard: Case Study

To analyse the impact on sustainability of time windows, a comparison was made between the current situation (with the time windows selected by customers), a possible variant without time windows, an alternative based on only two time windows (morning and afternoon deliveries) and an alternative based on a time window system using historical data (enabling the 3 most demanded 2-hour windows, together with the morning and evening window).

To determine the impact of time windows on the sustainability of the last mile, first, the current situation (multiple time windows) is compared to scenario one (elimination of all time windows). Table 4 shows a summary of how time windows affect the sustainability of the last mile.

Sustainability pillar	Indicator	Current situation (with time window)	Scenario 1 (without time window)	% Improvement
Economic pillar	Cost (€/delivery)	3,95 €	2,82 €	29%
	% of failed deliveries	4,88%	10,00%	-105%
	Customer satisfaction (out of 5)	4,00	2,16	-46%
	% occupancy	53,85%	94,33%	75%
Environmental pillar	Pollutant emissions (kg/delivery)	1,220	0,660	46%
	CO_2 emissions (kg CO_2/delivery)	0,190	0,103	46%
	Fuel consumption (l/100km)	0,080	0,043	46%
	Air pollution cost (€/delivery)	0,0400 €	0,0215 €	46%
	Congestion cost (€/delivery)	0,2800 €	0,1500 €	46%
	Climate change cost (€/delivery)	0,0400 €	0,0215 €	46%
	Noise costs (€/delivery)	0,0300 €	0,0161 €	46%
Social pillar	Accident costs (€/delivery)	0,138 €	0,074 €	46%
	Number of routes per day	13	10	23%
	Number of orders per route	6,85	8,60	26%
	Number of routes per driver	3,25	2,50	23%
	Loading time (min/delivery)	1,75	0,77	56%
	Driving time (min/delivery)	14,82	6,62	55%
	Delivery time (min/delivery)	1,60	2,48	-55%

Table 4. Comparison between current situation and scenario 1 (without time windows)

When assessing the sustainability impact of deliveries with and without time windows, it is important to recognise that the latter approach allows e-grocers to optimise delivery routes more effectively. Without the constraint of meeting specific delivery times at customers' homes, routes can be planned to minimise total distance travelled, resulting in improved vehicle utilisation and fewer required routes. Consequently, fewer kilometres are needed to complete all deliveries, with a significant reduction in kilometres per order of 46% (from 1.42 to 0.77 km per order). This 46% reduction benefits all distance-related metrics, including environmental factors (e.g., pollutant emissions, CO_2 levels, air pollution costs, fuel consumption, traffic congestion, noise, and climate-related costs) and social factors such as accident costs.

In terms of the economic pillar, the elimination of time windows has an ambiguous effect. On the positive side, a 29% reduction in the cost per delivery is observed, as increased route flexibility enables more efficient deliveries, thus lowering delivery costs. Additionally, vehicle occupancy rates improve significantly, by 75%, as greater flexibility in route organisation allows e-grocers to maximise route occupancy, sending vehicles as fully loaded as possible. However, a downside is the 46% drop in customer satisfaction, coupled with a 105% increase in failed deliveries. Without time windows, customers are not offered alternative slots aligned with their availability, creating uncertainty about delivery timing and increasing the likelihood of customers being unavailable when the delivery arrives.

From a social perspective, the introduction of time windows negatively impacts certain metrics, such as the number of routes assigned per driver, as time windows typically increase the number of routes required. However, other social indicators, such as the number of deliveries per route, benefit from time windows. While time windows may increase drivers' workloads, the resulting reduction in deliveries per route could help to alleviate some of this strain.

In conclusion, eliminating time windows leads to significant improvements across all sustainability pillars. However, time windows also bring substantial advantages that are affected by this elimination. By eliminating the time windows, the e-grocer no longer has a differentiating variable that allows the customer to make a greater decision on their order, leading to a decrease in customer satisfaction. To address this, two additional scenarios are analysed below in an effort to find a better balance between customer satisfaction and other sustainability elements.

The current situation is then compared with scenario two (the use of two time windows). Table 5 shows a summary of how this second proposal affects the sustainability of the last mile.

Sustainability pillar	Indicator	Current situation (with time window)	Scenario 2 (two time window)	% Improvement
Economic pillar	Cost (€/delivery)	3,95 €	3,32 €	16%
	% of failed deliveries	4,88%	5,00%	-2%
	Customer satisfaction (out of 5)	4,00	3,23	-19%
	% occupancy	53,85%	94,33%	75%
Environmental pillar	Pollutant emissions (kg/delivery)	1,220	0,862	29%
	CO_2 emissions (kg CO_2/delivery)	0,190	0,134	29%
	Fuel consumption (l/100km)	0,080	0,057	29%
	Air pollution cost (€/delivery)	0,0400 €	0,0285 €	29%
	Congestion cost (€/delivery)	0,2800 €	0,2000 €	29%
	Climate change cost (€/delivery)	0,0400 €	0,0285 €	29%
	Noise costs (€/delivery)	0,0300 €	0,0214 €	29%
Social pillar	Accident costs (€/delivery)	0,138 €	0,098 €	29%
	Number of routes per day	13,00	10,00	23%
	Number of orders per route	6,850	7,900	15%
	Number of routes per driver	3,250	2,500	23%
	Loading time (min/delivery)	1,750	2,285	-31%
	Driving time (min/delivery)	14,820	9,250	38%
	Delivery time (min/delivery)	1,600	1,980	-24%

Table 5. Comparison between current situation and scenario 2 (two time windows)

The positive effect of eliminating time windows is also evident when looking at the impact of using only two-time windows. However, the benefits are less than in the first scenario. Regarding the environmental pillar, an improvement is observed due to reductions in the number of kilometres per delivery and per route compared to the current situation. This translates into a 29% improvement across all indicators in this pillar (compared to a 46% improvement in scenario 1). Thus, this second scenario offers significant advantages over multiple time windows, although not as significant as those observed with no time windows. This result is mainly due to limiting the number of time windows to two per day, as opposed to using multiple time windows or no time windows at all.

Regarding the economic pillar, the 16% reduction in the cost per delivery is noteworthy. As in the previous scenario, improving route efficiency reduces delivery costs (although to a lesser extent than in scenario 1 due to the presence of two-time windows). In addition, the 75% increase in the vehicle occupancy rate, the same value obtained by eliminating the time windows, also stands out positively. This is due to the capacity of the case study to organise and integrate, in the same number of routes as in scenario 1, the delivery of all orders already assigned to the two-time windows offered.

On the other hand, also in relation to the economic pillar, the service level is penalised. Thus, in this second scenario, a smaller variety of time windows is offered than in the current situation, which offers less flexibility to the customer. Customer satisfaction is estimated to decrease by 19% (27% better than expected in scenario 1). The percentage of failed deliveries increases slightly compared to the current situation, but to a lesser extent than in scenario one (2% compared to 105% in scenario 1). This is because it is easier for consumers to wait for their order if it arrives in the morning or in the afternoon (rather than throughout the day). In addition, by offering wider time windows, it is much more likely that all orders will arrive in the promised time window (and no delays in delivery).

As for the social pillar, despite the increase in the number of orders per route, which may add pressure on drivers, scenario two reduces the number of routes per driver, as well as driving time. This reduction would therefore make the drivers' work easier, decreasing the time spent on deliveries and the pressure to deliver orders at certain times of the day.

Again, an improvement in all pillars of sustainability is achieved by reducing the time demands generated by shorter time windows. Having a larger time window in each slot results in increased vehicle occupancy and greater flexibility for route management. Compared to scenario one (elimination of time windows), this proposal achieves a lower improvement on most sustainable indicators but provides a better balance between sustainability and service level. Greater customer satisfaction is achieved than in scenario one, although there is still a deterioration compared to the current situation.

To reduce this deterioration, finally, a third scenario will be analysed in which the three 2-hour time windows most demanded by customers will be enabled. This demand was estimated based on historical data from the case study. In addition, the two windows of the previous proposal, corresponding to the morning and evening periods, are also maintained. Thus, the aim is to achieve a scenario with greater flexibility for both the customer and the e-grocer. Table 6 shows a summary of how this third proposal affects the sustainability of the last mile.

Regarding the environmental pillar, as in the two previous scenarios, an improvement is observed due to reductions in the number of kilometres per delivery and per route compared to the current situation. This translates into a 34% improvement across all indicators in this pillar (compared to a 46% improvement in scenario 1 and a 29% improvement in scenario 2). The improvement in this scenario compared to scenario two (only two-time windows) is enabled by the use of a greater number of shorter routes (10% compared to scenario two). This approach reduces vehicle occupancy but also the number of kilometres travelled. It should be noted that this reduction in kilometres may be linked to the specific distribution of orders in certain time windows along certain routes (inherent to the case study). Thus, in this particular case, the orders allocated to each time window (and distributed along certain specific routes) favour the completion of shorter routes. However, this cannot be generalised to other scenarios where the orders assigned to each time window could be widely spaced. In this sense, the improvement in scenario three could be smaller than in scenario two.

In the economic pillar, in this case, this scenario achieves a 4% reduction in delivery costs. Thus, while this scenario enhances route efficiency compared to the current situation, it increases delivery pressure compared to scenarios one and two. On the other hand, it should also be highlighted the improvement in vehicle occupancy by 59% compared to the current situation, which translates into a better use of transport resources. However, due to the new restrictions, this occupancy is lower than in the previous scenarios (one and two).

Sustainability pillar	Indicator	Current situation (with time window)	Scenario 3 (historical data)	% Improvement
Economic pillar	Cost (€/delivery)	3,95 €	3,79 €	4%
	% of failed deliveries	4,88%	1,00%	80%
	Customer satisfaction (out of 5)	4,00	3,62	-10%
	% occupancy	53,85%	85,76%	59%
Environmental pillar	Pollutant emissions (kg/delivery)	1,220	0,800	34%
	CO_2 emissions (kg CO_2/delivery)	0,187	0,124	34%
	Fuel consumption (l/100km)	0,080	0,053	34%
	Air pollution cost (€/delivery)	0,0400 €	0,0265 €	34%
	Congestion cost (€/delivery)	0,2800 €	0,1840 €	34%
	Climate change cost (€/delivery)	0,0400 €	0,0265 €	34%
	Noise costs (€/delivery)	0,0300 €	0,0197 €	34%
Social pillar	Accident costs (€/delivery)	0,138 €	0,091 €	34%
	Number of routes per day	13,000	11,000	15%
	Number of orders per route	6,850	7,820	14%
	Number of routes per driver	3,250	2,750	15%
	Loading time (min/delivery)	1,750	2,080	-19%
	Driving time (min/delivery)	14,820	9,380	37%
	Delivery time (min/delivery)	1,604	1,234	23%

Table 6. Comparison between current situation and scenario 3 (time windows based on historical data)

As in the previous scenarios, customer satisfaction is penalised by 10% as the range of options available to consumers is reduced. However, this scenario achieves higher satisfaction than the previous ones (46% decrease in scenario 1 and 19% in scenario 2) by offering more time windows, which provides greater flexibility for the customer. Furthermore, the percentage of failed deliveries significantly improves compared to all scenarios (current situation, scenario one and two). By offering 2-hour windows, it is easier for consumers to be at home at the time of delivery. In addition, by reducing the number of available time windows, delivery efficiency is higher than in the current situation. This makes it easier for all orders to be delivered within their window (provided the customer is at home). It should be noted that in the current situation, due to the high number of time windows available, orders have often not arrived in the time window chosen by the customer.

In terms of the social pillar, the number of routes is reduced due to an increase in the number of deliveries per route. However, comparing this indicator with scenario two, in this case there is a slight increase in the number of routes (10%). In this sense, by maintaining the number of vehicles and drivers, the pressure to complete all routes in the appropriate time window may be greater in scenario three. On the other hand, driving time is reduced by 37% due to the decrease in kilometres per delivery and route. In addition, delivery time is also reduced by 23% as customers have a better idea of when to expect their deliveries.

In general, the elimination of time windows helps to reduce the environmental impact of last-mile deliveries and has a positive impact on some aspects of the economic and social pillars. However, this choice has a significant impact on service level. In this situation, intermediate alternatives, such as offering a limited time windows system based on historical data, can largely maintain the benefits of time windows elimination without significantly affecting the service level.

6. Discussion

Despite the interest in the literature on the sustainability impact of the last mile, and particularly the higher impact associated with time windows, its quantification has been neglected in previous research. Thus, although some authors have attempted to demonstrate that time windows negatively impact the sustainability of the last mile (e.g., Arévalo-Ascanio et al., 2023; Arévalo-Ascanio, Roel & Wouter, 2023; Tebaldi et al., 2020), these analyses have focused on specific economic (delivery costs) and environmental (CO_2 emissions) elements of sustainability.

In this sense, the literature has attempted to quantify or redesign last-mile strategies with time windows to reduce this impact. For example, Tebaldi et al. (2020) redesigned the vehicle routing problem with time windows to minimise travel time. In addition, Arévalo-Ascanio, Roel, et al. (2023) created a model to quantify the impact of last-mile strategies with time windows on CO_2 emissions. Furthermore, González-Romero and Prado-Prado (2024) also conducted a sustainable analysis of time windows. However, despite these efforts, the literature has not yet been able to provide a method or tool to assess the impact of time windows on the sustainability (and its three pillars) of the last mile. Therefore, the scoreboard-based method presented in this article fills this gap in the literature. It provides a tool to quantify the impact of any last-mile strategy with time windows on the three pillars of sustainability, making it an excellent instrument for comparison and evaluation.

To confirm the applicability of this scoreboard, this article also presents its implementation in a specific case study. Thus, based on data from an e-grocer, it is confirmed that, for its specific conditions, the implementation of time windows in last-mile strategies has a high impact on the three pillars of sustainability. Thus, aspects mentioned by previous literature such as the impact of time windows on CO_2 emissions (e.g., Arévalo-Ascanio, Roel et al., 2023), delivery costs (e.g., Dumez et al., 2021; Orjuela-Castro, Orejuela-Cabrera & Adarme-Jaimes, 2019) or drivers' working conditions (e.g., De-Kervenoael et al., 2020) are confirmed by this study.

However, compared to previous research, the analysis developed in this article presents key differences. First, in addition to confirming certain findings (e.g., negative impact on delivery costs, CO_2 emissions), this article also measures time windows' effects on other sustainability elements, such as customer satisfaction, congestion costs, and accident costs—essential yet previously overlooked sustainability elements.

Second, this analysis further identified aspects of sustainability (mainly from the economic pillar) that benefit from time windows. These elements relate to service level (customer satisfaction and percentage of failed deliveries). Although this positive impact was also mentioned by González-Romero and Prado-Prado (2024), this study uniquely demonstrates that time windows allow the analysed e-grocer to enhance customer satisfaction (as the consumer perceives a better service) and to reduce missed deliveries (by ensuring the delivery of orders at specific times of the day chosen by the customer). This insight results from the global view of sustainability employed in this study, as opposed to more specific analyses conducted in previous research (focusing on specific pillars of sustainability).

Thus, in general, despite the large impact time windows have on most elements of sustainability, to achieve a balanced performance, the findings suggests that intermediate alternatives, such as offering a limited time windows system based on historical data, can largely maintain the benefits of time windows elimination without significantly affecting the service level.

7. Conclusions

Although there has been considerable research interest in sustainable last mile, there remains a gap in the analysis of how time windows affect sustainability. Much of the existing literature has focused on studying and optimising vehicle routing problems with time windows (e.g., Dumez et al., 2021) without thoroughly quantifying their impact on sustainability. As a result, these studies have not provided a comprehensive explanation of how time windows affect the three pillars of sustainability.

Therefore, this study aimed to analyse the real impact of time windows on last-mile sustainability through an analysis method applied to a specific case study. Thus, first, a method that can be used to evaluate the impact of time windows on last-mile sustainability was defined. Second, applying this method to a specific case study, the findings of this article provided a description of how four different scenarios influenced by time windows (routes with multiple time windows, without time windows, with only two time windows and limited time windows system based on historical data) impact on sustainability, serving as a guide for e-retailers.

Specifically, through desk research, a method that can be used to measure the impact of time windows on last-mile sustainability was identified and defined. This method (presented in Section 4) is based on a scoreboard that integrates the three pillars of sustainability and eighteen indicators. After the creation of this scoreboard, through its implementation to a specific case study, this study identified the negative impact time windows has on the sustainability of the last mile. Thus, the use of time windows triggers an increase in the number of kilometres online orders must travel. This is due to the complexity of managing the last mile and organising efficient routes in strategies with tight time window. This increase leads to a greater impact on the environmental pillar and on some elements of the economic (occupancy of vehicles) and social (accidents cost, number of routes per day and number of routes per driver) pillars. However, at the same time, offering time windows significantly improves service level, as the percentage of failed deliveries and customer satisfaction are positively impacted by time windows. Thus, by selecting a specific time window, consumers perceive a higher service level. In addition, they have more information about the estimated time of arrival of their order and are therefore more likely to wait at home for it to arrive. In this sense, after the comparison of four different scenarios, the findings suggests that intermediate alternatives, such as offering a limited time windows system based on historical data, can largely maintain the benefits of time windows elimination without significantly affecting the service level.

These findings (the creation and implementation of the scoreboard) provide both theoretical and managerial contributions. In the latter case, retailers can use these findings as a reference when evaluating and implementing sustainable last-mile strategies, helping them to determine whether the use of time windows is both necessary and sustainable. Thus, the comparison of different scenarios through this scoreboard could be a great starting point for reducing the impact of time windows on sustainability.

Finally, a limitation of this study is that it focuses on a single case study. Future research should extend the application of the scoreboard to different companies in different sectors, sizes and countries. A broader analysis could reveal additional and different sustainability impacts associated with the use of time windows. In this respect, the findings of this study can provide a basis for future research.

Declaration of Conflicting Interests

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