POLITECNICO DI TORINO

Master of Science in
Engineering and Management

Master of Science Thesis

Carbon emissions in city logistics: a literature review

Supervisor:
Prof.ssa Anna Corinna Cagliano

Candidate:
Aurelio Christopher Dichio

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Introduction

City logistics is defined as "*the process for totally optimizing the logistics and transport activities by private companies with the support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of a market economy*" (Taniguchi and Thompson, 2015).

Multiple objectives should be optimized in city logistics, and the most important are mobility, sustainability, livability, and resilience (Taniguchi and Thompson, 2015). Congestion needs to be alleviated to improve mobility. Air pollution, noise, and vibrations should be decreased to improve sustainability. Safety and security are the main goals to assure livability. Finally, regarding resilience, the distribution of food, water, and daily commodities to displaced people after a catastrophic disaster should be guaranteed (Taniguchi and Thompson, 2015). The main stakeholders involved in city logistics are shippers, freight carriers, administrators, and citizens. Shippers want to have reliable logistics at lower costs. Freight carriers must provide better service to shippers that usually set time windows for receiving their goods. Administrators must promote economic development and environmental savings. And finally, citizens want to live in safe, livable, and attractive cities (Taniguchi and Thompson, 2015).

Nowadays, three main trends are affecting city logistics, and these are the increasing urbanization of the world, the growth of e-commerce, and the growing concerns about environmental pollution. The world's population is being increasingly concentrated in cities. More than 50% of the world population currently lives in urban areas (United Nations, 2019). In 2050, 68% of the world's population is expected to be urban, reaching 6.3 billion (United Nations, 2019). There are also a growing number of megacities (cities with a population of over 10 million) in the world (United Nations, 2019). Urban areas require a massive quantity of goods, services, and resources, causing many problems for citizens (L. Ranieri *et al.*, 2018). Then, e-commerce is rapidly increasing, which causes an increase in delivery services. Volumes of e-commerce showed a worldwide growth rate of 23.3% in 2018 and have drastically increased during the COVID-19 pandemic, leading to a massive number of parcels being deliverer in cities (Patella *et al.*, 2021). Due to the increasing number of goods vehicles movements in urban areas, modern cities face congestion, lack of public space, air pollution, noise, etc. (Patella *et al.*, 2021).

Lastly, city logistics is a relevant part of the environmental emissions deriving from transport (Giordano, Fischbeck and Matthews, 2018). In Europe, about 25% of greenhouse gas (GHG) emissions from the transport sector are attributable to urban mobility, and 6% of these urban emissions are due to city logistics (Giordano, Fischbeck and Matthews, 2018). The European Commission (EC) proposed a 60% reduction of GHG emissions reduction from transport, compared to 1990 levels, by 2050, and as part of this strategy, they set the goal of "CO2-free city logistics" by 2030 (Giordano, Fischbeck and Matthews, 2018).

In this thesis, a literature review regarding carbon emissions in city logistics will be done. The latest research on this theme will be analyzed to show the academic interest in this research field, the main topics discussed, and research trends and gaps.

After this introduction, chapter 1 gives an overview of environmental sustainability research in city logistics. Then, in chapter 2, the literature review is carried out. Finally, in chapter 3, the thesis's benefits are discussed, together with future steps that can be undertaken in this field of research and limitations of this work.

As will be discussed in the thesis, it is possible to confirm that city logistics' academic interest in carbon emissions is increasing. Papers have been classified into ten categories which are: drones, cargo bikes, electric vans, urban consolidation centers, parcel lockers, crowdshipping, collaboration, delivery robots, other solutions, and online shopping. The most discussed solutions are drones, cargo bikes, electric vans, and urban consolidation centers. Drones' delivery is found to be environmentally friendly only in some cases. Green vehicle routing problems (GVRP) in drones are discussed, and the impact of other pollutant emissions should be calculated in future studies. Cargo bikes are more environmentally friendly than conventional last-mile delivery solutions. The effect of non-CO2 pollutants should also be calculated in this case and the air pollution at the urban transshipment point. Electric vehicles and UCCs are also found to be environmentally friendly. Crowdshipping, collaboration, and parcel lockers show a potential to decrease emissions and should be further studied. Delivery robots also demonstrated the potential to lower emissions, depending on the type of delivery robots and conditions. The lifecycle impact of this type of vehicle should be calculated. Finally, Online shopping and traditional shopping carbon intensity depend on the assumption made, and it is not easy to know which of the two is more environmentally friendly.

Chapter 1

Overview of research in Carbon Emissions in City Logistics

This chapter presents an overview of research inherent with carbon emissions-related studies in city logistics. To this aim, search results of the most important keywords related to this thesis's topic are analyzed with the Scopus tool "*Analyze search results*". Scopus is an abstract and citation database of peer-reviewed literature. Elsevier launched it in 2004 and covers the research fields of science, technology, medicine, social science, and art and humanities and features smart tools to track, analyze, and visualize research. Analyzing the search results of the most significant keywords gives an overview of trends in this research field, like the number of documents published over the past years, where and by who, relative to documents present in the Scopus database.

A summary of the essential literature reviews related to carbon emissions and city logistics is given then. Three recent literature reviews are analyzed, and these are (Patella *et al.*, 2021), (Luigi Ranieri *et al.*, 2018), and (Dolati Neghabadi, Evrard Samuel and Espinouse, 2019). The first two reviews are related to last-mile logistics. The third review instead focuses on city logistics in general. In this last review, a focus on a particular category of articles, sustainability, is given. These three reviews represent the most pertinent background knowledge before reviewing carbon emissions in city logistics. In the end, final considerations about the overview of research are given.

1.1 Analysis of Scopus search results

The search results associated with the keywords "city logistics carbon emissions" have been analyzed from the Scopus tool *Analyze search results,* updated on Dec 8, 2020. As can be seen from figure 1, results show an increasing number of documents associated with these keywords in the last years. The most publishing sources among the results are the scientific journals Sustainability Switzerland and Transportation Research Procedia. Most publishing authors are Dablanc L., Li J., Lo. K., Yang J., and Zhang D. with three documents each. The most publishing university is the Chinese Academy of Sciences with five documents. China is the most active state, with 50 documents in the results. The US is the second one with 14 documents, and the United Kingdom the third one with 12. 61.2% of the search results' documents are scientific articles, while 26.6% are conference papers. Principal subjects' areas are engineering (20.9%), social sciences (17.1%), and environmental science (14.6%).

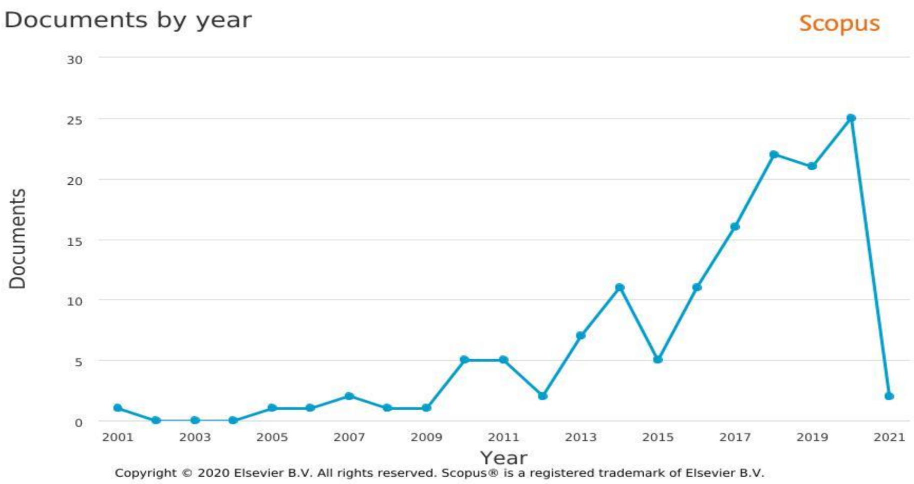

Figure 1: Number of documents per year in the results from the keyword search "carbon emissions city logistics" in Scopus. Updated Dec 8, 2020.

1.2 Summary of the paper "The adoption of green vehicles in last mile logistics: A systematic review" by Patella, S. M., Grazieschi, G., Gatta, V., Marcucci, E. and Carrese, S.

This paper by Patella S., Grazieschi G., Gatta V., Marcucci E., and Carrese S. presents a systematic literature review on studies investigating the adoption of green vehicles in city logistics, paying specific attention to e-commerce. A total of 159 articles have been analyzed by the authors and classified into three categories: optimization and scheduling (O), policy (P), and sustainability (S). Among these, a further selection of 17 papers dealing with e-commerce, i.e., studies related to integrating green vehicles in e-commerce, is performed. Most of the papers are recent and have been published in the last ten years, as shown in Figure 5. Figure 6 instead shows the work per category's distribution: 42% of the papers are related to optimization and scheduling (O), 34% to policy, and 24% to sustainability.

11% of papers are related to e-commerce, with 5.7% belonging to the policy group. Most authors are from Europe and North America, as shown in Figure 7.

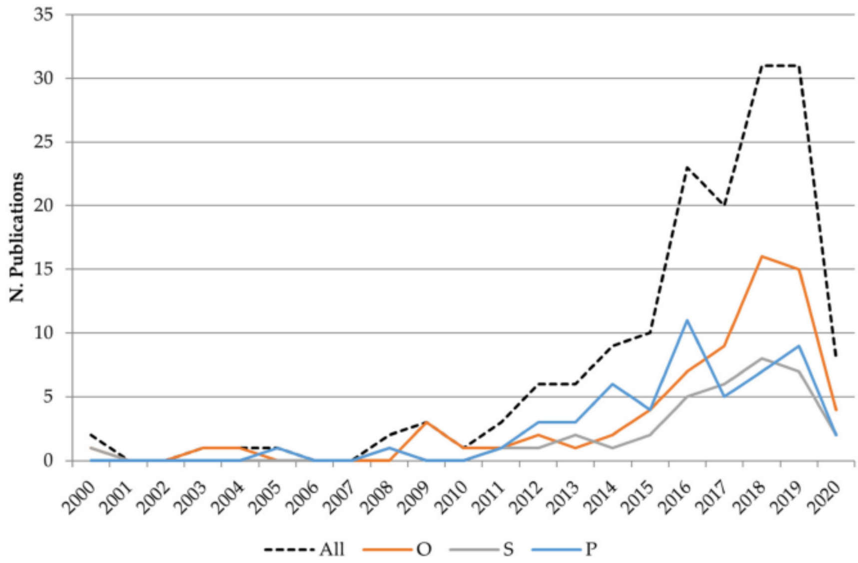

Figure 2: Number of papers considered per category and year of publication. Source: (Patella *et al.*, 2021)**.**

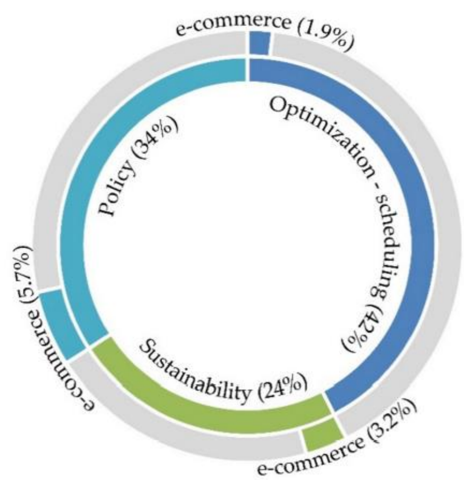

Figure 3: Representativeness of every category and e-commerce related works. Source: (Patella *et al.*, 2021)**.**

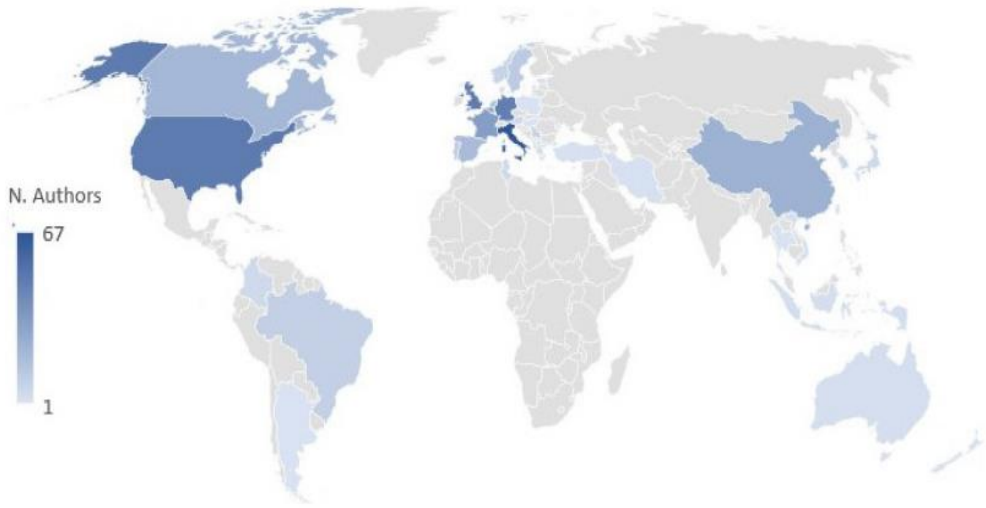

Figure 4: Colored map - the number of authors per country. Source: (Patella *et al.*, 2021).

A brief description of the categories and results presented by the authors is given in the next.

- *Optimization and scheduling*: papers investigating operational research problems are included in this category. Green vehicle routing problems (GVRP) are the most studied problems in this category and the number of studies on this field increases.
- *Policy*: papers included in this category focus on governance, planning, regulations, and incentive for innovative technologies. Collaboration between stakeholders seems to be a critical factor in increasing urban freight sustainability.
- *Sustainability*: papers related to environmental, economic, or social sustainability considerations are included in this category.

The authors point out that e-commerce seems to be more sustainable than traditional retail shopping. Last-mile delivery and warehouse management are the most impacting phase for the environment.

Moreover, they stated that the increased competition among online sellers, the always fastest delivery options, and the small size of the most significant part of the delivered items challenge the consolidation of diesel vehicles and increase negative externalities. In response to this, green vehicles (lightweight electric vehicles, cargo bikes, unmanned aerial vehicles (UAVs), etc.) are being evaluated. Authors conclude that the lifecycle economic and environmental sustainability is still debated since batteries' impacts and the necessity of new depots and facilities worsen the scenario.

The authors point out that vehicle technologies such as EVs, connected and automated vehicles, drones, and the introduction of new business models for freight transportation require new strategies to control the urban transportation system effectively. They encourage researchers to explore how overall urban transport sustainability can be enhanced. Moreover, they suggest that behavioral analysis based on stated preference methods is needed to investigate stakeholder's acceptability when new technologies are implemented.

1.3 Summary of the paper "A review of last mile logistics innovations in an externalities cost reduction vision" by Ranieri, L., Digiesi, S., Silvestri, B. and Roccotelli, M.

In this paper by L. Ranieri, S. Digiesi, B. Silvestri, and M. Roccotelli, a literature review of academic research papers and expert reports on innovative technologies and strategies able to reduce externalities in urban last-mile delivery is undertaken based on the Systematic Literature Review (SLR) method.

The model used by authors to evaluate external costs is taken from (Digiesi *et al.*, 2017):

$$EC_{k,i} = f(D, M, E_i, v, c_k)$$

Where:

- $EC_{k,i}$(€) is the cost of the *k-th* externality caused by the transport performed with the *i-th* transport mode.
- $D(km)$ is the demand for freight transport, that is, the total overall distance traveled by all transport means to deliver all parcels; A reduction of D reduces externality costs.
- $M(ton)$ is the load transported; Improvement of M means less trip and decreases the D factor.
- $E_i(\frac{unit}{ton*km})$ is the emission factor for the *i-th* transport means adopted at a given transport speed and is mainly related to vehicle technology and driving behavior.
- $v(\frac{km}{h})$ is the average speed travel; emissions are reduced up to a certain speed and then increase again as a reverse bell curve; noise instead increases with speed.

- $c_k \left(\frac{€}{unit}\right)$ is the unit cost of the k-th externality.

Authors point out that several aspects of the externalities model used are addressed in the scientific literature analyzed: reduction of the overall distance traveled (D, solving VRP problems, increasing the load factor and/or adopting logistic reconfiguration), of emission factor (E_i, adopting low or zero-emission vehicles or sharing vehicles) or increase the travel speed (v, delivering in appropriate time windows).

Main transport externalities in city logistics are air pollution, noise pollution, accidents, congestion, land use, infrastructure wear and tear, and energy dependency. Authors classified the scientific literature into five main categories of innovations able to reduce impact and externalities: innovative vehicles, proximity stations or points, collaborative urban logistics, optimization of transport management and routing, and innovations in public policies and infrastructures.

Finally, they identify literature gaps in each category mentioned that are summarized in the following. For innovative vehicles, they identify for each type of vehicle different aspects to be further investigated. For EVs, they suggest exploring new technologies able to provide greater autonomy, reduced charging time, and lower prices. For fuel cell electric vehicles (FCEVs), they mention infrastructure and standardization as the main issues to be further studied. For electric L-category vehicles (EV-Vs), they suggest investigating the impact on the externalities reduction achievable with their diffusion. Authors report that autonomous vehicles are still in the testing phase, and the latest research focuses on software systems. For UAVs, autonomous and remote driving with specific algorithms can be studied.

According to the authors, optimization should be further studied to allow high saturation rates regarding proximity stations or points capacity.

Also, they mention that the best positions for these points should be identified.

Collaborative and cooperative solutions are divided into two sub-categories: UCC using ICT and ITS tools that authors believe can improve their performance through innovative forms of management, and share a resource that expands the research field.

In optimizing transport management and routing, authors report that real-time data, prediction methods, and decision support systems still require research attention.

The authors believe that public policies and infrastructures still need to be explored to study new strategies to reduce externalities. They mention time windows, traffic management systems with sensors, intelligent traffic light management, urban pricing area, and mobility credits as exciting solutions. Finally, the authors point out that all stakeholders' commitment and the application of the solutions mentioned in this review are necessary to decrease externalities in last-mile delivery activities and achieve sustainable logistics in the urban area.

1.4 Summary of the paper "Systematic literature review on city logistics: overview, classification and analysis" by Dolati Neghabadi, P., Evrard Samuel, K. and Espinouse, M. L.

P. Dolati Neghabadi, K. Evrard Samuel, and M. Espinouse perform a bibliometric analysis and a systematic literature review from surveying more than 370 papers and research works published from 2010 to 2016 on city logistics. The bibliometric analysis focused on paper type analysis and its regional profile. Three types of work have been taken into consideration in this review: conference papers, which form the majority of works in the last six years, scientific articles and books, and book chapters. As we can see from figure 5, the number of research works in city logistics increases, especially from 2012. Around 52% of the papers analyzed are empirical, which increases to 63% if we only consider conference papers. This high percentage of empirical papers shows that it is crucial to know real-world cases in city logistics, as the authors pointed out. Regarding the regional profile, many papers have been published by European countries, especially France, Italy, Poland, and the Netherlands, as we can see from figures 6(a) and 6(b).

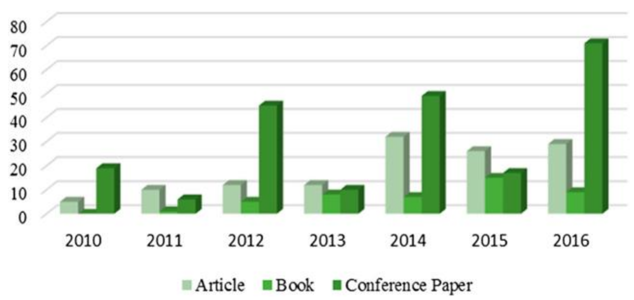

Figure 5: Classification of different scientific works by origin and by year. Source: (Dolati Neghabadi, Evrard Samuel and Espinouse, 2019)**.**

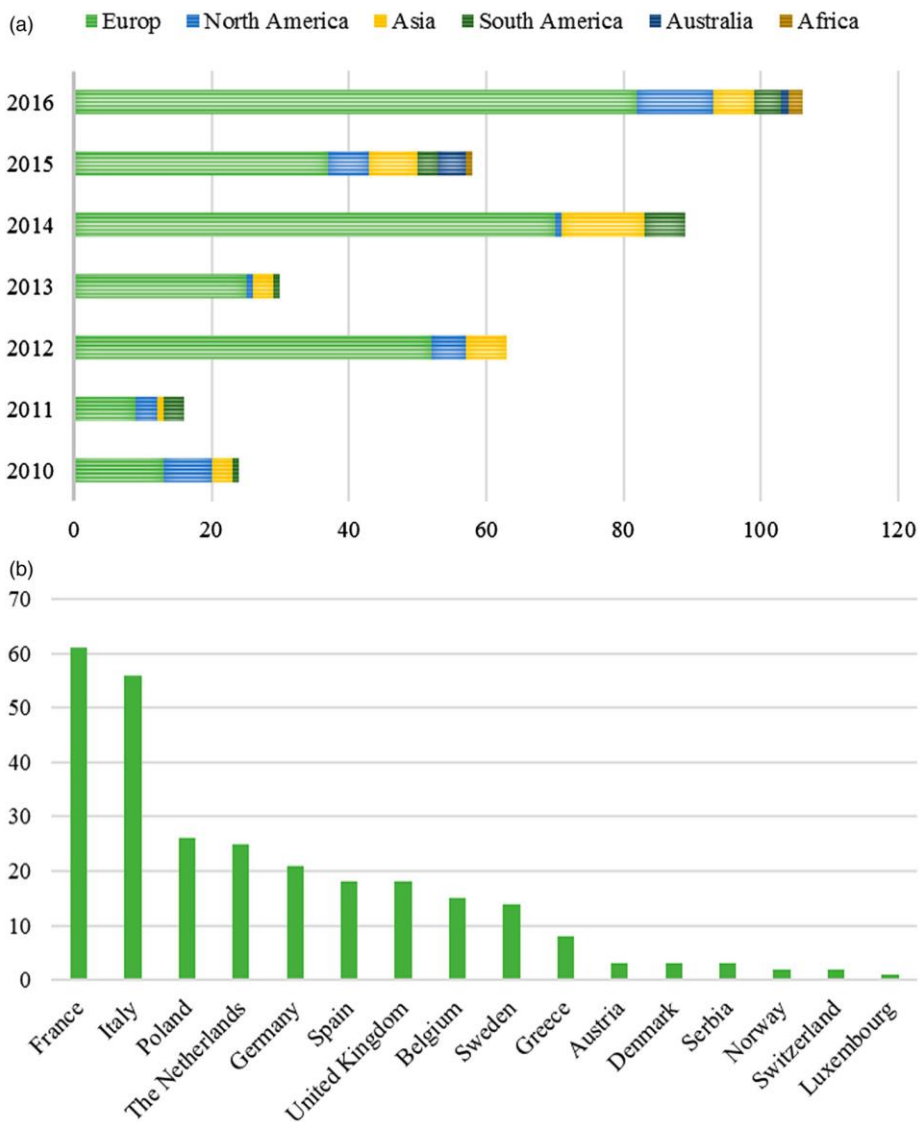

Figure 6: (a) Regional profiles by continents, (b) regional profiles, comparing European countries. Source: (Dolati Neghabadi, Evrard Samuel and Espinouse, 2019).

The authors introduced six categories: definition and perimeters, policy, innovative solutions, sustainability, methods, and stakeholders.

We focus on the sustainability category since it is the most relevant to this thesis. This category includes environmental, social, and economic considerations, which are very significant in city logistics research.

As pointed out by authors, the sustainability concept has been reported in different city logistics sectors such as *sustainable urban freight, sustainable mobility, sustainable urban logistics plan*. Environmental impacts are mainly *fuel consumption* and *polluting emissions*. Instead, social issues mainly point to the *quality of life, congestion*, and *historical urban area preservation*. As we can see from table 1, a significant percentage of articles in this category talk about environmental impacts, especially carbon emissions.

Table 1: Number of articles per year for 'Sustainability' class. Source: (Dolati Neghabadi, Evrard Samuel and Espinouse, 2019)**.**

Sustainability	Year							
	2010	2011	2012	2013	2014	2015	2016	*Sum*
Sustainability	1	3	4	-	10	2	8	28
Environmental impacts	3	-	1	2	4	3	13	26
Social impacts	-	1	2	1	5	-	-	9
Sum	4	4	7	3	19	5	21	63

The authors pointed out that most works are related to environmental impact and negative externalities of city logistics policies, initiatives, or innovative solutions studied in this category. Economic and social considerations are less discussed, and only in some cases, costs related to carbon emissions are computed. Authors believe other factors like profitability and livability of projects should be formulated to calculate economic effects in the long term. Moreover, the authors suggest evaluating consequences related to the projects' social aspects to guarantee cities' attractiveness and quality of life for the inhabitants. Authors suggest a new classification called 4A's: awareness, avoidance, act and shift, and anticipation of new technologies proposed by Macharis and Kin (Macharis and Kin, 2017) to evaluate the sustainability of city distribution differently.

1.5 Final considerations about the overview of research

From the previous analysis, it is possible to conclude that there is an academic interest in environmental sustainability in city logistics.

Research on city logistics, in general, is increasing as well as research on sustainability aspects in city logistics (Dolati Neghabadi, Evrard Samuel and Espinouse, 2019). Green vehicles (lightweight electric vehicles, cargo bikes, unmanned aerial vehicles (UAVs), etc.) are being increasingly adopted to decrease negative externality (air pollution, congestions, noise, etc.) (Patella *et al.*, 2021), and studies related to these vehicles show an increasing trend (Patella *et al.*, 2021). However, the authors in (Patella *et al.*, 2021) conclude that the lifecycle economic and environmental sustainability of green vehicles is still debated.

(Luigi Ranieri *et al.*, 2018) instead identify five main innovations able to decrease externalities in urban logistics: innovative vehicles, proximity stations or points, collaborative urban logistics, optimization of transport management and routing, and innovations in public policies and infrastructures. They mention that a further investigation of the impact of externalities reduction achievable with EL-Vs diffusion (electric L category vehicles, which also includes electric cargo bikes and tricycle) is needed. These aspects are a good starting point for this thesis, aiming to review papers related to carbon emissions in city logistics. The increasing interest in research on city logistics' environmental sustainability represents a basis for this literature review. Moreover, city logistics includes the last mile logistics concept, so green vehicles discussed in (Patella *et al.*, 2021) and innovations identified by (Ranieri et al., 2018) will be discussed in this review from an environmental perspective. This discussion will help understand the lifecycle economic of green vehicles and the impact achievable with EL-V diffusion, and more in general, which aspects of city logistics are being investigated in research from a carbon emissions viewpoint.

Chapter 2

Literature review

In this chapter, the literature review about carbon emissions in city logistics is carried out. First, we explain the data collection process. Then a bibliometric analysis is presented to show some paper's characteristics, like the years of publication and the types of paper. Afterward, a classification of the papers analyzed is proposed. For each class, the most important papers are described. In the end, the final considerations of the literature review are given.

2.1 Data Collection

The papers collected have been found using the abstract and citation database Scopus. The research in Scopus has been done using keywords. The combination of keywords searched was, in order of importance: city logistics carbon emissions, last-mile delivery carbon emissions, urban freight transport carbon emissions, and urban logistics carbon emissions. Papers with qualitative and quantitative results regarding carbon emissions and papers that include the carbon emissions aspect have been selected.

From the recent, a sample of 50 papers has been collected. The keywords associated with the papers are reported in table 2.

Table 2: Keywords associated with the papers analyzed.

Adaptive large neighbourhood search metaheuristic	Agent-based modelling	Air drone
Air pollution	Autonomous delivery robot	Autonomous drones
Autonomous vehicles	Cap and trade	Carbon
Carbon credit points	Carbon emission	Carbon emissions
Carbon emissions reduction	Carbon footprint	Carbon footprint mapping
Carbon reduction	Carbon tax	Cargo bike
Cargo tricycle	Central management of distribution	China
City hub	City logistic	City logistics
CML2001	CO2	CO2 emissions
Collaboration	Collaborative distribution	Commercial battery electric vehicle
Complex network	Complex network-based analysis	Courier services

Crowdsourcing distribution	Customer pick-up	Cycle logistics
Delivery	Delivery industry	Delivery problem
Delivery services	Delivery vans	Discrete optimization
Distribution channels and markets	Drone	Drone delivery
Drones	Eco-logistic	E-commerce
Economic lifecycle analysis (LCA)	E-grocery delivery network	Electric light commercial vehicles (eLCV)
Electric cargo bikes	Electric mobility	Electric trucks
Electric vehicle Emissions mitigation	Electric vehicles Empirical analysis	Emissions
Energy	Energy consumption	Energy efficiency
Environmental benefits	Environmental LCA	Environmental saving
Exclusive lanes	Exclusive motorcycle lanes	Express delivery
Express delivery industry	Express delivery	Express delivery industry

Externality	Freight distribution	Freight distribution network
Freight transport	Freight transportation	Fuel consumption
Fuzzy clustering	Greenhouse gases (GHG) emissions	Green logistics
Green vehicle routing (VRP)	Green VRP	Greenhouse gas emissions
Grocery shopping	Ground robot	Heterogeneous fleet
Home delivery	Home delivery and pick-up site services	Hybrid immune algorithm
Hybrid two-phase algorithm	Idling	ILS
Improving delivery time	Incentives	Information
Internet shopping	Last mile	Last mile delivery
Last mile problem	Last-mile distribution	Last-mile logistics
LCA	Lifecycle emissions	Light commercial vehicle
Linear programming	Location-routing	Location-routing problem

Logistics multi-layer distribution network	Logistics system	Low carbon
Lucca	Minimization model	Mixed fleet routing
Mixed-integer linear programming	Motorcycle delivery	Multi agent techniques
Multi-tenant buildings	Network flow problem	Network planning
Online retailing	Online shopping	Optimization of distribution
Outsourcing	Parcel delivery	Parcel lockers
Parking	Path selection	Pedemontana Veneta
Plug-in hybrid powertrain	Pollution-routing problem	Public procurement
Resource deployment	Robot	SIMMAG 3D
Simulated annealing	Smart city	Spatial analysis
Supply chain management	Supply chain sustainability	Sustainability of unmanned aerial vehicles
Sustainable delivery	sustainable development	Sustainable economy
Sustainable logistics	Sustainable mobility	Sustainable parcel delivery

Sustainable transport	Sustainable transportation	Sustainable urban deliveries
Sustainable urban logistics	Total cost of ownership	Traffic simulation
Tricycles	Two-echelon location routing with the mixed fleet and mixed satellites	UAV (unmanned aerial vehicle)
UAV drone	UAV policy	Unmanned aerial vehicle
Unmanned Aerial Vehicles	Urban consolidation centres	Urban consolidation centre
Urban freight	Urban freight transport	Urban logistics
Urban planning	Urban transhipment point	Vehicle arrangement
Vehicle logistics	Vehicle routing	Vehicle routing problem
Vehicle routing problems	Vehicles	Vehicles miles of travel (VMT)
Well-to-wheel analysis	Zero emission transport	

A database has been built for the papers collected with the following information:

- Title
- Author/s
- Paper type
- Year of publication
- Journal
- Volume
- Pages
- Objective
- Input information
- Methodology
- Results
- Future research.

2.2 Bibliometric Analysis

The distribution of the papers by year is shown in figure 7. The oldest paper dates back to 2009. 36% of papers were published in 2020, 14% in 2019, 12% in 2018, 14% in 2017, and lower percentages in previous years and 2021. 88% of papers analyzed have been published from 2016 until now.

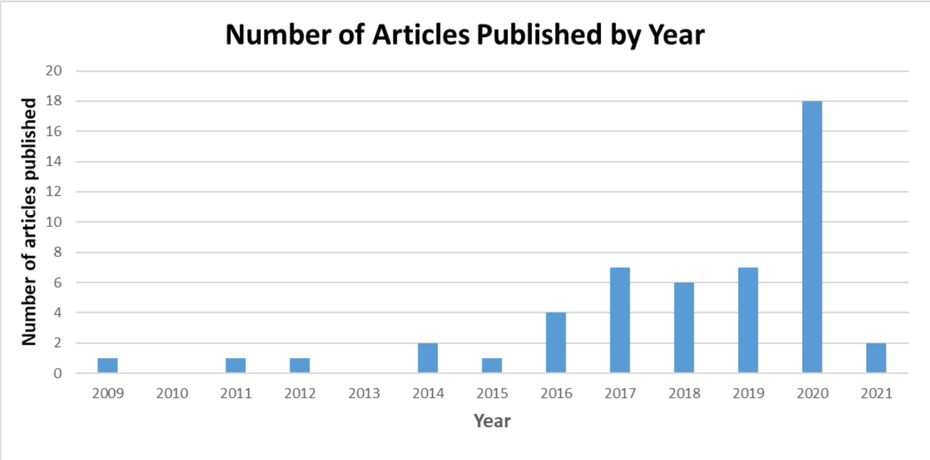

Figure 7: Number of articles published by year within the dataset.

Among the 50 papers, 45 are journal articles, 4 are conference papers, and 1 is a journal article in press. Among these, 18% (9 articles) are published on Transport Research Part D: Transport and Environment, 14% (7 articles) on Sustainability, 6% (3 articles) on IEEE access, 4% (2 articles) on International Journal of Logistics Research and Application, Energy, and Research in Transportation Economics, respectively. The remaining 46% belongs to other journals with only one occurrence within the dataset. Figure 11 summarizes these results.

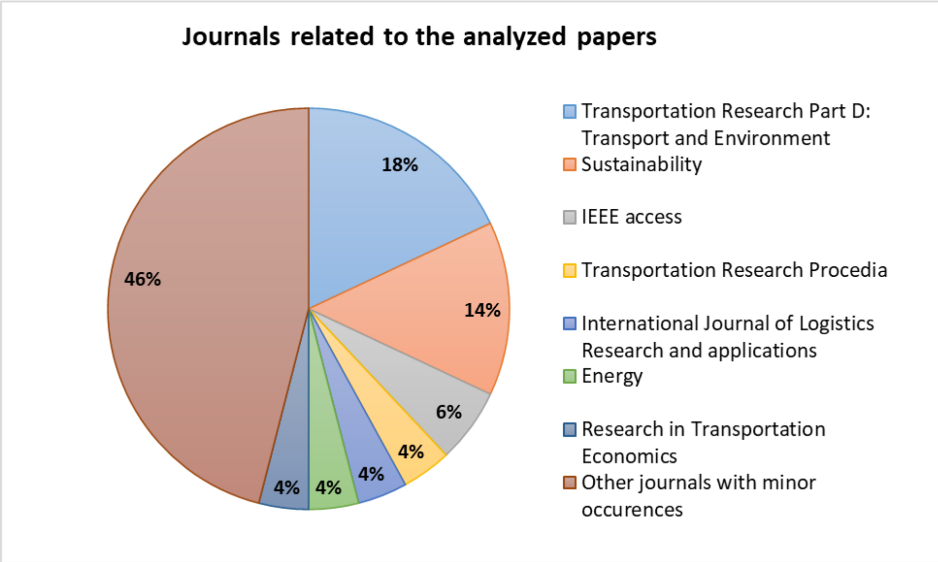

Figure 8: Percentage of articles within the dataset belonging to specific journals.

Each article treats one or more innovative solutions in city logistics. The innovative solutions treated in the articles are electric cargo bikes/ tricycle/ quadricycle, electric vans, drones, parcel lockers, crowdshipping, delivery robots, urban consolidation centers, collaboration among carriers, and other minor solutions different from the previous ones and with few papers each. One more group of articles treat carbon emissions of online versus conventional retailing. Some articles study more than one solution, like urban consolidation centers combined with electric vans or bikes. If we consider only the main solution treated in each article, drones are discussed in 20% of the analyzed papers, followed by cargo bikes/ tricycle/ quadricycle with 18% and urban consolidation centers with 10%. The percentage of each solution treated is shown in figure 8.

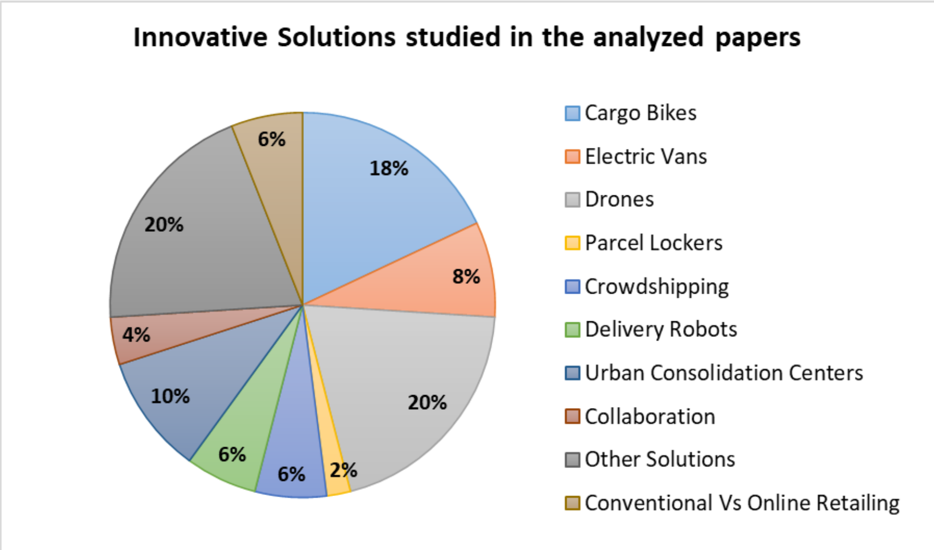

Figure 9: Percentage of articles within the dataset studying specific innovative solutions.

2.3 Classification

The articles have been classified by the innovative solution treated. A description of the categories is given below:

- Cargo bikes: this category includes papers that study the use of human-powered or electrically assisted standard bicycles, cargo bikes, and cargo tricycles for the transport of goods in urban areas (Schliwa *et al.*, 2015);
- Electric vans: use of electric vehicles designed and constructed for the carriage of goods, having four wheels, a maximum mass not exceeding 3.5 tonnes (Tsakalidis *et al.*, 2020);
- Drones: aircraft without a human pilot onboard to transport packages, medical supplies, food, or other goods;
- Parcel lockers: boxes that are located in public spaces (or which are at least publicly accessible) and which can be unlocked by the

recipient with the linked unlocking code (e.g., transmitted via email) (Prandtstetter *et al.*, 2021);

- Crowdshipping: strategies that take advantage of citizens' movements to transport parcels and maximize their utility (Giret *et al.*, 2018);
- Delivery Robots: often called autonomous delivery robots (ADRs), they are electrically powered motorized vehicles that can deliver items or packages to customers without human intervention. ADRs can be divided into two types: sidewalk autonomous delivery robots (SADRs) that are pedestrian-sized robots that only utilize sidewalks or pedestrian paths, and on-road or simply road autonomous delivery robots (RADRs) that travel on roadways (Figliozzi and Jennings, 2020);
- Collaborative solutions: this type of solutions try to reduce the unnecessary waste of transportation resources through collaboration from carriers' perspective (Yao, Cheng and Song, 2019);
- Urban consolidation centres (UCCs): a logistic facility situated in relative proximity to the urban area that it serves in which goods destined to the locations served are dropped off. The UCC operator sorts and consolidates these loads dropped off by logistics companies and makes deliveries to the final destinations (Browne, Allen and Leonardi, 2011);
- Online vs. traditional retailing: online or e-commerce channels allow the customer to initiate the purchase electronically without visiting the physical store, while conventional shopping involves visiting the item's physical location (Brown and Guiffrida, 2014). In conventional shopping, the customer picks up the purchased item from the retailer and self-delivers the item to their home using their vehicle (Brown and Guiffrida, 2014). In e-commerce, the item is

delivered to the customer by the retail seller or by an agent contracted by the seller to provide a home delivery service (Brown and Guiffrida, 2014);

- Other solutions: mainly distribution network and vehicle routing models that take carbon emission reductions into considerations. Also, other minor solutions are included in this category.

In table 3, the classification of the papers can be seen.

Innovative Solution	**Articles in the category**
Cargo Bikes	(McLeod *et al.*, 2020), (Giret *et al.*, 2018), (Assmann *et al.*, 2020), (Saenz-Esteruelas *et al.*, 2016), (de Mello Bandeira *et al.*, 2019), (Shahmohammadi *et al.*, 2020), (Figliozzi, Saenz and Faulin, 2020), (Ben Rajesh and John Rajan, 2020), (Melo and Baptista, 2017), (Browne, Allen and Leonardi, 2011).
Electric Vans	(Faccio and Gamberi, 2015), (Tsakalidis *et al.*, 2020), (Giordano, Fischbeck and Matthews, 2018), (Millo *et al.*, 2017), (Browne, Allen and Leonardi, 2011).
Drones	(Chiang *et al.*, 2019), (Figliozzi, 2017), (Resat, 2020), (Figliozzi, 2020), (Koiwanit, 2018), (Goodchild and Toy, 2018), (Stolaroff *et al.*, 2018b), (Li, Yang and Huang, 2020), (Eun *et al.*, 2019), (Elsayed and Mohamed, 2020).
Parcel Lockers	(Liu *et al.*, 2021), (Jiang *et al.*, 2019).
Crowdshipping	(Suh, Smith and Linhoff, 2012), (Giret *et al.*, 2018), (Bi, Yang, Zahid, *et al.*, 2020).

Delivery Robots	(Figliozzi, Saenz and Faulin, 2020), (Liu *et al.*, 2021), (Figliozzi, 2020).
UCCs	(Dupas *et al.*, 2020), (Anand, van Duin and Tavasszy, 2019), (Nocera and Cavallaro, 2017), (Browne, Allen and Leonardi, 2011), (Wasiak *et al.*, 2017).
Collaborative Solutions	(Bi, Yang, Zhou, *et al.*, 2020), (Yao, Cheng and Song, 2019).
Online Retailing	(Van Loon *et al.*, 2014), (Edwards, McKinnon and Cullinane, 2010), (Brown and Guiffrida, 2014), (Shahmohammadi *et al.*, 2020).
Other Solutions (e.g., vehicles routing and distribution network models with carbon emission reduction)	(Letnik *et al.*, 2018), (Kang *et al.*, 2020), (Yang, Guo and Ma, 2016), (Lee *et al.*, 2020), (Wang, Tian and Liu, 2017), (Tan *et al.*, 2019), (Behnke and Kirschstein, 2017), (Pilati *et al.*, 2020), (Nina *et al.*, 2020), (Koç *et al.*, 2016).

Table 3: Classification of the analyzed papers.

Some articles are present in more than one category since they study multiple innovative solutions (e.g., urban consolidation centers combined with e-vans and cargo bikes).

2.4 Discussion of paper results and future research directions

An overview of the analyzed papers for each category is given in the following. Only CO2-related aspects are discussed, which is the research's focus in most papers. Future research directions highlighted by authors in the papers are also discussed at the end of each subparagraph.

2.4.1 Drones

M. A. Figliozzi performs a lifecycle assessment (LCA) of UAVs CO2e emissions and found that they are more CO2 efficient for small payloads than conventional diesel vans on a per-distance basis. However, they are not if more customers can be grouped in the same delivery route (Figliozzi, 2017). Compared to tricycles and electric vans, UAVs are not more CO2 efficient if few customers can be grouped in a route (Figliozzi, 2017). The current practical range of multi-copters (about 4km) would also require a new network of urban warehouses or waystations as support, and the additional warehouse energy required would increase lifecycle impacts (Stolaroff *et al.*, 2018b, 2018a). J. K. Stolaroff suggests that the drone's extra warehousing and size should be minimized to achieve environmental benefits (Stolaroff *et al.*, 2018b, 2018a).

M. A. Figliozzi found that drones are more efficient in term of energy and emissions in time-constrained and low-density delivery scenarios compared to other ground autonomous delivery services (SADRs and RADRS), to electric and ICE vans, and driving to a store utilizing electric and conventional vehicles (Figliozzi, 2020). A. Goodchild and J. Toy instead found that drones are likely to provide CO2 benefits when service zone are close to the depot, have a few stops, or both (Goodchild and Toy, 2018). Kirschstein found that using UAVs for delivery shows no environmental benefits over diesel vans (DVs) and electric vans (EVs) in most cases (Kirschstein, 2020). Also, in rural settings, he found that the CO2e coefficient for electricity generation must be very low (below 0.3 kg CO2 per kWh) for UAVs to emit less CO2e than DVs.

Many authors studied green vehicle routing problems (Chiang *et al.*, 2019; Li, Yang and Huang, 2020; Resat, 2020) to optimize the route of a fleet of UAVs (Li, Yang and Huang, 2020; Resat, 2020) or a mixed fleet of EVs and UAVs (Chiang *et al.*, 2019). W. C. Chiang, et al. show that if adequately performed, delivery with UAVs would cut CO2 emissions. This would be possible shifting smaller package delivery from trucks to drones. So, a firm should plan and control vehicles and drones' routing and coordination to achieve environmental benefits (Chiang *et al.*, 2019). Y. Li and Huang propose a green routing model with two typical traffic restrictions for UAVs, vehicle-type restrictions and half-side traffic, and show that UAVs delivery can effectively save costs and cut CO2 emissions under these two restrictions (Li, Yang and Huang, 2020).

M. Elsayed and M. Mohamed instead studied the impact of UAVs flight regulations and policies on CO2e emissions and found that strict policy can increase GHG emissions in an urban context by up to 400% (Elsayed and Mohamed, 2020).

Future research should focus on calculating the impact of other pollutant emissions, including nitrous oxides and particulate matter, and other logistical structures, including the use of depots not central to the delivery region (Goodchild and Toy, 2018). Also, alternative power sources, such as fuel cells, should be investigated (Chiang *et al.*, 2019).

Regarding policies, the urban setting's impact, such as the change in building density versus the variation between policies, should be investigated, and cases in which strict flight regulations do not allow UAV flights, like near highways or airports (Elsayed and Mohamed, 2020).

Table 4: Topics of the papers described in the "drone" category.

Paper	**Topic**
(Figliozzi, 2017)	LCA of drones.
(Stolaroff *et al.*, 2018a), (Stolaroff *et al.*, 2018b)	Energy use model for drones.
(Figliozzi, 2020)	This paper studies the efficiency of autonomous (driverless) air and ground delivery vehicles in vehicle-miles, energy consumption, and CO2 emissions.
(Kirschstein, 2020)	Energy consumption model for drones.
(Chiang *et al.*, 2019)	Mixed-integer (0–1 linear) green routing model for UAV.
(Li, Yang and Huang, 2020)	Mixed-integer (0-1 linear) green routing model for UAVs.
(Resat, 2020)	This paper presents a novel two-stage solution method for sustainable last-mile delivery systems in urban areas.
(Elsayed and Mohamed, 2020)	This paper presents an estimate of the CO2e emissions for UAVs under different policies compared to diesel and electric ground delivery modes.
(Goodchild and Toy, 2018)	Estimation of carbon dioxide (CO2) emissions and vehicle-miles traveled (VMT) levels of two delivery models, one by trucks and the other by unmanned aerial vehicles (UAVs) or drones.

2.4.2 Cargo Bikes

J. Saenz et al. perform an LCA of cargo tricycle. Using real-world data from a tricycle logistics company operating in Portland, Oregon, found that CO2e emissions are reduced between 51% and 71% using tricycle instead of diesel vans in last-mile delivery (Saenz, Figliozzi and Faulin, 2016). Results depend on the electricity mix and are beneficial (at least 46% CO2 reduction) also for carbon-intensive electricity generation (Saenz, Figliozzi and Faulin, 2016). S. Melo and P. Baptista found that cargo bikes can replace up to 10% of conventional vans without changing the network efficiency. This case, urban logistics well-to-wheel (WTW) CO2 emission impact can be reduced by up to 73% (Melo and Baptista, 2017). Benefits of cargo tricycle in terms of lifecycle emissions are obtained by utilizing small vehicles for small loads, in dense service areas, and when the depot is located close to the delivery area (Figliozzi, Saenz and Faulin, 2020). Most tricycle emissions are generated in vehicle production and disposal, so increasing the vehicle payload, speed, and production/ disposal energy intensity would increase the benefits (Figliozzi, Saenz and Faulin, 2020).

In (McLeod *et al.*, 2020), authors propose a model not seen in the practice in which collection and delivery points (CDPs) such as general stores, post offices, or locker banks are used to transfer the parcel between van drivers and porters or cycle couriers. They found a 45% reduction in CO2 emissions and a 33% reduction in NOx associated with the use of cargo bikes instead of diesel vans in last-mile delivery in an area of central London, UK. T. Assmann et al. instead studied the urban transshipment points and suggested that the best strategy and network vehicle configuration to decrease GHG emissions is sitting cooperative urban transshipment points at a district's periphery and having trucks performing the in- and outbound processes (Assmann *et al.*, 2020).

Future research should focus on finding the optimal tricycle power/ payload limits and include the impact on non-CO2 pollution (Figliozzi, Saenz and Faulin, 2020). In the model proposed by F. N. McLeod et al., CO2 emission reduction in parcels with lighter weight profiles (e.g., those in the business-to-consumer market) should be investigated since authors believe savings would be even more significant (McLeod *et al.*, 2020). Moreover, the effect on air pollution at urban transshipment point locations should be further studied (Assmann *et al.*, 2020).

Table 5: Topics of the papers described in the "cargo bikes" category.

Paper	**Topic**
(Saenz, Figliozzi and Faulin, 2016)	Compare the carbon footprint of a tricycle logistics service with a traditional urban logistics company.
(Melo and Baptista, 2017)	Impacts of electric cargo bikes, from a public policy perspective.
(Figliozzi, Saenz and Faulin, 2020)	Lifecycle emissions minimization model for the fleet size and composition problem.
(McLeod *et al.*, 2020)	Evaluation of the potential environmental and financial benefits of switching from traditional van-based deliveries to an alternative operating model, where porters or cycle couriers undertake deliveries.
(Assmann *et al.*, 2020)	Examination of different strategies for siting urban transshipment points in a single district and its effect on traffic, the carbon footprint, and air quality to give strategic insights on where to create candidate locations for such facilities.

2.4.3 Electric Vans

Giordano et al. perform an LCA of battery-electric delivery vans against diesel alternative and found that if the electricity mix is relatively clean, CO2 emission and air pollutants decrease by 93-98% and 85-99%, respectively (Giordano, Fischbeck and Matthews, 2018). If electricity is coming from coal, reductions are in the order of 12-13% and 0-92%, respectively (Giordano, Fischbeck and Matthews, 2018). Results improve if battery life is longer and annual mileage is higher (Giordano, Fischbeck and Matthews, 2018).

M. Faccio and M. Gamberi implement a new eco-logistic model with the use of electric vehicles in last miles delivery and with actual tests found a reduction of 84% for diesel and methane vehicles (Faccio and Gamberi, 2015). An ambitious scenario of electrification in Europe can lead to a decrease of CO2 emissions from LCVs by 30%, which corresponds to a total carbon emission reduction in transport of 3% (Tsakalidis *et al.*, 2020). Air pollutants would decline as well, specifically NOx by nearly 5% and PM by 3% on an EU average (Tsakalidis *et al.*, 2020). The local concentration of PM2.5 is reduced to below 2% if emissions reduction is distributed within the member state (Tsakalidis *et al.*, 2020). The impact could be more substantial at the city level due to higher LCV activity (Tsakalidis *et al.*, 2020). For plug-in hybrid light commercial vehicles, F. Millo et al. found possible improvements in terms of CO2 emissions reductions in comparison to conventional diesel vehicles of 23% and 11%, respectively, on NEDC and WLTC test cycle (Millo *et al.*, 2017).

Table 6: Topics of the papers described in the "electric vans" category.

Paper	Topic
(Giordano, Fischbeck and Matthews, 2018)	Assessment of diesel and BEV vans' environmental impact using a life cycle assessment (LCA) methodology.
(Faccio and Gamberi, 2015)	Implementation of a new eco-logistic system that serves multiple adjacent cities by using electric vehicles to deliver goods of any type within their urban areas.
(Tsakalidis *et al.*, 2020)	Exploration of various electric Light Commercial Vehicles (eLCV) deployment scenarios until 2030 and calculation of their impact on carbon dioxide (CO2) and other pollutant emissions as well as pollutant concentrations.
(Millo *et al.*, 2017)	Fuel economy potential along the NEDC (New European Driving Cycle) and WLTC (Worldwide harmonized Light-duty Test Cycle) driving cycles of a Plug-in hybrid powertrain developed for a light-duty delivery vehicle.

2.4.4 Urban Consolidation Centers (UCCs)

M. Browne et al. perform a trial project in central London, UK, and evaluate the before and after emissions of a stationery and office supplies company. The company substituted delivery from a depot located in the suburbs using diesel vans with delivery from a micro-consolidation center located in the delivery area using electrically assisted cargo bikes and electric vans (Browne, Allen and Leonardi, 2011). They found a 54% reduction of CO_2e emissions per parcel delivered due to the new delivery system.

S. Nocera and F. Cavallaro design a WTW model and assess the carbon potentialities of a new UCC in the city of Lucca, Italy (Nocera and Cavallaro, 2017). They found a potential yearly saving of up to 190 tCO_2.

R. Dupas et al. found that increasing the connectivity degree between massive shopping centers (multi-tenant buildings) and intermediate depots (urban consolidation centers) brings to a significant reduction in CO_2 emissions (up to 36% in the tested case in the city of Tokyo) (Dupas *et al.*, 2020).

R. Dupas et al. suggest inserting time-flow in their model (Dupas *et al.*, 2020). They also suggest applying their distribution modeling approach to other cities to carry out comparative studies between the practices used in different countries to identify best practices. S. Nocera and F. Cavallaro instead suggest comparing their results with other case studies to highlight similarities or disparities with cities of comparable dimensions and to assess any geographic context-specific features in considering the CO_2 effectiveness of policies (Nocera and Cavallaro, 2017).

Table 7: Topics of the papers described in the "UCCs" category.

Paper	Topic
(Browne, Allen and Leonardi, 2011)	The role that can be played by urban consolidation centers (UCCs) in reducing freight traffic and its environmental impacts in towns and cities.
(Nocera and Cavallaro, 2017)	Quantification of CO2 emissions through a Well-To-Wheel methodology; economic evaluation of them, using a meta-analysis of 700 studies.
(Dupas *et al.*, 2020)	Methodology for evaluating the performance of a parcel distribution network in city logistics.

2.4.5 Delivery robots

M. A. Figliozzi found that SADRs can significantly reduce carbon emissions concerning ICE vans and other delivery vehicles when a mothership is not required, i.e., in a scenario where the delivery area surround the depot (Figliozzi, 2020). RADRs are more efficient than e-vans when delivering to a relatively low number of customers (Figliozzi, 2020). If mothership is required, SADRs are hardly appealing in terms of CO2 emissions (Figliozzi and Jennings, 2020). D. Liu et al. studied a sustainable two-echelon E-grocery delivery system, motivated by the adoption of ADRs and parcel lockers (PLs) in the E-grocery distribution industry (Liu *et al.*, 2021). They formulate the system as a two-echelon location-routing problem with mixed vehicles and mixed satellites (2E-LRP-MVMS). The goal is to determine location facilities, optimize the number of parcels delivered to two echelons and routes at each level, and reduce costs caused by carbon emissions (Liu *et al.*, 2021). They also develop a solution algorithm, which has been demonstrated to be superior to two other algorithms used to solve similar problems (Liu *et al.*, 2021). M. A. Figliozzi and D. Jennings suggest further study the evolution of ADRs and how they can complement or replace conventional vehicles (Figliozzi and Jennings, 2020). Figliozzi suggests considering their lifecycle emissions (Figliozzi, 2020). D. Liu et al. instead suggest applying real-life data in the model and algorithm they proposed (Liu *et al.*, 2021).

Table 8: Topics of the papers described in the "delivery robot" category.

Paper	**Topic**
(Figliozzi, 2020)	The efficiency of autonomous (driverless) air and ground delivery vehicles in terms of vehicle-miles, energy consumption, and CO2 emissions.
(Figliozzi and Jennings, 2020)	Model for understanding potential ADR energy and emissions reductions.
(Liu *et al.*, 2021)	Sustainable two-echelon E-Grocery delivery system.

2.4.6 Crowdshipping

A. Giret et al. propose an innovative approach to last-mile delivery in which citizens that move in the city because of their own needs became temporal deliverers and eliminate needs for logistics moves (by cars/ trucks) (Giret *et al.*, 2018). Tests show a high reduction of CO2 emission coming from the delivery trucks that are no longer needed with the new delivery system (Giret *et al.*, 2018). K. Bi et al. instead propose a new distribution model in which end crowdsourcing service stations (ECSSs), operated by express enterprises or an alliance between these enterprises and a third-party agent, provides a unified terminal for distribution for enterprises (Bi, Yang, Zahid, *et al.*, 2020). Some of the express packages will be then delivered to endpoints (EPs). Some will be delivered to intelligent express cabinets (IECs) by crowdsourcing couriers who are part-timers, professional couriers grouped by the third-party agent, or couriers from the express enterprises (Bi, Yang, Zahid, *et al.*, 2020). The end customers can then pick up the deliveries in the IECs according to their schedule (Bi, Yang, Zahid, *et al.*, 2020). Tests in Beijing, China, found carbon emissions reduction of 23.79-28.49% for the end of the distribution, 16.27-16.35% for the front-end, and approximately 17% for the entire distribution (Bi, Yang, Zahid, *et al.*, 2020). Finally, K. Suh et al. found that pick-up location delivery systems in suburban settings may increase emissions (Suh, Smith and Linhoff, 2012). Instead, if a social network is employed to assist in the pick-up service, a reduction in CO2 emissions of 93% in the urban settings and 78% in the suburban setting can be realized (Suh, Smith and Linhoff, 2012).

Regarding future research, authors in (Giret *et al.*, 2018) suggest introducing new aspects in their network analysis, such as delivery deadlines and security issues. Authors in (Bi, Yang, Zahid, *et al.*, 2020) instead suggest studying their model's behaviour for larger areas and further improving the location model. Additionally, they suggest investigating results in a real test with the vehicles' actual consumption. Finally, they suggest studying the impact of new energy vehicles on their distribution model.

Table 9: Topics of the papers described in the "crowdshipping" category.

Paper	**Topic**
(Giret *et al.*, 2018)	Provide an intelligent approach for Sustainable Last-Mile Delivery to reduce the number of movements originated by the parcel's delivery by taking advantage of the citizens' movements.
(Bi, Yang, Zahid, *et al.*, 2020)	Proposes a comprehensive and environmentally friendly mode for city distribution based on end crowdsourcing service stations (ECSSs).
(Suh, Smith and Linhoff, 2012)	Use of social relationships spatial and networked information for sharing excess capacity to reduce the environmental impacts associated with "last-mile" package delivery systems from online purchases, particularly in low population density settings.

2.4.7 Collaborative solutions

K. Bi et al. propose a new model of distribution based on intelligent end service station (IESS) (Bi, Yang, Zhou, *et al.*, 2020). In this model, enterprises only need to deliver their package the IESSs instead of their distribution outlets. Through the integration of the expresses to be delivered, the collaborative distribution from the IESS to the endpoints can be realized (Bi, Yang, Zhou, *et al.*, 2020). For the front-end, carbon emissions are reduced by 21.9% and for the back end by 68.21% (Bi, Yang, Zhou, *et al.*, 2020). Overall, carbon emissions are reduced for the whole distribution process by 24% (Bi, Yang, Zhou, *et al.*, 2020). Authors estimate that carbon emissions for the distribution demand in Beijing's city can be decreased daily by 22.26 t and annually by 8125 t with the implementation of the collaborative system (Bi, Yang, Zhou, *et al.*, 2020).

Yao et al. instead study the influence of collaboration between two carriers and found that carbon emissions abatement can be achieved (Yao, Cheng and Song, 2019).

Authors in (Bi, Yang, Zhou, *et al.*, 2020) suggest estimating more precisely carbon emissions using positioning devices on vehicles. Moreover, they suggest further study of the mathematical relationship between carbon emissions and express vehicles' load. Finally, they suggest improving the measurement models of carbon emissions. Yao et al. instead suggest further expand their study considering more carriers within the model (Yao, Cheng and Song, 2019).

Table 10: Topics of the papers described in the "collaborative solution" category.

Paper	Topic
(Bi, Yang, Zhou, *et al.*, 2020)	A new collaborative distribution model based on intelligent end service station (IESS).
(Yao, Cheng and Song, 2019)	Study the actual influence of collaboration between two different carriers.

2.4.8 Parcel Lockers (PLs)

L. Jiang et al. propose a TSP problem with carbon emission reduction in last-mile delivery (Jiang *et al.*, 2019). The problem aims to reduce the total costs and carbon emission by deciding on parcel lockers allocation while scheduling delivery routes. Authors found that carbon emissions can be reduced by 18.7%-51.2% respectively by using PLs in areas where they are highly accepted. D. Liu et al. design a sustainable two-echelon E-grocery delivery system, which integrated van, robot, and parcel lockers in the last mile delivery (Liu *et al.*, 2021). A two-echelon location-routing problem with mixed vehicles and mixed satellites is formulated, with the carbon emission reduction among the goals. The authors also develop an algorithm to solve the problem, which is superior to other algorithms that solve similar problems.

Authors in (Liu *et al.*, 2021) suggest applying real-life data to the proposed model and algorithm in future studies.

Table 11: Topics of the papers described in the "parcel lockers" category.

Paper	Topic
(Jiang *et al.*, 2019)	Traveling salesman problem with carbon emission reduction in last-mile delivery.
(Liu *et al.*, 2021)	Sustainable two-echelon E-Grocery delivery system, with the use of autonomous delivery robot (ADRs) and parcel lockers.

2.4.9 Conventional versus Online Retailing

Studies that compare online and conventional retail's environmental impact are underpinned by numerous assumptions and delimited by system boundaries (Van Loon *et al.*, 2014). The relative carbon intensity of these two retailing forms depends on the nature of these assumptions and the extent of the boundaries (Van Loon *et al.*, 2014).

J. B. Edwards et al. found that while neither home delivery nor conventional shopping has an absolute CO2 advantage, on average, the home delivery operation is likely to generate less CO2 than the typical shopping trip (Edwards, McKinnon and Cullinane, 2010).

Jay R. Brown and A. L. Guiffrida determine and analyze the break-even number of customers for carbon emissions equivalence for the feasibility of last-mile delivery at the desired service level based on the radius of the demand region and the delivery time available (Brown and Guiffrida, 2014). They formulate and demonstrate a methodology for calculating the difference in expected carbon emissions to quantify which method has the least harmful impact on the environment.

Regarding future research, authors in (Van Loon *et al.*, 2014) suggest assessing the sensitivity of comparing the assumptions made in different studies analyzed. Authors in (Edwards, McKinnon and Cullinane, 2010) suggest applying their methodological approach to other retail sectors and small non-food items. Finally, authors in (Brown and Guiffrida, 2014) suggest conducting additional research on customer trip chaining since distance applied to the depot impacts the break-even number of customers. Also, they suggest exploring alternative delivery scenarios not originating from the central depot. Finally, they suggest that the break-even methodology employed could be extended to include stochastic input parameters.

Table 12: Topics of the papers described in the "conventional vs. online retailing" category.

Paper	**Topic**
(Van Loon *et al.*, 2014)	Examines the carbon impact of online retailing and compares it with conventional retailing. It discusses the effect of varying the scope of the calculation, the system boundaries, and the underlying assumptions.
(Edwards, McKinnon and Cullinane, 2010)	Focus on the carbon intensity of "last mile" deliveries (i.e., deliveries of goods from local depots to the home) and personal shopping trips.
(Brown and Guiffrida, 2014)	Comparing carbon emissions resulting from conventional shopping involving customer pick-up with trip chaining versus e-commerce-based online retailing involving last-mile delivery to customers' homes.

2.4.10 Other solutions

Article 26, 28, 30 formulate distribution network models with carbon emissions reduction. J. Yang et al. propose a novel carbon tax constrained city logistics distribution network planning model that can help the city logistics distribution operator cut down its carbon dioxide discharge by around 54.5% (Yang, Guo and Ma, 2016).

Y. Wang et al. realize optimization of the city's distribution network using a two-echelon location-routing problem (2E-LRP) considering the external cost of carbon emissions (Wang, Tian and Liu, 2017).

Y. Tan et al. build an environmental and effective last-mile distribution model considering fuel consumption and greenhouse gas emission, vehicle capacity, and two practical delivery service options: home delivery (HD) and pick-up site service (PS) (Tan *et al.*, 2019). Results show improvement of carbon emissions in the last mile distribution. Authors in (Yang, Guo and Ma, 2016) suggest future studies aiming at network operational strategy and tactical adjustments under the policies considered. They also suggest a comparison between various low carbon policies. Authors in (Wang, Tian and Liu, 2017) suggest considering that emissions will change in the future. They also suggest taking the time factor into account and consider the development of the distribution center in the model.

Lee et al. and Behnke and Kirschstein formulate vehicle routing model with carbon emission reduction (Behnke and Kirschstein, 2017; Lee *et al.*, 2020). K. Lee et al. develop and test a model to solve a Vehicle Routing Problem with Exclusive Links (VRP-EL), which considers restrictions present in Vietnam's urban areas (Lee *et al.*, 2020). They propose an estimation of reduced carbon emissions. Results show that the proposed model leads to a sustainable road environment. M. Behnke and T. Kirschstein formulate an emission-minimizing vehicle routing problem with heterogeneous vehicles (Behnke and Kirschstein, 2017). The experiments suggest an emission saving potential of about 2-4%. Authors in (Behnke and Kirschstein, 2017) suggest that integrating load-dependent emission-minimal shortest paths into time-dependent VRPs may result in additional reductions of CO2 emissions.

The remaining articles treat other aspects of city logistics related to carbon emissions reduction and are discussed afterward. T. Letnik et al. develop a model for dynamic assignment of loading bays for urban last-mile deliveries (Letnik *et al.*, 2018). It aims to solve the problem of defining the most optimal number of loading bays and their management for energy-efficient urban freight deliveries. Results show significant savings of CO2 emissions. P. Kang et al. create a spatially based dynamic model to quantify the impacts (measured in CO2eq) from the express delivery in China (Kang *et al.*, 2020). Specifically, intracity (urban) express delivery services—delivery and pick-up services located within the same city—was chosen for analysis. The results indicated that the carbon emissions from the transportation phase of the express delivery sector in Chinese cities varied from 20 t to 4000 t in 2017, of which 18% was attributable to the weight of extra packaging materials. Ça˘grı Koç et al. investigate the combined impact of depot location, fleet composition, and routing on vehicle emissions in city logistics and found that the shortest path is not always the cheapest, fastest, and least polluting path in city logistics since it may be advantageous to follow circuitous tours to achieve faster speeds and hence lower costs and CO2 emissions (Koç *et al.*, 2016).

Table 13: Topics of the papers described in the "other solutions" category.

Paper	Topic
(Yang, Guo and Ma, 2016)	Novel carbon tax-constrained city logistics distribution network planning model.
(Wang, Tian and Liu, 2017)	A two-echelon location-routing problem which considering the external cost of carbon emissions.
(Tan *et al.*, 2019)	Environmental and effective last-mile distribution model considering fuel consumption and greenhouse gas emission, vehicle capacity, and two practical delivery service options: home delivery (HD) and pick-up site service (PS).
(Lee *et al.*, 2020)	Vehicle Routing Problem which takes Southeast Asian cities' road usage restrictions into account.
(Behnke and Kirschstein, 2017)	Emission-minimizing vehicle routing problem with heterogeneous vehicles.
(Letnik *et al.*, 2018)	Model for dynamic assignment of loading bays for urban last-mile deliveries.
(Kang *et al.*, 2020)	A spatially based dynamic model to quantify the impacts (measured in carbon emissions, CO2eq.) from delivering letters and parcels.

(Koç *et al.*, 2016)	Investigates the combined impact of depot location, fleet composition, and routing decisions on vehicle emissions in city logistics.

2.5 Final considerations about the literature review

This literature review showed that the academic interest in carbon emissions in city logistics increases, as documented by the increasing number of publications on this topic in recent years.

Final considerations about analyzed papers are reported in the following. Drone delivery's environmental sustainability is studied in 10 papers over 50 in this review. Drones seem to be more environmentally efficient than diesel vans only for small payloads on a per-distance basis, in time constrain and low-density delivery scenarios, and when service zones are close to the depot. However, a new network of warehouses or waystations is needed as support, which worsens the environmental impact. Results also depend on the electricity mix. Green vehicle routing problems (GVRPs) for drones are discussed in this research field. The impact of non-CO2 pollutants on drones should be considered in future studies.

Carbon emissions of cargo bikes/ tricycles/ quadricycles use in last-mile delivery is also studied in 10 papers over 50 in this review. The use of cargo bikes/ tricycles/ quadricycles is more environmentally friendly than diesel vans, and benefits are obtained by utilizing small vehicles for small loads, in dense service areas, and when the depot is located close to the delivery area. Results are also beneficial in the case of carbon-intensive electricity generation. The best solution to sit urban transshipment points from a carbon footprint viewpoint is at the district's periphery and having trucks performing in- and outbound processes. The impact of non-CO2 pollutants should be considered in future studies.

Electric vans are also a promising solution to solve city logistics' environmental problems. Their use is much more environmentally friendly than diesel vehicles (more than 80%, if the electricity mix is clean), and an ambitious scenario of electrification in Europe can lead to a decrease in CO2 emissions from light commercial vehicles (LCVs) of 30% by 2030. Urban consolidation centers also can reduce environmental impact in city logistics, and their potential to decrease emissions should be further investigated.

Delivery robots are distinguished in SADRs and RADRs. SADRs can reduce emission confronted with ICE vans delivery when a mothership is not required, i.e., where the delivery area surrounds the depot. RADRs are more efficient than e-vans when customers are few. Few studies are available for this vehicle, and their potential should be further investigated. Also, the lifecycle impact of these vehicles should be calculated. Crowdshipping and collaborative solutions are less studied than previous solutions from a carbon emission perspective. Some attractive, innovative models based on these concepts have been analyzed in this review, which shows exciting results regarding carbon emissions reductions. The potential to decrease these innovative solutions' emissions needs to be further studied. Parcel lockers also show a potential to decrease emissions, but few studies on this field are available. Many authors also study distribution network models and vehicle routing models with carbon emissions reduction.

Finally, online shopping's carbon emissions have been compared with conventional shopping in 4 papers in this review. Online shopping is more environmentally friendly in some papers, but the relative carbon intensity varies and depends on different assumptions made and the boundaries considered.

Chapter 3

Conclusions

In this chapter, a discussion about the benefits brought to the literature by the thesis will be given. Then, the limitations of this thesis will be discussed. Finally, future steps in this topic that can be undertaken starting from the thesis results will be highlighted.

3.1 Benefits of the thesis

Interested researchers can benefit from this thesis to overview the latest research on this theme, understand which topics are the most discussed, and know research gaps. With the author's hope, this will foster the development of this area of research. Moreover, this thesis partially covers research gaps identified in (Patella *et al.*, 2021) on the lifecycle impact of green vehicles (drones, cargo bikes, etc.). Many papers in this review analyzed this impact, and the main results have been discussed. Also, this thesis partially fills the research gaps mentioned in (Luigi Ranieri *et al.*, 2018) on externalities reduction achievable with electric L-category vehicles (EL-V), which includes cargo bikes and tricycles. This research gap is partially covered since carbon emissions reduction associated with these vehicles' use is discussed in this thesis.

3.2 Limitations of the thesis

This thesis presents some limitations. First, some relevant studies may have been omitted because not covered by keywords. Then, the search excluded book, chapters, reports, and articles not in English, which may potentially be relevant to the review.

3.3 Future steps in research

From this literature review, it has been possible to identify research gaps within this research area. Some solutions which show the potential to decrease emissions but are understudied in research have been identified. Moreover, the papers analyzed in the review propose future steps to investigate. A list of possible future research directions has been identified, which is given in the following:

- Impact of non-CO2 pollutants emissions for drones;
- Use of alternative power source (e.g., fuel cells) for drones;
- Finding the optimal tricycle power/ payload limit and impact of non-CO2 pollutants for cargo bikes;
- Air pollution at urban transshipment points for cargo bikes;
- Further studying carbon emissions impact of UCCs;
- Lifecycle emissions of ADRs;

- Further studying carbon emissions impact of crowdshipping solutions;
- Further studying carbon emissions impact of collaborative solutions;
- Further studying carbon emission reduction with the use of parcel lockers.

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