Strategic Multi-Echelon and Cross-Modal CO_2 Emissions Calculation in Parcel Distribution Networks. A First Step Toward a Common Language

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Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: Arevalo-Ascanio Rafael, Gevaers Roel, Dewulf Wouter; data collection: Arevalo-Ascanio Rafael, Gevaers Roel; analysis and interpretation of results: Arevalo-Ascanio Rafael, Dewulf Wouter; draft manuscript preparation: Arevalo-Ascanio Rafael. All authors reviewed the results and approved the final version of the manuscript.

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Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Abstract

Sustainability in distribution networks is currently the focus of study at institutional, academic, and commercial levels. Reducing greenhouse gas emissions is on all the programmatic agendas, and the goals are clear for years toward carbon neutrality. As one of the main polluting sectors and growing trends with e-commerce, transport must align its efforts to contribute to the cause. In this paper, a strategic model is proposed for the calculation of CO_2 emissions in the distribution of parcels. Novel in this research is that it integrates both line-haul transport and last-mile distribution at a strategic level and includes key elements such as time windows and population density in the calculation. Through an applied case in the parcel distribution in Belgium, the calculation of CO_2 emissions with the proposed model is illustrated. The model is enhanced by analysing the time windows effect and the electrification of the last-mile fleet. The results of CO_2 emissions in parcel distribution in Belgium show that it is possible to reduce emissions not only through the electrification of the fleet but also with an efficient distribution network. The effect of the network structure will be more evident with international shipments that include more polluting modes of transport. However, the results for Belgium show that the last mile is currently the most polluting segment. The proposed model could further be complemented by including reverse logistics, in-house calculation, and packaging emissions.

Keywords: CO_2 emissions, calculation, integrated modelling, supply network, parcel distribution

1 Introduction

One of the significant concerns today is climate change and global warming. These concerns are reflected in global and regional agreements for reducing pollutant emissions and setting sustainable development objectives by the United Nations. The European Commission has defined the main objective of the Green Deal as the reduction of greenhouse gas emissions by 55% compared to 1990 levels by 2030 [1]. Specifically, for commercial vehicles such as vans, the reduction of CO_2 emissions should be 50% by 2030, and for 2030 the goal is zero emissions for new cars. Transportation is the most significant source of greenhouse gas emissions in the United States (27%) [2], and the second worldwide (24%), only surpassed by electricity and heat producers (42%) [3].

Road transport had the highest emissions within the transport sector in 2018 worldwide (74.5%), corresponding to 45.1% to passenger transport and 29.4% to freight [4]. Aviation contributed 11.6% of total CO_2 transport-related emissions, of which 19% come from freight; shipping counted for 10.6%. With these figures, it can be established that freight transport, in all modes contributed 42.2% to total transport CO_2 emissions in 2018. Since 2019/2020, these values have changed significantly because of the Covid-19 pandemic, especially in the passenger transport segment. According to the European

Parliament [5], with data from the European Environmental Agency, in 2019, only 11% and 1.3% of the emissions generated by road transport correspond to light-duty trucks and motorcycles, respectively. These vehicles are used in last-mile distribution, which shows that the bulk of the emissions is generated in line-haul transportation.

Measuring greenhouse gas emissions is a step toward achieving the emissions reduction goals. But at this point a question arises, do we speak the same language when calculating emissions? Although some stakeholders are already measuring the CO_2 emissions generated in transport, as is the case of airlines [6], a standard measurement throughout the whole supply network is essential. In this case, it is not enough to add separate measurements; integrated models are needed. The need for a standard emissions calculation also exists in the distribution of parcels. The global growth of retail Business-to-Customers (B2C) e-commerce has been such that by 2020 it already represented 18% of total sales. It is expected to grow at least 1% in the following years. A comprehensive calculation of CO_2 emissions in the parcel supply network must integrate both the last-mile and the line-haul transportation.

The objective of this paper is to propose a strategic model for the calculation of CO_2 emissions in parcel distribution networks. The strategic component contemplates integrating the line-haul and last-mile transport in a multi-echelon network and including all modes of transport. In order to take the modelling of the last-mile distribution from an operational level (classical Vehicle Routing Problem – VRP) to a strategic level, theoretical estimations of the route length are used. The paper is structured as follows; section 2 shows the literature overview and the bases for calculating CO_2 emissions in transport. Section 3 develops the description of the problem and the definition of the model. An application of the CO_2 emissions calculation in the parcel distribution network in Belgium is presented in section 4. Finally, in section 5, the practical implications and conclusions are presented.

2 Transport CO_2 emissions: Literature overview, approaches, and calculators

Searches in databases such as SCOPUS show that the literature on calculating CO_2 emissions in transport, using terms such as last-mile, supply chain, or network, has grown recently due to the sustainability boom. The CO_2 emissions as a decision variable have been used in the design of supply networks. Multi-objective optimisation minimises costs and CO_2 emissions [7] or selects an adequate transport mode [8]. Also, as a criterion for selecting suppliers with lower CO_2 emissions or higher green factors [9]. The base formulation is maintained using the weight of the load, the vehicle's capacity, the distance travelled, and the emission rate (emission factor) for loaded and empty vehicles [10].

In biomass supply chains, CO_2e emissions (CO_2e – equivalents is the conversion of all greenhouse gas emissions to CO_2 emissions) are part of the environmental assessment of the transport of raw materials [11]. In addition to the transportation of biomass, the CO_2 emissions from cultivating and harvesting oil palm [12] or sugar cane [13] are also contemplated in the biomass supply chain. More comprehensive models such as life cycle analysis – LCA complemented with geographic and simulation analyses also use measurements of CO_2 emissions in biomass production.

The calculation of CO_2 emissions in supply chains of consumer goods has also contributed to the development of measurement methodologies. Multimodal approaches, including road and maritime transport, still use distance travelled averages instead of the actual network [14]. However, the methodological framework model for calculating emissions proposed by Mubarak & Zainal [14] does take into account the emissions from the transhipment centres. This is a differentiator in emission calculation models since it includes variables such as packaging, handling, and refrigeration energy. This methodology has also been used to compare logistic emissions in some Asian countries, as the authors argue that standard methods do not apply in these regions [15]. More specifically, in the last-mile distribution, Edwards et al. [16] performed a comparative analysis in terms of CO_2 emissions of conventional and online retailing. The authors showed that the CO_2 emission per item delivered using a van that drops 120 deliveries on a 50-mile route is around 181g/drop.

One direct measure for reducing CO_2 emissions in road transport is the electrification of vehicles. Since Tank-To-Wheel CO_2 emissions from electric vehicles are nominally zero, electric light commercial vehicles are the best for urban distribution [17]. Woody et al. [18] show the counterpart of electrification with an analysis of the trade-off between minimising costs and minimising GHG emissions in recharging electric vehicles. Recharging strategies at certain hours of the day show both economic and environmental benefits in this regard.

Even though bibliographical production is growing, most of the methodologies for calculating CO_2 and CO_2e emissions do not come from the scientific literature. Davydenko et al. [19], [20] and Wild [21] present a good account of current standards and methods for CO_2 and CO_2e emissions measuring and reporting. Elements from the regulatory point of view or institutional programs can be consulted in those works. Methodological approaches and key variables such as the emission factors in the emissions calculation will be described below.

The EN16258 standard establishes a 3-step methodology, where the transport service is first divided into individual sections or legs [22]. Then the calculation of greenhouse gas emission is made from the energy consumption, to add later the results of all the legs of the transport service [23]. Similarly, Mckinnon & Piecyk [24] proposed a 5-step methodology for measuring and reporting emissions, 1) define the objective, 2) select the calculation approach and system limits, 3) collect data and emission factors, 4) calculate, and 5) verify and report. The Greenhouse Gas Protocol – GHG [25] sets the emission measurements in three scopes, direct emissions (scope 1), indirect emissions from electricity (scope 2), and supply chain emissions (scope 3). However, this protocol is seen from the corporate level. For this reason, emissions due to transportation from suppliers are considered in scope 3.

According to the Green Logistics project executed by the Fraunhofer Institute, there are three emission calculation approaches consumption-based approach, distance-based approach (or activity), and key figure-based approach [26]. The approaches are related to the scopes proposed by the GHG protocol, scope 1 emissions are usually calculated with the consumption-based approach. For emissions in scope 3, an activity-based calculation is more appropriate. The approach based on key figures seeks to aggregate the calculation of emissions from corporate figures and averages.

A broader methodological framework is proposed by the Smart Freight Centre [27] for the calculation of logistical emissions. The framework is based on the GHG protocol and contemplates three steps, from defining boundaries and objectives to calculating emissions in the different scopes. The distribution network view is contemplated in the Lean & Green program in the Netherlands, where optimisation in transportation planning is established as a measure to reduce emissions [28]. The program proposes that better planning of the tactical/operative operations in the distribution leads to eliminating unnecessary trips and consequently reducing emissions and costs.

Regarding the emission factors, the CE Delft [29] presents a wide range of Well-To-Wheel (WTW) emission factors for all modes of transport (except air). According to this study, for road transport, large vans, trucks, and semitrailer trucks have emission factors of 1153, 259, and 82 g/tkm, respectively. Likewise, in 2019 the French Ministry for the Ecological and Inclusive Transition published a methodological guide on greenhouse gas information for transport services [30]. This guide shows a complete list of energy sources with their respective emission factors for the operation and upstream phases. The official software of the European Commission for calculating energy consumption is the Vechicle Energy Consumption Tool – VECTO [31]. With this tool, the energy consumption of heavy-duty vehicles can be simulated to estimate the emission factors. Some results of the simulation with VECTO show that the emission factors for delivery vans and rigid and trailer trucks are 113.07, 275.2, and 61.2 g/tkm, respectively. The van emissions factor shows significant discrepancies between the values simulated by VECTO and those reported by CE Delft.

EcoTransIT World is an industry-driven platform for calculating the carbon footprint of freight transport [32]. The methodology used by EcoTransIT is in line with EN16258 standards and uses cargo type parameters for all modes of transport. It is worth highlighting the use of the resistance factor, which, although the tool does not contemplate routing, allows smaller vehicles to enter urban roads if comparable to taking longer routes by highways. Another tool is BigMile, a carbon analytics service that provides insights on the carbon footprint related to transportation. This service analyses shipments, customers, subcontractors, periods, and regions [33]. There are also tools for calculating emissions specialised in a single mode of transport. Perhaps the most comprehensive emissions calculator is CarbonCare, which integrates all transport modes and storage and cold chain emissions [34]. Based on the EN16258 standard, Carbon Care calculates Great Circle Distances and emissions segment by segment.

In the postal and parcels sector, the UPU [35] has launched the Online Solution for Carbon Analysis and Reporting – OSCAR tool for calculating, reporting, and mitigating greenhouse gas emissions. Oscar is built based on the Greenhouse Gas Protocol methodology, which calculates emissions at the corporate level in 3 scopes [25]. Similar to the Smart Freight Centre methodological framework. Likewise, private initiatives such as the DHL [36] emissions calculator allow estimating the emissions of a shipment. This tool considers shipment legs with different modes of transport between two points.

In conclusion to this section, the unanimous call for a globally standardised calculation of CO_2 emissions is highlighted. Institutional and private initiatives have proposed standards for measuring CO_2 emissions that should be adopted in an integrated methodology. No CO_2 emissions calculator or methodologies simultaneously focus on last-mile deliveries and line-haul transportation. Integration of last-mile with network calculation in a strategic sense is the added value of this research. Wild [21] concludes that a global emission standard should be based on five aspects: simplicity, accuracy, flexibility, feasibility, and transparency.

3 Methods

3.1 Problem description

The calculation of CO_2 emissions in the parcel distribution network is not only the last-mile distribution but also all the other levels upstream, as shown in Figure 1. Depending on each parcel player, there can be as many levels as the network is complex. In this study, the emissions reporting is defined per unit of cargo i.e., one parcel. Unit allocation is standardised to TTW (tank-to-wheel) CO_2 grams per parcel. In addition to the network approach, the multimodal character in the parcel distribution has significant implications on CO_2 emissions. Each mode of transport has different fuel consumption and, therefore, different emission factors. Although the emission factor of each vehicle is defined based on fuel consumption, the integrated calculation has an activity-based approach, as proposed for scope 3 emissions in the Greenhouse Gas Protocol [25].

Integrating the last-mile distribution in the calculation ex-ante of emissions (before the operation) is a challenge from a modelling and computational point of view since the classic vehicle routing is an NP-Hard problem [37] i.e., very complex to solve in polynomial time by a nondeterministic Turing machine. Thus, the strategic calculation of the distance for the last-mile distribution is proposed, theoretically estimating the length of the route. The needed distance to distribute n parcels in a delimited area is explained in the model formulation.

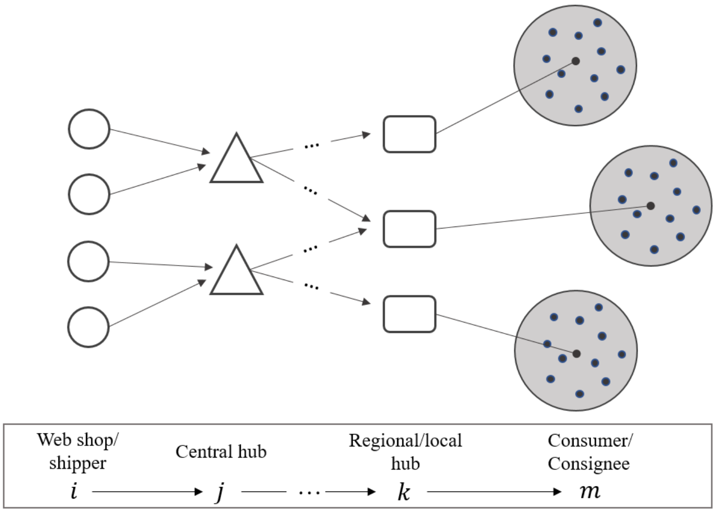

Figure 1. The global parcel distribution network

3.2 Model formulation

Calculating CO_2 emissions generated during parcel distribution includes the last-mile distribution and line-haul transport. The identification of segments or legs proposed in the EN16258 standard is used to define the last-mile segment and the different legs in the line-haul transport. A general expression for the total CO_2 emissions per parcel is defined as ϵ_p in Equation (1), see Appendix A for the complete list of parameters.

$$\epsilon_p = eLh_p + eLm_p \tag{1}$$

The emissions corresponding to line-haul and last-mile transport are represented as eLh_p and eLm_p, respectively. Equations (2) and (3) show the composition of each term.

$$eLh_p = \frac{\left(d_{i,j} + d_{j,k} + \cdots + d_{l,m}\right)\varepsilon f_v \, p_{vol/we}}{v_{vol/we}^{cap}} \tag{2}$$

$$eLm_p = \widehat{D}_{lm} + \varepsilon f_v \tag{3}$$

Where d represents the distance between two different nodes in the network. In multi-echelon networks, there will be as many indices as different nodes are: Set of nodes $S = \{i, j, k, \dots, l, m\}$. There are four types of distance metrics for line-haul transport [38]: “Great Circle Distance” (GCD), which calculates the distance between two points on the earth's surface, “Actual Driven Distance” (ADD) measured by the same vehicle, “Planned Distance” (PD) the route of the vehicle is optimised by the planning software, and “Shortest Feasible Distance” (SFD) within a specific network. Davydenko et al. [38] found that the GCD is the most appropriate for calculating the carbon footprint. In this formulation, the GCD is ideal for modes of transportation such as air or maritime, while for road transportation, the PD provides greater accuracy in ex-ante calculations.

The emission factor per vehicle type v is represented by εf_v. The parcel dimensions are entered as $p_{vol/we}$ either in terms of volume (vol) or weight (we). $v_{vol/we}^{cap}$ represents the vehicle capacity either in terms of volume or weight. $\widehat{D}_{lm}$ is defined as the estimated average last-mile route length.

3.2.1 Estimation of average last-mile route length $\widehat{D}_{lm}$

Multiple studies have demonstrated the use of theoretical route length estimation for last-mile distribution. A generalisation of the Traveler Salesman Problem (TSP) proposed by Beardwood et al. [39] found that the distance needed to visit n points from a depot within its area of influence tends to Equation (4). Where k is a constant based on the distance metric used and A is equal to the area of the influence.

$$\lim_{n \to \infty} E[d_{TSP}(n, A)] = k\sqrt{nA} \tag{4}$$

Later, Daganzo [40] complemented this formulation, including the line-haul as $2r\frac{n}{C}$ with r an average distance from the depot to the delivery area and C as the capacity of the vehicle. Since the calculation of CO_2 emissions is based on a multi-echelon distribution network (Figure 1), the line-haul distance is calculated as separate legs as shown in Equation (2). Recently, this estimation has been implemented in the calculation of transport costs for the last-mile distribution [41]–[43]. Different values for the constant k have been proposed, Bergmann et al. [44] summarise some of them like $k \approx 0.765$ for Euclidian distances and $k \approx 0.97$ when using Manhattan distances.

Equation (4) is enhanced with two coefficients that modify the number of stops in the distribution route, namely the effect of time windows (w) and the population density (ad) in the delivery area. Previously, improvements to this general formulation have also been proposed, as in the case of Cardenas et al. [45], for the inclusion of failed deliveries in the calculation of costs. Gevaers et al. [46] showed the relationship of these coefficients with the number of stops as $\left[\frac{stops}{w}\right]$ and $[stops * ad]$ for the time windows and the population density, respectively. Thus, the estimation of the route length with these coefficients is determined by Equation (5).

$$\widehat{D}_{lm} = k\sqrt{\frac{(n * ad)A}{w}} \tag{5}$$

In order to get the amount of CO_2 emission generated by each parcel, it is necessary to understand the participation of each parcel during the entire route. Consider any parcel on a delivery route, the two extreme scenarios in which this parcel can be delivered are: being the first or the last. If the parcel is the first, the distance the parcel travel in the last mile is nominally zero, in contrast to being the last, where the parcel has travelled the entire route. In this way, it is easy to find that the average distance that any parcel travels on the route is half of the route $\frac{\widehat{D}_{lm}}{2}$.

Similarly, the contribution of each parcel to the total CO_2 emissions depends on the number of parcels in the route following economies of scale. Assuming that each stop is a parcel delivered, the vehicle's capacity determines the initial number of stops. Thus, if the vehicle travels at its maximum capacity, the CO_2 emission charged to each parcel is less than if it travels with a single parcel. With this logic, the average amount of CO_2 emissions charged to any parcel is calculated with the average vehicle capacity or half of the stops, so it is equal to $\frac{\varepsilon f_v}{\frac{n}{2}} = \frac{2\,\varepsilon f_v}{n}$. Equation (6) shows the calculation of CO_2 emissions per parcel in the last mile.

$$\hat{D}_{lm} = \frac{k\sqrt{\frac{(n*ad)A}{w}}}{2}\,\frac{2\,\varepsilon f_v}{n} = \frac{k\sqrt{\frac{(n*ad)A}{w}}}{n}\,\varepsilon f_v \qquad (6)$$

According to the above, the extensive form of Equation (1) is presented in Equation (7).

$$\epsilon_p = \left[\frac{\left(d_{i,j} + d_{j,k} + \cdots + d_{l,m}\right) p_{vol/we}}{v^{cap}_{vol/we}} + \frac{k\sqrt{\frac{(n*ad)A}{w}}}{n}\right]\varepsilon f_v \qquad (7)$$

4 The Belgian parcel distribution case

In Europe, e-commerce has grown steadily recently. In the last five years, the percentage of people who buy on the internet (e-shoppers) went from 65% in 2017 to an expected value of 76% in 2022 [47]. This indicator is higher in Belgium, where e-shoppers are expected to grow to 80% by 2022. In addition, the COVID-19 pandemic has impacted e-retail, expanding accessibility to non-food products [48] and consequently increasing the demand for parcel transport. According to the Belgian Institute for Postal Services and Telecommunications [49], the five leading parcel players (PP) hold more than 80% of the market of the parcel and express mail in terms of volume, as shown in Figure 2. The parcel players in the Belgian market have been classified into the following typology: National Postal Operators, integrators, parcel carriers, and last-mile specialists [45].

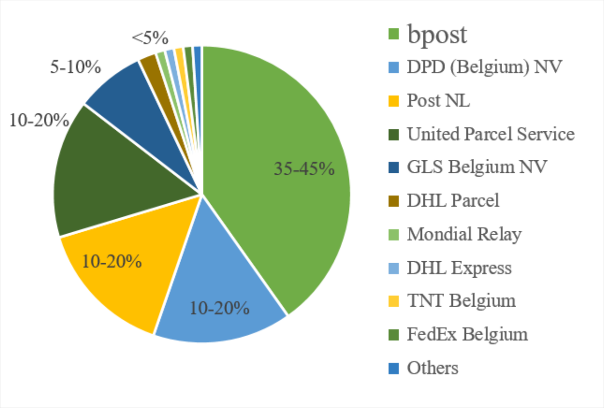

Figure 2. Market share within the segment of the parcel and express mail in Belgium. Source: [49]

The calculation of the CO_2 emissions is carried out in two scenarios to see the implications of the network. **Scenario 1:** The five leading parcel players (PP) have been considered, namely Bpost, DPD, Post NL, UPS, and GLS. The distribution networks have been identified with information from different sources, including the official sites of these PP. Henceforth, the operators will be referred to as PP1 to PP5, since the objective of this paper is not to evaluate the performance of any of them but rather to illustrate the calculation of CO_2 emission in an applied context. Although the warehouses/hubs network structures are not mentioned, it is noted that out of the five PP, four have a three levels-echelon network and one a four levels-echelon network. Results in this scenario are presented as the weighted average of CO_2 emissions based on the market share of each PP.

Scenario 2: A sixth parcel player (PP6) is analysed to see the implications of a shorter distribution network. The parcel distribution model of PP6 has as its core the location of depots on the outskirts of cities. This configuration results in a 2-echelon distribution network, with each city's depot as the intermediate node. Results in this scenario show the actual CO_2 emissions using the PP6 distribution network.

4.1 Travelled distance

The planned distances between the network nodes that compose the line-haul are calculated using *OpenStreetMap*. The entire model has been programmed in Python. The last-mile distance is calculated with Equation (5). The number of base stops is assumed to be $n = 70$, considering the capacity of a van in an 8-hour working day. As mentioned in the model formulation, the number of stops is affected by time windows and population density. Table 1 show the values for these coefficients based on [46]. In this analysis, a value of $k \approx 0.97$ is assuming the calculation of Manhattan distances.

Table 1. Time window and population density coefficients for last-mile distribution. Taken from Gevaers et al. [46]

Window length	Coefficient w	Number of inhabitants per km^2	Coefficient ad
1 hour	2.1	0 – 50	0.5
2 hours	1.8	51 – 200	0.93
3 hours	1.6	333 (average in Belgium)	1
4 hours	1.3	201 – 400	1.09
No time window	1	401 – 600	1.24
		601 – 800	1.31
		801 – 1000	1.35
		1001 – 1200	1.38
		1201 – 1500	1.39
		> 1500	1.41

4.2 Vehicle fleet and emission factors

In the case of parcel distribution in Belgium, the predominant mode of transport is by land. According to observations in the operation of the PP, some types of vehicles are assumed for different network segments. Trailer trucks and rigid trucks are used for line-haul transport, while delivery vans are used for last-mile distribution. Table 2 shows the characteristics of the vehicles used. The average payload and emission factors have been simulated with the VECTO tool [31]. In Section 2, the emission factors were expressed in g/tkm. A conversion of those factors is shown here using the average payload. The reason for this conversion is to move from ton analysis to unit of cargo analysis, such as parcels. For scenario 2, the PP6 case is used to assess the impact of fleet electrification for the last mile on total CO_2 emissions. Electric vehicles have nominally zero CO_2 emissions TTW.

Table 2. Vehicle information and emission factors.

Vehicle type	**Average Payload**	**Dimensions LxWxH**	**TTW CO_2 Emissions Factor**
Trailer truck	13.482 Ton	13.6x2.45x3 m	825.0984 g/km
Rigid truck	2.355 Ton	7.2x2.4x2.35 m	648.096 g/km
Delivery van	1.3 Ton	4.1x1.8x1.75 m	147 g/km

4.3 Results and discussion: CO_2 emissions per parcel in Belgium

Initially, the results of the calculation of the CO_2 emissions without time windows are presented. For each of the scenarios described above the emissions of two routes are calculated, from a national origin in the city of Namur, Belgium (Wallonia region) and an international origin from Waalwijk in the Netherlands. The distribution is illustrated in 8 cities where PP6 operates, comparable in both scenarios. According to each PP, the distribution network includes different national, regional, and local hubs. The assumed average parcel dimensions LxWxH are 30x30x25 cm. As the weight of the parcels is low, the capacity of the vehicles is determined by the volume. Table 3 summarizes the results of the CO_2 emissions calculation, detailing the emissions in the line-haul (LH) and in the last-mile (LM).

Table 3. Results of CO_2 emissions calculation [CO_2 g/parcel]

Destination/Origin	**Scenario 1**				**Scenario 2**			
	Namur		Waalwijk		Namur		Waalwijk	
	LH	LM	LH	LM	LH	LM	LH	LM
Antwerp	26	243	30	243	31	243	22	243
Brussel	23	216	27	216	22	216	36	216
Ghent	33	212	37	212	39	212	41	212
Hasselt	42	172	46	172	21	172	29	172
Leuven	28	127	32	127	17	127	31	127
Charleroi	37	172	41	172	10	172	50	172
Liege	42	141	46	141	19	141	41	141
Mechelen	68	137	72	137	23	137	29	137
average	37	178	41	178	23	178	35	178
Global average	215		219		200		212	

LH: Line-haul; LM: Last-mile

The CO_2 emissions per parcel per scenario for each of the eight selected cities from Namur, BE are shown in Figure 3. The global average of CO_2 emissions in scenario 1 is 215 g/parcel and 200 g/parcel in scenario 2. Interestingly, cities like Charleroi, relatively close to the Namur origin, do not necessarily have the lowest emissions. This corresponds to the fact that line-haul transport considers the actual distribution network of the PP, and many of them have their central hub in Brussels. In this way, regardless of the geographical proximity between the origin and the destination, the parcel must follow the route given by the PP. In large cities, the largest PP in scenario 1 already has a hub, so emissions are lower compared to scenario 2. This is reversed in small cities, where the positioning of the depots in scenario 2 allows a more efficient distribution. Distances travelled in both scenarios are shown in Appendix B.

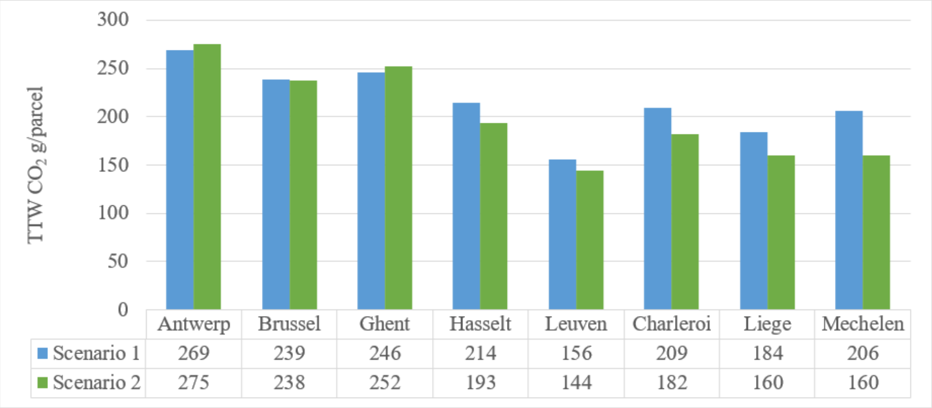

Figure 3. Average CO_2 emissions per parcel in 8 Belgian cities. Distribution from Namur, BE

In the international case with origin in Waalwijk, NE, the global average of CO_2 emissions is 219 g/parcel in scenario 1 and 212 g/parcel in scenario 2. The results by the city are presented in Figure 4. Although the origin is international, the national distribution network is the same. That is, the parcels must enter the national distribution network that each PP owns. This fact emphasises the importance of the distribution network and implications for emissions beyond origin and destination. In both cases, international and national, Leuven presents the lowest emissions. This situation responds to the geographical location near Brussels, where all PP's distribution hubs converge. In general terms, the results show that a shorter distribution network (PP6 in scenario 2) translates into a more efficient operation and therefore generates lower CO_2 emissions.

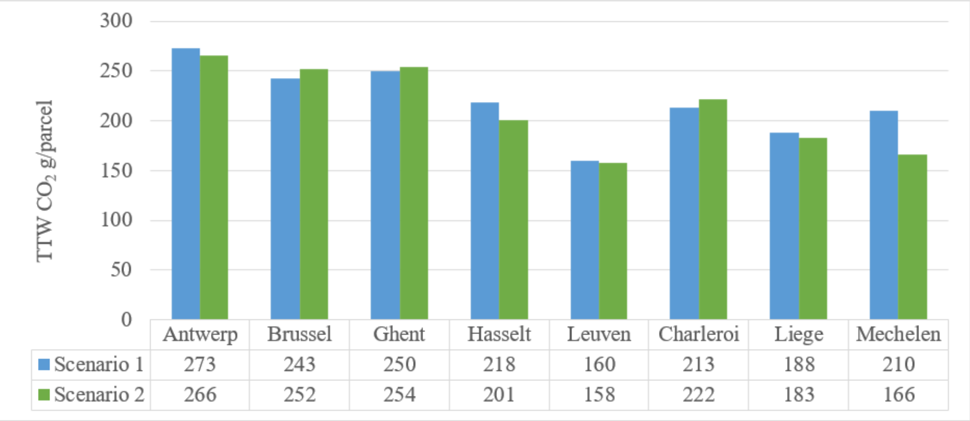

Figure 4. Average CO_2 emissions per parcel in 8 Belgian cities. Distribution from Waalwijk, NE

To illustrate the effect of time windows on CO_2 emissions during the parcel distribution, Figure 5 shows the emissions per parcel in the cities of Antwerp and Charleroi. It is evident that by implementing narrower time windows, the CO_2 emissions increase. This is a pure last-mile effect. At tighter time windows, fewer parcels can be delivered [46] since routes result in a ping pong effect. Not necessarily because the distance travelled increases, but because economies of scale are lost in the capacity of the vehicles and the CO_2 emissions that are charged to each parcel increase. According to Equation (5), as the number of stops decreases due to the effect of the time windows, the estimated distance for the last mile is expected to decrease.

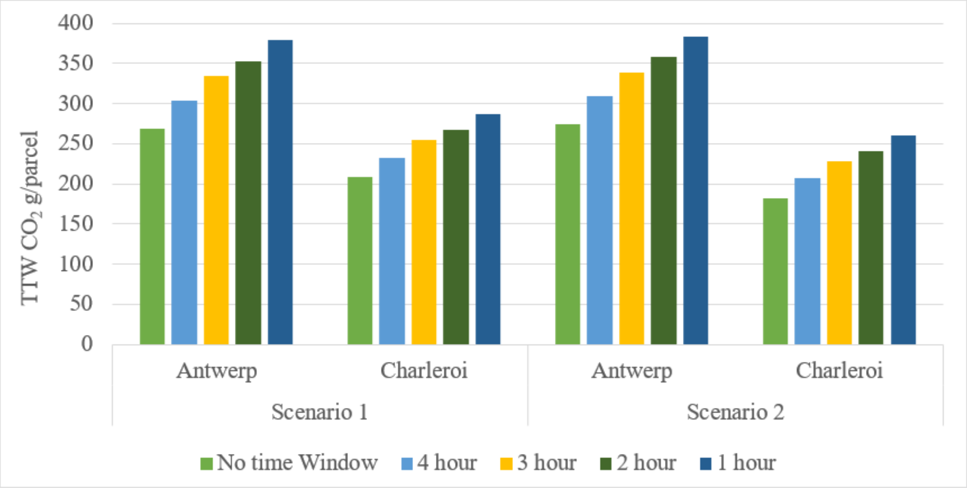

Figure 5. Average CO_2 emissions per parcel in 2 Belgian cities with different time windows. Distribution from Namur, BE

The electrification of the last-mile distribution fleet reduces CO_2 emissions as expected (See Figure 6). However, total CO_2 emissions go from 200 g/parcel using conventional vans to 23 g/parcel with a 100% electric fleet. This shows that in the distribution of parcels in Belgium, more than 80% of the emissions are generated in the last mile.

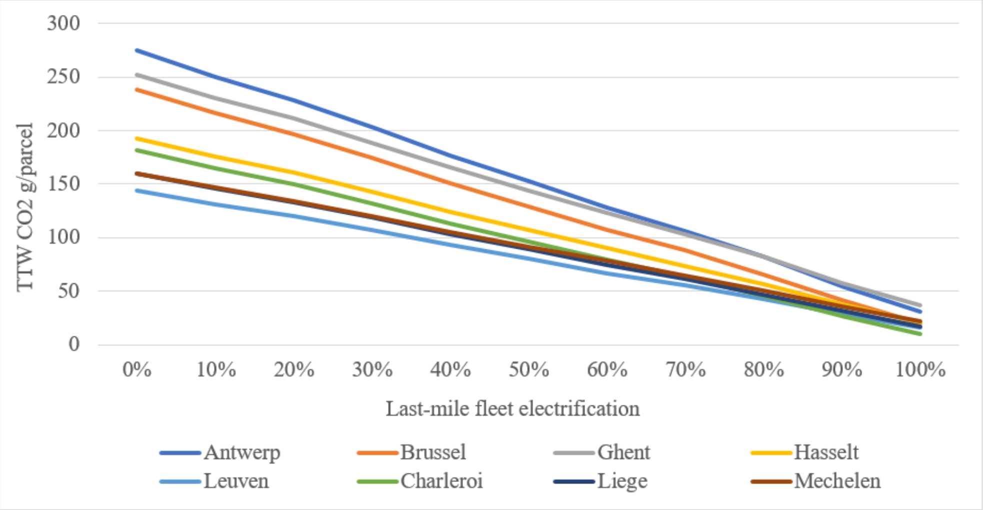

Figure 6. Average CO_2 emissions per parcel with last-mile fleet electrification. Distribution from Namur, BE

5 Conclusion

The results of CO_2 emissions in parcel distribution in Belgium show that it is possible to reduce emissions not only through the electrification of the fleet but also with an efficient distribution network. The effect of the network structure will be more evident with international shipments that include more polluting modes of transport. However, the results for Belgium show that the last mile is currently the most polluting segment. Although the transport CO_2 emissions are the focus of attention, it cannot be ignored that other operations in the e-commerce supply chain are generating emissions. In 2020 the breakdown of estimated e-commerce greenhouse gas emissions mainly came from packaging level (45%), followed by return rates (25%); compared to traditional retail, where transportation is the most significant pollutant source (70%) [50]. These are elements that should be considered in a comprehensive CO_2 emissions calculation.

The existing methodologies support calculating CO_2 emissions and provide the guidelines according to the different approaches. Accepting the guidelines of the EN16258 standard regarding the calculation segmented by transport legs but using the same calculation methodology is fundamental. Adding the results of isolated calculations carried out by each operator is not the same. The integration of the last mile in transport emissions calculations is essential, and the strategic formulation allows estimating the distances of this segment without the need for classical routing algorithms. The formulation presented in this paper provides the flexibility and simplicity necessary to standardise emissions calculation.

The results of this study have practical implications for different stakeholders. First, for parcel distribution companies an additional opportunity to achieve green goals is the reconfiguration of their distribution networks. Not only does the electrification of the fleet have direct effects on the reduction of the level of emissions, but the redesign of the routes could generate a positive greening effect. Second, in terms of policy development, knowing that the last mile is the most polluting segment should indicate where the greatest efforts are needed. Even though the loss of economies of scale by using smaller-capacity vehicles is an aggravation of the situation, the trend towards the use of cargo bikes or small electric vehicles is correct. Third, consumers must be aware that some of their consumption practices have a negative impact on emissions. This study shows that the shorter the time windows, the higher the emissions. In order to meet consumer expectations, the e-commerce sector is incurring higher costs and higher emissions, although only the former is transferred to users.

As future research, expanding the results of this study with regional and global supply networks is necessary. Maritime and air transport modes certainly have an impact on the level of emissions and could balance emissions between the line haul and the last mile. As already mentioned, sources of emissions other than transportation could be included in general calculations. The effects of electrification seen in this study as a sensitivity analysis could be confirmed with more in-depth case studies, and analyze specific electrification strategies in more detail.

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References

[1] European Commission, "European Green Deal Communication," 2021.

[2] EPA, "Sources of Greenhouse Gas Emissions | US EPA," 2020. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed Jul. 13, 2022).

[3] IEA, "CO2 emissions by sector, World 1990-2019," 2019. https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=CO2 emissions&indicator=CO2BySector (accessed Jul. 13, 2022).

[4] IEA, "Cars, planes, trains: where do CO2 emissions from transport come from?," *Our World in Data*, 2020. https://ourworldindata.org/co2-emissions-from-transport (accessed Jul. 13, 2022).

[5] European Parliament, "CO2 emissions from cars: facts and figures (infographics)," *News - European Parliament*, 2019. https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics (accessed Jul. 13, 2022).

[6] ICAO, "ICAO Carbon Emissions Calculator." https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx (accessed Jul. 13, 2022).

[7] Y. Guo, F. Hu, H. Allaoui, and Y. Boulaksil, "A distributed approximation approach for solving the sustainable supply chain network design problem," *https://doi.org/10.1080/00207543.2018.1556412*, vol. 57, no. 11, pp. 3695–3718, Jun. 2018, doi: 10.1080/00207543.2018.1556412.

[8] D. C. Gong, P. S. Chen, and T. Y. Lu, "Multi-Objective Optimization of Green Supply Chain Network Designs for Transportation Mode Selection," *Sci. Iran.*, vol. 24, no. 6, pp. 3355–3370, Dec. 2017, doi: 10.24200/SCI.2017.4403.

[9] F. Yu, Y. Yang, and D. Chang, "Carbon footprint based green supplier selection under dynamic environment," *J. Clean. Prod.*, vol. 170, pp. 880–889, Jan. 2018, doi: 10.1016/J.JCLEPRO.2017.09.165.

[10] A. Jerbi, H. Jribi, A. M. Aljuaid, W. Hachicha, and F. Masmoudi, "Design of Supply Chain Transportation Pooling Strategy for Reducing CO2 Emissions Using a Simulation-Based Methodology: A Case Study," *Sustain.*, vol. 14, no. 4, p. 2331, Feb. 2022, doi:

10.3390/SU14042331/S1.

[11] D. Klein, C. Wolf, C. Schulz, and G. Weber-Blaschke, “Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change,” *Sci. Total Environ.*, vol. 539, pp. 45–60, Jan. 2016, doi: 10.1016/J.SCITOTENV.2015.08.087.

[12] H. R. Nurul, H. Haslenda, N. Alafiza Yunus, and J. Jaromír Klemeš, “Integrated GIS-AHP Optimization for Bioethanol from Oil Palm Biomass Supply Chain Network Design,” *Chem. Eng. Trans.*, vol. 83, p. 2021, 2021, doi: 10.3303/CET2183096.

[13] J. A. Lozano-Moreno and F. Maréchal, “Biomass logistics and environmental impact modelling for sugar-ethanol production,” *J. Clean. Prod.*, vol. 210, pp. 317–324, Feb. 2019, doi: 10.1016/J.JCLEPRO.2018.10.310.

[14] A. Mubarak and F. Zainal, “Development of a framework for the calculation of Co2 emissions in transport and logistics in Southeast Asia,” *Int. J. Technol.*, vol. 9, no. 4, pp. 787–796, 2018, doi: 10.14716/IJTECH.V9I4.1432.

[15] A. Mubarak and I. Rahman, “A comparative analysis of carbon emissions from transportation and logistics of the consumer goods industry in Southeast Asia,” *Int. J. Technol.*, vol. 11, no. 2, pp. 333–341, 2020, doi: 10.14716/IJTECH.V11I2.3466.

[16] J. B. Edwards, A. C. McKinnon, and S. L. Cullinane, “Comparative analysis of the carbon footprints of conventional and online retailing: A ‘last mile’ perspective,” *Int. J. Phys. Distrib. Logist. Manag.*, vol. 40, no. 1–2, pp. 103–123, 2010, doi: 10.1108/09600031011018055/FULL/XML.

[17] A. Tsakalidis, J. Krause, A. Julea, E. Peduzzi, E. Pisoni, and C. Thiel, “Electric light commercial vehicles: Are they the sleeping giant of electromobility?,” *Transp. Res. Part D Transp. Environ.*, vol. 86, p. 102421, Sep. 2020, doi: 10.1016/J.TRD.2020.102421.

[18] M. Woody, M. T. Craig, P. T. Vaishnav, G. M. Lewis, and G. A. Keoleian, “Optimizing future cost and emissions of electric delivery vehicles,” *J. Ind. Ecol.*, vol. 26, no. 3, pp. 1108–1122, Jun. 2022, doi: 10.1111/JIEC.13263.

[19] I. Davydenko, V. Ehrler, D. de Ree, A. Lewis, and L. Tavasszy, “Towards a global CO2 calculation standard for supply chains: Suggestions for methodological improvements,” *Transp. Res. Part D Transp. Environ.*, vol. 32, pp. 362–372, Oct. 2014, doi: 10.1016/J.TRD.2014.08.023.

[20] I. Davydenko, M. Hopman, R. N. van Gijlswijk, A. Rondaij, and J. S. Spreen, “Towards

harmonization of Carbon Footprinting methodologies," 2019. Accessed: Jul. 14, 2022. [Online]. Available: http://resolver.tudelft.nl/uuid:6bbcdab9-abb3-4c12-9a04-ec4c61f80642.

[21] P. Wild, "Recommendations for a future global CO2-calculation standard for transport and logistics," *Transp. Res. Part D Transp. Environ.*, vol. 100, p. 103024, Nov. 2021, doi: 10.1016/J.TRD.2021.103024.

[22] CLECAT, "Calculating GHG emissions for freight forwarding and logistics services," 2012.

[23] V. Konečný and F. Petro, "Calculation of selected emissions from transport services in road public transport," *MATEC Web Conf.*, vol. 134, Nov. 2017, doi: 10.1051/MATECCONF/201713400026.

[24] A. Mckinnon and M. Piecyk, "Measuring and Managing CO 2 Emissions of European Chemical Transport," 2011. Accessed: Jul. 13, 2022. [Online]. Available: www.cefic.org.

[25] Greenhouse Gas Protocol, "The GHG Emissions Calculation Tool," 2014. https://ghgprotocol.org/ghg-emissions-calculation-tool (accessed Jul. 15, 2022).

[26] Green Logistics, "Green Logistics method for the ecological assessment of logistics service providers," 2015. Accessed: Jul. 18, 2022. [Online]. Available: https://www.researchgate.net/publication/280736205_Green_Logistics_method_for_the_ecological_assessment_of_logistics_service_providers_Calculation_of_emissions_step_2_and_validation_of_scope.

[27] Smart Freight Centre, "Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting ," 2019.

[28] Lean & Green, "Optimalisatie transportplanning - Lean & Green." https://www.lean-green.nl/maatregelen/optimalisatie-transportplanning/ (accessed Jul. 15, 2022).

[29] CE Delft, "STREAM Freight transport - Emissions of freight transport modes," 2016. Accessed: Jul. 14, 2022. [Online]. Available: www.cedelft.eu.

[30] Ministry for an ecological and solidary Transition, "GHG information for transport services," 2019. Accessed: Jul. 14, 2022. [Online]. Available: www.ecologique-solidaire.gouv.fr.

[31] European Commission, "Vehicle Energy Consumption calculation TOol - VECTO," 2018. https://ec.europa.eu/clima/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/vehicle-energy-consumption-calculation-tool-vecto_en (accessed Jul. 11, 2022).

[32] EcoTransIT, "Ecological Transport Information Tool for Worldwide Transports," 2019. Accessed: Jul. 15, 2022. [Online]. Available: https://ecotransit.org/methodology.en.html.

[33] BigMile, “BigMile Carbon Analytics – The standard in CO2 footprint calculation and optimization.” https://bigmile.eu/bigmile-carbon-analytics/ (accessed Jul. 14, 2022).

[34] CarbonCare, “Methodology adopted to compute CO2 and other Greenhouse gases emissions by Cabon-Care.” https://www.carboncare.org/en/co2-emissions-calculator/co2-calculator-methodology.html (accessed Jul. 18, 2022).

[35] UPU, “OSCAR,” *Universal Postal Union*, 2020. https://www.upu.int/en/Postal-Solutions/Technical-Solutions/Products/OSCAR (accessed Jul. 15, 2022).

[36] DHL, “Carbon Calculator,” 2022. https://www.dhl-carboncalculator.com/#/home (accessed Jul. 18, 2022).

[37] G. Laporte and Y. Nobert, “Exact Algorithms for the Vehicle Routing Problem,” *North-holl. Math. Stud.*, vol. 132, no. C, pp. 147–184, 1987, doi: 10.1016/S0304-0208(08)73235-3.

[38] I. Davydenko, R. T. M. Smokers, W. M. M. Hopman, and H. Wagter, “Great Circle Distance as the optimal distance metric for CO2 allocation in freight transport,” *TNO Publications*. 2021, Accessed: Jul. 18, 2022. [Online]. Available: http://resolver.tudelft.nl/uuid:6e3d257c-ab6e-4f55-b254-ddc6ea33ce71.

[39] J. Beardwood, J. H. Halton, and J. M. Hammersley, “The shortest path through many points,” *Math. Proc. Cambridge Philos. Soc.*, vol. 55, no. 4, pp. 299–327, 1959, doi: 10.1017/S0305004100034095.

[40] C. F. Daganzo, “The Distance Traveled to Visit N Points with a Maximum of C Stops per Vehicle: An Analytic Model and an Application,” *https://doi.org/10.1287/trsc.18.4.331*, vol. 18, no. 4, pp. 331–350, Nov. 1984, doi: 10.1287/TRSC.18.4.331.

[41] I. Cárdenas, J. Beckers, and T. Vanelslander, “E-commerce last-mile in Belgium: Developing an external cost delivery index,” *Res. Transp. Bus. Manag.*, vol. 24, pp. 123–129, Sep. 2017, doi: 10.1016/j.rtbm.2017.07.006.

[42] J. C. Pina-Pardo, M. Moreno, M. Barros, A. Faria, M. Winkenbach, and M. Janjevic, “Design of a two-echelon last-mile delivery model,” *EURO J. Transp. Logist.*, vol. 11, p. 100079, 2022, doi: 10.1016/J.EJTL.2022.100079.

[43] M. Winkenbach, A. Roset, and S. Spinler, “Strategic Redesign of Urban Mail and Parcel Networks at La Poste,” *Interfaces (Providence).*, vol. 46, no. 5, pp. 445–458, Oct. 2016, doi: 10.1287/INTE.2016.0854.

[44] F. M. Bergmann, S. M. Wagner, and M. Winkenbach, “Integrating first-mile pickup and last-mile delivery on shared vehicle routes for efficient urban e-commerce distribution,” *Transp. Res.*

Part B Methodol., vol. 131, pp. 26–62, Jan. 2020, doi: 10.1016/J.TRB.2019.09.013.

[45] I. D. Cardenas, W. Dewulf, T. Vanelslander, C. Smet, and J. Beckers, "The e-commerce parcel delivery market and the implications of home B2C deliveries vs pick-up points," *e-commerce Parcel Deliv. Mark. Implic. home B2C Deliv. vs Pick. points*, vol. 44, no. 2, pp. 235–256, Jun. 2017, doi: 10.19272/201706702004.

[46] R. Gevaers, E. Van de Voorde, and T. Vanelslander, "Cost Modelling and Simulation of Last-mile Characteristics in an Innovative B2C Supply Chain Environment with Implications on Urban Areas and Cities," *Procedia - Soc. Behav. Sci.*, vol. 125, pp. 398–411, Mar. 2014, doi: 10.1016/J.SBSPRO.2014.01.1483.

[47] Ecommerce Europe, "European e-commerce report 2022," 2022. Accessed: Jul. 09, 2022. [Online]. Available: www.ecommerce-europe.eu.

[48] J. Beckers, S. Weekx, P. Beutels, and A. Verhetsel, "COVID-19 and retail: The catalyst for e-commerce in Belgium?," *J. Retail. Consum. Serv.*, vol. 62, p. 102645, Sep. 2021, doi: 10.1016/J.JRETCONSER.2021.102645.

[49] BIPT, "Market share based on volume within the segment of parcel and express mail items," 2021. https://www.bipt.be/operators/market-share-based-on-the-volume-within-the-segment-of-parcel-and-express-mail-items (accessed Jul. 09, 2022).

[50] MIT Real State Innovation Lab, "Retail Carbon Footprints: Measuring Impacts from Real Estate and Technology," 2021.