On Decarbonizing City Logistics: Analytical Models for Sustainable Package Delivery and Pickup

by

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Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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Abstract

City logistics significantly contributes to greenhouse gas emissions (GHGs) due to the extensive use of conventional vehicles. GHGs are the main driver of climate change (CC) and reducing them is essential to achieving greener cities. Following a comprehensive literature review on decarbonizing city logistics (DCL), this study proposes a two-stage mathematical model for last-mile business-to-customer (B2C) e-commerce operations. The first stage of the model assigns customers to the nearest parcel locker (PL) to optimize zoning. The second stage is formulated as a variant of the vehicle routing problem (VRP) that addresses a critical gap in the DCL literature by considering home deliveries, package returns, and missed deliveries simultaneously while utilizing PLs. We evaluated the proposed model regarding quadruple bottom line pillars (QBL) of sustainability—environment, economy, society, and culture. A benchmark model is also developed to evaluate the proposed model's results. Our findings indicate that implementing the proposed model could reduce CO_2 emissions by 17% and operational costs by 9%. Furthermore, our model offers several social and cultural benefits. We conclude the study by discussing future research directions.

Keywords: greening city logistics; optimization; transportation; decarbonization; emissions; sustainability; supply chain management; quadruple bottom line; culture; bibliometric analysis

List of Abbreviations Used

B2B	Business-to-Business
B2C	Business-to-Customer
CC	Climate Change
CH_4	Methane
CO_2	Carbon Dioxide
CT	Cost
CPU	Central Processing Unit
CU	Culture
DC	Delivery-Customer
DCL	Decarbonizing City Logistics
EC	Economy
EN	Environment
EM	Emission
EV	Electric Vehicle
GHGs	Greenhouse Gas Emissions
GVRPMD	Green Vehicle Routing Problem with Missed Deliveries
IM	Index Modulation
LRP	Location Routing Problem
MD	Missed Delivery
MINLP	Mixed Integer Non-linear Programming
N_2O	Nitrous Oxide
PC	Pickup-Customer
PL	Parcel Locker

PR	Package Return
RQ	Research Question
QBL	Quadruple Bottom Line
SI	Social Impact
SLNA	Systematic Literature Network Analysis
SM	Spatial Modulation
SO	Social
TC	Total Cost
TEC	Total Environmental Cost
TOC	Total Operational Cost
TR	Travel Distance and Time
TSP	Travelling Salesman Problem
TVRPCR	Time-definite Vehicle Routing Problem with Variable Capacity and Product Returns
UCC	Urban Consolidation Centre
VRP	Vehicle Routing Problem

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CHAPTER 1: Introduction

Scientific reports indicate that the world's temperature has risen by approximately 1.1◦C from the late 1800s to 2020, highlighting the increasing severity and frequency of climate change (CC) impacts (IPCC, 2021; Yun & Ülkü, 2023). Consequences of CC include but are not limited to several disasters, sea level rise, extreme weather events, and intense droughts, all of which influence life on Earth. For instance, rising sea levels lead to floods, while wildfires result in the loss of forests and biodiversity (United Nations, 2020). Hurricanes and cyclones may cause loss of life and property, and drought and flooding create health issues (NOAA, 2024). These are only some examples of the severe consequences of CC, rampantly impacting humanity and all life on the planet. These indicate the necessity of determining the root causes of CC and acting to curb them.

Several factors contribute to global warming and, ultimately, to CC. Research demonstrates that the main drivers of global warming are greenhouse gas emissions (GHGs) produced primarily by burning fossil fuels used in conventional vehicles (Koç et al., 2014) and heat and electricity production. These GHGs comprise carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several others, where CO_2 accounts for approximately 75% of the total amount of

gases emitted as of 2023 (Wang & Lyu, 2023). Studies identify production, transportation, and residential life as the primary sources of GHGs. Scientists underline that the continuously increasing global temperatures seriously threaten the sustainability of human society (Guo et al., 2022). Therefore, it is crucial to generate solutions to minimize the GHGs released into the atmosphere and take action to lessen the drivers of and mitigate the rampant and severe impacts of CC.

1.1 Problem Definition

Transportation-related operations produce approximately one-fourth of the CO_2 emissions contributing to global warming (Bruglieri et al., 2019). Most of these emissions are produced during logistics operations where the primary mode of transportation is conventional vehicles that use fossil fuels (Islam et al., 2021). This study emphasizes logistics operations in urban areas, which we will call city logistics. In thesis, the terms “urban” and “city” will be used interchangeably. Unlike rural areas, urban areas are populated and congested, adding complexity to city logistics. In Figure 1, we present a pictorial description of a typical city logistics process where high levels of GHGs are produced due to the transportation of various goods. This mainly comprises business-to-business (B2B)/business-to-customer (B2C) e-commerce and food deliveries, which are

accountable for a significant portion of GHGs emitted in cities. Since the population and demand for city logistics continuously increase, these emissions are expected to rise (Jiao et al., 2023; Mansouri et al., 2023). This exacerbates environmental and societal well-being by increasing global warming and air pollution, raising various health concerns (Fraselle et al., 2021). However, logistics operations play significant roles in cities in terms of economic development and transportation of essential goods and passengers that meet urban life demands (cf. Habib, 2024). Therefore, removing these operations cannot be feasible in terms of the sustainability of cities. Yet, decarbonizing city logistics (DCL) is possible by developing sustainable solutions in terms of quadruple bottom line pillars (QBL) of sustainability involving environment, economy, society, and culture.

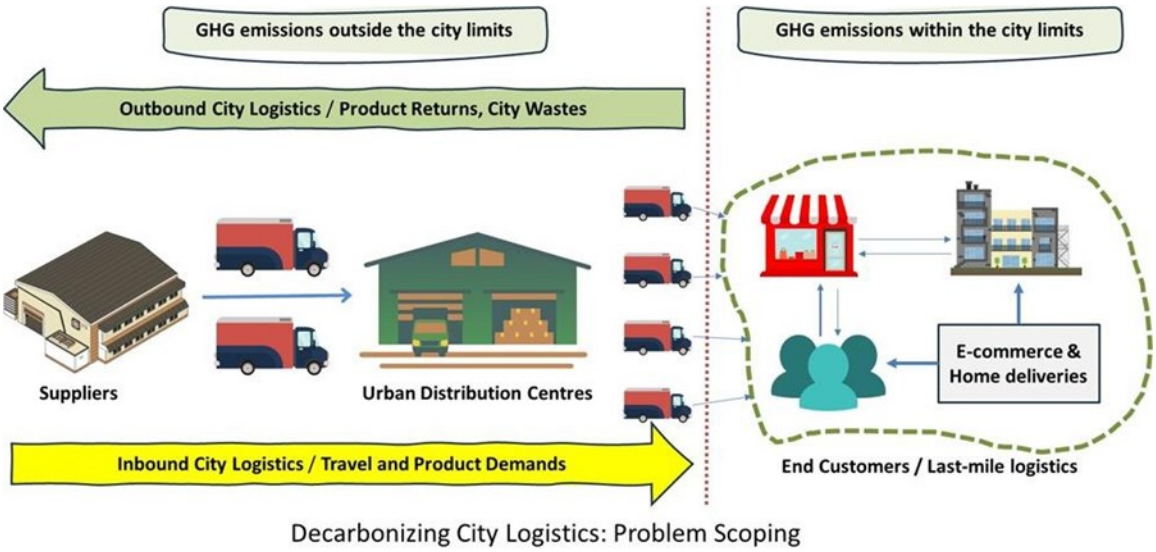


Figure 1. Schema framing city logistics operations

1.2 Research Questions

This study aims to address the following research questions (RQs):

RQ1- What is the current state of the research on DCL?

RQ2- What analytical approaches have been adopted?

RQ3- Which QBL aspects are studied in the DCL literature?

RQ4- How is DCL research evolving? What are the barriers, enablers, and future research venues?

RQ5- How can an optimized B2C e-commerce last-mile network be developed to address package deliveries, returns, and missed deliveries?

RQ6- How would implementing the proposed network benefit the QBL sustainability of B2C e-commerce operations?

RQ7- What is the optimal assignment of customers to the PLs? How should the vehicle fleet be composed? What are the optimal routes for the selected vehicles? What are the time windows for visiting each customer?

RQ8- What are some potential future areas of research for optimization in the B2C e-commerce and last-mile city logistics?

Table 1 displays which chapters address the related RQs.

Table 1. Research questions answered in each chapter

Chapters	**Research Questions**							
	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8
Ch. 2	✓	✓	✓	✓				
Ch. 3					✓	✓	✓	
Ch. 4					✓	✓	✓	
Ch. 5					✓	✓	✓	
Ch. 6								✓

1.3 Research Contribution

This thesis has the following six distinct theoretical and practical contributions:

1) We contribute to the DCL literature by addressing a significant gap. The proposed mathematical model, Green Vehicle Routing Problem with Missed Deliveries (GVRPMD), simultaneously considers deliveries, package returns, and missed deliveries. Additionally, we integrate a relatively newer technology, referred to as PLs, into the proposed network to enhance these operations. Moreover, we adopt a QBL perspective rather than the typical triple bottom line (TBL) approach in developing the proposed model, evaluating the network's environmental, economic, social, and cultural sustainability. To our knowledge,

there is currently no study in the literature that considers all these factors. Most studies do not include missed deliveries and package returns in their models (Toktaş et al., 2024). Additionally, among the studies that address sustainability, there is an emphasis on environmental and economic aspects, often overlooking social and cultural perspectives.

2) In the proposed network, each customer is assigned to the nearest PL. If a missed delivery occurs at a customer node, we ensure that the package is delivered to the assigned PL. This study's findings indicate that the GVRPMD model minimizes the impact of missed deliveries, as CO_2 emissions do not increase even with a rise in the number of missed deliveries. Moreover, the proposed model is compared with a benchmark model. Results show that implementing the proposed model can achieve a 17% reduction in CO_2 emissions and a 9% reduction in operational costs. These represent novel and practical contributions that can guide practitioners and policymakers in the e-commerce industry. The authorities can implement GVRPMD in regions where missed deliveries occur more frequently, potentially due to various cultural norms and lifestyles. This would contribute to the cultural sustainability in certain regions.

3) In the DCL literature, time windows were typically defined as parameters. In this study, we redefined time windows as decision variables, contributing theoretically to the field.

4) We developed a two-stage mathematical model in which the output of stage-I serves as input to stage-II. Stage-I model is designed as Delivery Demand Zoning and Customer Assignment Problem (DDZCAP).

5) In stage-II model, we defined vehicle selection as a decision variable, which was typically considered as a parameter in the VRP literature.

6) Implementing the GVRPMD can improve service quality and contribute to social sustainability. This is because the customers are offered multiple options for package delivery and return. For package deliveries, customers can choose either home delivery or self-pickup from a PL. For package returns, customers can request a pickup from their home, or they can return their package simply by dropping it off at the nearest PL. Additionally, suppose a customer is away from home during a scheduled delivery (for reasons like being at work). In that case, the package will be delivered to the nearest PL instead of returning to the depot, allowing them to retrieve their packages easily. Based on these, this study makes a valuable contribution to the literature and potentially to the practice by promoting social sustainability.

Table 2 demonstrates the articles emphasizing e-commerce operations in urban areas.

Table 2. Comparison of similar articles to this thesis research

Articles	QBL Aspects[1]				Emphasis[2]			Approach[3]	Contribution
	EN	EC	SO	CU	PL	PR	MD		
Enthoven et al. (2020)	✓	✓			✓			Coverage + VRP	The study proposes a last-mile e-commerce package delivery network in which the problem is formulated as a two-echelon vehicle routing problem with parcel lockers and cargo bikes. The study results demonstrate that using parcel lockers for e-commerce home deliveries can reduce travel distances by approximately 60%. It is also shown that the operational costs can be reduced by 35.4% when the customers are assigned to be served either by a cargo bike (from a satellite location) or by a parcel locker for pickup, based on their home location.
Pourmohammadreza & Jokar (2023)	✓	✓	✓		+	✓	+	LRP	The study introduces a novel last-mile delivery problem that considers home deliveries, customer self-pickup, and different delivery pricing. It presents a mathematical model to decide the optimal locations for pickup and delivery points and routes while aiming to minimize the total financial cost of the proposed network. The model also contributes to social sustainability by maintaining customer satisfaction. The study's findings show that transportation-related costs can be reduced by up to 25%.
Sun & Wang (2023)	✓	✓	✓			✓		VRP	The paper developed a multi-objective mathematical model for a vehicle routing problem in the construction sector, considering simultaneous freight delivery and collection. The objective function of the optimization model involves environmental, economic, and social aspects to achieve sustainability. The study produced efficient results in terms of sustainability. The solution is obtained quickly even though the model includes complex constraints.
Yang et al. (2023)	✓	✓	✓		✓	✓		Coverage + VRP	The research proposed a package delivery and collection network for rural areas as a vehicle routing problem. A mathematical model was developed to minimize the economic and carbon emission costs, thus considering environmental and economic sustainability. Express delivery nodes (similar to parcel lockers) are integrated into the model to be used for customer self-pickup. Study results show that vehicle loading and service coverage rates can be increased with the proposed model while economic costs can be reduced.
Ozyavas et al. (2024)	✓	✓			✓	✓		LRP	The research proposes a solution where the parcel lockers are utilized as collection points and transfer points for package distribution. It is modelled as a location-routing problem where parcel locker locations and capacities are decided, and the delivery routes for the vehicles are to minimize the total costs. The article's findings show that such utilization of parcel lockers significantly reduces the total distance travelled by the delivery vehicles/cargo bikes, potentially contributing to the environmental sustainability of the distribution network.

Song et al. (2024)		✓	✓		✓		✓	VRP	The paper proposes an optimization model to minimize CO_2 emissions mainly associated with missed home deliveries. The study recommends implementing self-pickup points for missed deliveries at customer locations, similar to parcel lockers. This approach would replace the current practice of returning customers' parcels to the depot, where they are either rescheduled for the following day or require customer pickup. It also integrates electric vehicles into the problem to further reduce CO_2 emissions. The results demonstrate that the suggested distribution strategy and using electric vehicles (instead of conventional vehicles) can significantly reduce CO_2 emissions.
Redi et al. (2020)	✓	✓			✓	✓	+	VRP	The article proposes a solution that utilizes parcel lockers for B2C e-commerce deliveries in urban areas. They formulated the problem as a two-echelon vehicle routing and aimed to minimize the total operational costs. The results demonstrate that using parcel lockers can reduce the total transportation costs by approximately 70% when two or three vehicles are used for distribution in a given area. It was also discussed that using parcel lockers in this freight distribution network can reduce the cost caused by missed deliveries.
Yu et al. (2022)		✓			✓	✓	+	VRP	The study proposes the multi-purpose use of parcel lockers for different types of B2C e-commerce customers. The problem was formulated as a vehicle routing problem to minimize the total operational costs. Package returns are also integrated into the model alongside home deliveries. The study developed a metaheuristic approach for the given NP-hard problem and produced effective results.
Mancini & Gansterer (2021)		✓	+		✓			VRP	The research proposes a time-windowed vehicle routing problem with shared delivery locations where operational costs are minimized within a network of e-commerce home deliveries. The network allows companies to decide whether a customer's package will be delivered to their home or a nearby delivery location. The results show that the proposed solution outperforms the existing distribution systems. The authors found that operational costs can be reduced by 40% while providing the same service quality to the customers.
Amini & Haughton (2023)		✓			✓		✓	LRP	The study introduces a two-echelon location and routing problem that minimizes operational costs across a network of e-commerce home deliveries. The mathematical model developed produces reliable and influential results that can help authorities make operational cost-based decisions, such as opening a depot and determining routes for each vehicle in the fleet.
This Thesis	✓	✓	✓	✓	✓	✓	✓	**Zoning + VRP**	This thesis proposes a two-stage mathematical model for B2C e-commerce last-mile operations in urban areas. The proposed network considers home deliveries, package returns, and missed deliveries while utilizing PLs. The problem was formulated as mixed integer non-linear programming (MINLP) to minimize CO_2 emissions and operational costs. The findings show that CO_2 can be reduced by 17% and operational costs by 9%. Moreover, the proposed network has several social and cultural benefits.

[1] EN (Environment), EC (Economy), SO (Society), CU (Culture), [2] PL (Parcel Locker), PR (Package Return), MD (Missed Delivery),

[3] LRP (Location Routing Problem), VRP (Vehicle Routing Problem), + (Partially Considered)

1.4 Research Gaps in the Literature

Research on DCL has gained interest from scholars around the globe, especially in the past few years. However, there is still a need to address a significant research gap. Only a few analytical studies emphasize the forward and reverse logistics for e-commerce deliveries in urban areas while integrating the utilization of PLs to minimize GHGs and operational costs. Customer returns and missed deliveries appear to be significant challenges in B2C e-commerce operations as they require additional vehicle movement, increasing GHGs and economic costs. Despite their importance, only a few articles took customer returns and missed deliveries into account in their optimization effort. To our knowledge, no optimization article in the B2C e-commerce context modelled home deliveries, customer returns, and missed deliveries together.

Most studies in the DCL literature considered environmental and economic sustainability while studying DCL, but the consideration of social and cultural sustainability is scarce. These are crucial pillars of sustainability and might significantly influence the effectiveness and applicability of any proposed solution. Therefore, we aim to underline and fill this gap in this thesis study by discussing QBL pillars of sustainability.

1.5 Research Motivation

Given the urgent need for DCL to achieve more sustainable cities, we analyzed and reported the current research trends in the DCL literature. Considering our keywords, we analyzed the number of scholarly articles written in English each year between 2004 and 2023 to observe the emphasis on the DCL literature and the portion of articles that took sustainability into account. We obtained data on the number of scholarly articles from SCOPUS. First, we retrieved the number of articles published each year from the search term "city logistics" and its synonyms, represented with blue (see Figures 2 and 3). Second, we also added sustainability to city logistics and recorded the data (represented in yellow). Third, we added decarbonization to "city logistics" and excluded the sustainability term (represented with green). Finally, we combined all key terms (represented in red). Figure 2 illustrates the number of published articles we obtained when the key terms were searched in all fields (title, abstract, keywords, text) of the articles. On the other hand, Figure 3 represents the number of published articles we obtained when the key terms were searched only in articles' titles, abstracts, or keywords. We aggregated the years so that each of the five periods represents a four-year subperiod.

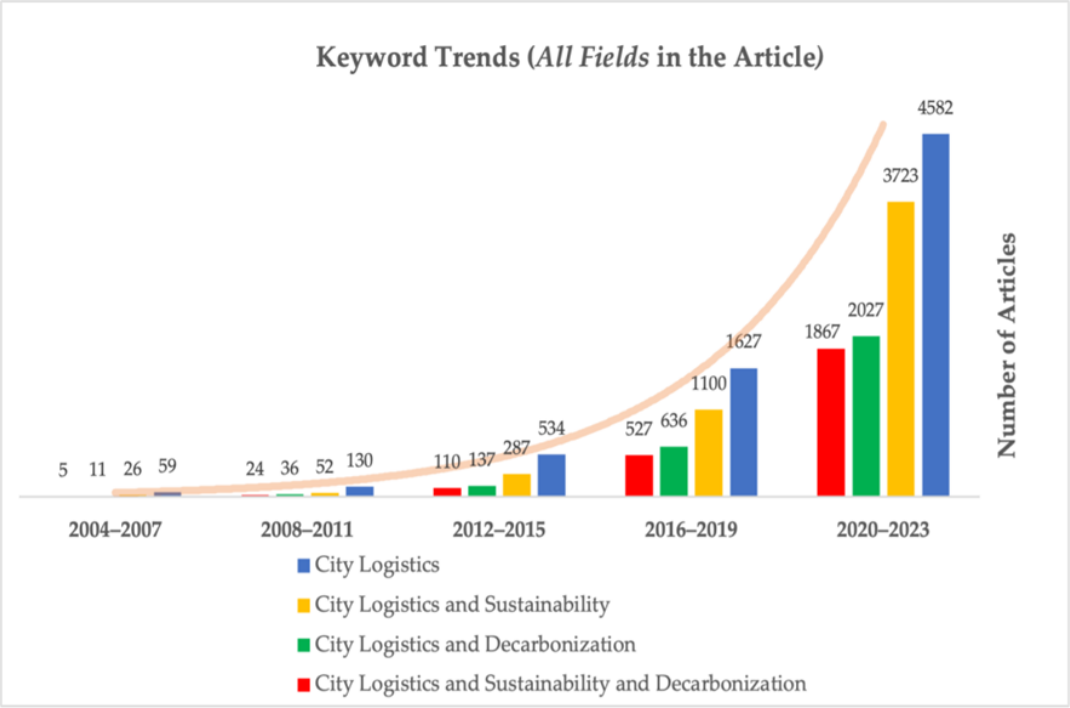


Figure 2. Keyword trends based on the search in *All Fields* (2004–2023)

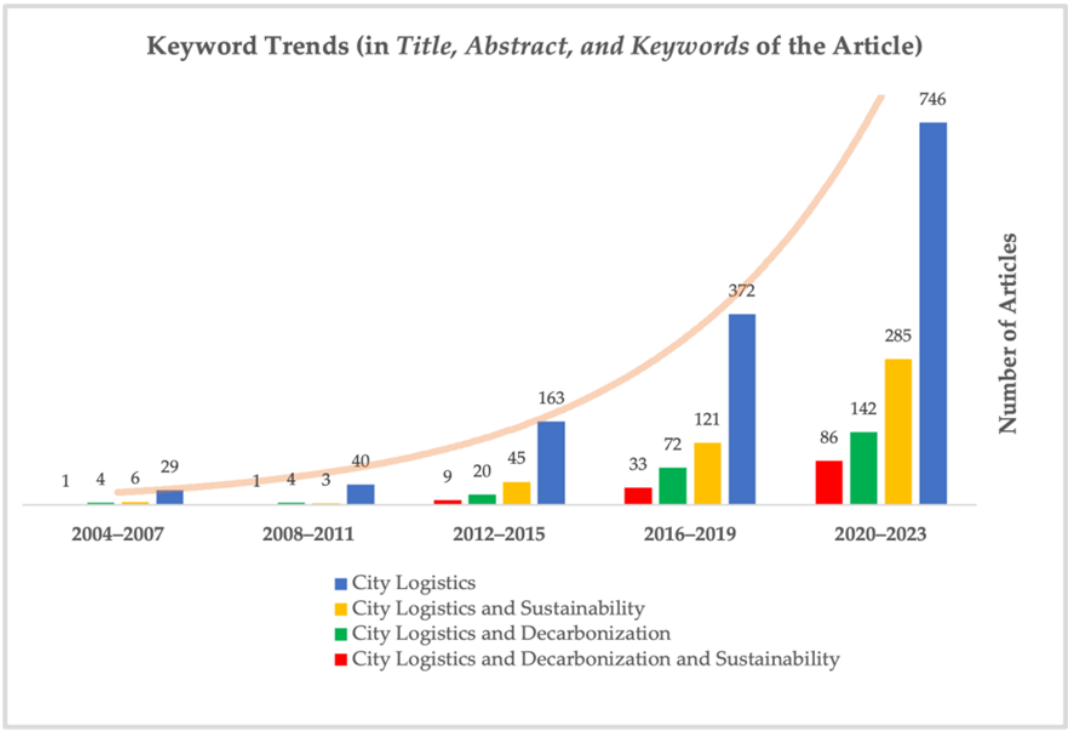


Figure 3. Keyword trends based on *Title, Abstract, and Keywords* (2004–2023)

We observe a similar trend in all four search terms in both Figures 2 and 3, demonstrating an increase in the number of scholarly articles published, especially after 2008–2011. Moreover, the number of articles has increased significantly in the final four-year period, 2020–2023. Considering these, we deduce that city logistics, decarbonization, and sustainability terms have recently drawn significant attention from researchers, which is reasonable considering the urgent need for action to minimize the impact of city logistics on CC. Second, we noticed that the concept of decarbonization has received relatively less attention in the context of city logistics. As given in the final period of Figure 3, only 86 articles used the term "decarbonization" in their titles, abstracts, or keywords, whereas there are 746 articles that used "city logistics". This ratio is even lower in the prior sub-periods. One potential reason for this can be the unfamiliarity of the term since, based on our observations, several studies have proposed solutions to reduce CO_2 emissions in city logistics, yet they do not explicitly use the term "decarbonization" in their papers. An overall deduction from Figure 3 is that research focusing on decarbonization and sustainability in the city logistics context is still scarce despite the consistent increase in studies published throughout the last 20 years.

Although it seems from the final period (2020–2023) of Figure 2 that a great majority of studies proposed integrating a sustainability perspective into their

research, Figure 3 shows that only a few considered sustainability as an essential part of their study. Specifically, looking at the final period, 2020–2023, Figure 2 shows that approximately 81% of the articles that include "city logistics" terms mentioned "sustainability". On the other hand, this percentage is approximately 38% in Figure 3, where the key terms are only looked up in articles' titles, abstracts, or keywords. Nevertheless, the number of articles containing the term sustainability in the context of city logistics has increased in both figures over the last two decades. This demonstrates that more researchers studying city logistics are considering sustainability in their articles. The increasing number of studies and the research gaps stated in sections 1.3 and 1.4 motivate this study.

City logistics raise several sustainability concerns regarding the environment, economy, society, and culture. These concerns motivate this study to propose a B2C e-commerce network to minimize the total operational costs (TOC) and total environmental costs (TEC) while benefiting society and culture.

1) Environment:

The main driver of climate change is GHGs. Conventional vehicles in various city logistics operations, such as B2B/B2C e-commerce deliveries, produce high amounts of GHGs. Moreover, several trucks used for transporting goods within the city limits significantly increase the traffic congestion in the respective areas.

This results in more frequent stops, further increasing the GHGs emitted. Transportation of goods includes forward and reverse logistics, where home deliveries and package returns are handled. Missed deliveries cause significant issues in the e-commerce industry as they increase vehicle movement. Overall, these operations have significant environmental consequences which must be addressed in the face of the climate crisis.

2) Economic:

The economic burden of city logistics operations is undoubtedly high due to the costs associated with vehicles, fuel, labour, and depots. For B2C e-commerce operations, optimizing vehicle routes and integrating PLs for customer pick-ups and missed deliveries can significantly improve fuel efficiency and reduce the labour and total distance travelled. As a result, these cost savings may lead to more affordable goods for consumers, supporting both economic development and sustainability efforts in cities. Furthermore, increased efficiency and reduced delivery times could enhance customer satisfaction, potentially contributing to economic growth.

3) Social:

Despite its contributions to economic development, city logistics impose several threats to society. Trucks that are being used for freight transportation are louder

and produce higher amounts of GHGs compared to passenger vehicles. This leads to air and noise pollution in cities and impacts people's quality of life. Moreover, increased traffic congestion affects travel times and reduces accessibility. Considering this, city logistics have several impacts on society, pointing out the need for socially sustainable solutions. Efficient routing combined with the use of PLs for customer pickups and missed deliveries can help reduce air and noise pollution, decrease traffic congestion, and lower GHGs by minimizing travel distances. As a result, public health and accessibility could be enhanced.

4) Cultural:

It is crucial to consider cultural aspects while developing sustainable solutions for DCL (Toktaş et al., 2024). This can be achieved by considering an area's unique cultural values and lifestyles. For instance, if individuals in a culture prefer being outdoors most of the time, this could increase the number of missed deliveries in a region. This, and various other cultural characteristics, can influence operational decisions. Therefore, failing to consider cultural aspects in developing solutions for city logistics can impact its applicability and effectiveness. The DCL literature's need for a QBL sustainability perspective also motivates this study.

1.6 Methodology

This section presents the research methodology that was adopted to provide an overview of the analytical studies in DCL literature. We adopted the systematic literature network analysis (SLNA) (cf. Ülkü et al., 2024) and conducted a systematic literature review followed by a bibliometric network analysis. We used SCOPUS, a well-known academic database, to determine the articles for our literature review. We used Boolean operators such as "AND" and "OR" to develop our search term. Following several adjustments, we decided to use the following search term on SCOPUS: ("city logistics" OR "urban logistics" OR "urban freight transport") AND (decarbon* OR emission) AND sustainab*. In our search term, we used two synonyms for "city logistics" to avoid missing studies that used different words to indicate it. Our initial search provided 243 results. However, we decided to include only journal articles in this study. Moreover, as we aim to review the current state of the DCL literature, we included journal articles published between 2003 and 2024. Finally, we excluded any articles that were not in English. As a result, we obtained 142 articles.

To determine articles that employed an analytical method, we analyzed the titles, abstracts, methodologies, and results of these articles. We selected relevant studies that used an analytical approach to study a solution by considering at

least two of the QBL pillars of sustainability. As a result, our final sample consists of 64 scholarly articles. All studies selected for review were published in one of the following 33 scholarly journals: Renewable and Sustainable Energy Reviews, Alexandria Engineering Journal, Applied Sciences, ISPRS International Journal of Geo-Information, Uncertain Supply Chain Management, Sustainability, European Journal of Operational Research, Research in Transportation Business and Management, Sustainable Cities and Society, Complex and Intelligent Systems, Computers and Operations Research, Computers and Industrial Engineering, Journal of Heuristics, International Journal of Physical Distribution and Logistics Management, Smart Cities, IEEE Access, Tunnelling and Underground Space Technology, PLoS O.N.E., Transportation Research Part D: Transport and Environment, Journal of Cleaner Production, Transportation Research Record, World Electric Vehicle Journal, Research in Transportation Economics, Energies, Mathematics, Transportation, Transportation Research Part C, Annals of Operations Research, International Journal of Production Research, European Transport, Journal of Transport Geography, European Transport Research Review, and Expert Systems with Applications.

Based on the literature review findings, we decided on the focus of this thesis research, where we developed a multi-objective optimization model. The model consists of two stages. In the stage-II, each customer is assigned to the nearest PL,

where they can pick up and return their packages. Stage-II model was formulated as a variant of the VRP. The purpose of the mathematical model is to minimize the environmental and economic cost of B2C e-commerce last-mile operations where home deliveries, return of packages, and missed deliveries are considered while utilizing PLs.

1.7 Structure of the Thesis

The rest of this thesis is structured as follows: Chapter 2 provides an overview of the extant DCL literature, where we discuss the analytical approaches that have been adopted, the QBL aspects considered, and future research venues. Chapter 3 describes the problem and presents the two-stage mathematical model developed for e-commerce home deliveries and returns using PLs. Chapter 4 integrates the missed deliveries into the stage-II model presented in Chapter 3. Chapter 5 presents and discusses the results obtained by solving the mathematical model. Chapter 6 concludes this thesis research and discusses the future research directions.

CHAPTER 2: Literature Review

Reducing GHGs helps green supply chains. A supply chain encompasses the operations concerning the flow and transformation of goods, from the extraction of raw materials to final delivery to the end customers, along with the associated information flows (Kaufman & Ülkü, 2018). Optimizing these operations and utilizing emerging technologies can help minimize GHGs in supply chains. For instance, greener vehicles (e.g., electric trucks, hydrogen vehicles, e-bikes, etc.) can be used for logistics operations in cities. Various green supply technologies, such as spatial modulation (SM) and index modulation (IM), can also be beneficial. These advanced communication technologies can improve the efficiency of information flow, help monitor vehicle conditions, and optimize routes (Li et al., 2023; Wen et al., 2019). Utilizing such innovative technologies is essential for achieving greener supply chains and decarbonizing city logistics (DCL). This chapter[1] reviews the extant literature on DCL from a QBL perspective.

Many recent studies on DCL have emerged. Decarbonization refers to reducing GHGs, and it is subject to several standards. For instance, European

[1] Most of this chapter was published as "Toktaş, D., Ülkü, M. A., & Habib, M. A. (2024). Toward Greener Supply Chains by Decarbonizing City Logistics: A Systematic Literature Review and Research Pathways. *Sustainability*, *16*(17), 7516."

Emission Standards limit GHGs per kilometre for passenger cars (e.g., CO_2 emissions are limited to 95 g) (Pacura et al., 2023). California Air Resources Board Zero-Emission Mandate requires all new automobile sales to be zero-emission vehicles by 2035 in California (CARB, 2024). These are some of the standards for decarbonization, and they are crucial to meeting international targets set in the Paris Agreement, which includes limiting global warming to below 2 ◦C (Cain et al., 2022).

This chapter reviews the analytical articles in the DCL literature that studied potential solutions to achieve more sustainable cities. Moreover, we discuss these articles considering the quadruple bottom line (QBL) pillars of sustainability within the supply chain framework, which involves the environment, economy, society, and culture, as introduced by Ülkü and Engau (2021). In that sense, current research efforts that propose analytical solutions for DCL by considering QBL aspects were reviewed.

First, we analyze relevant analytical articles and demonstrate the current state of the research on DCL. Second, we present various analytical approaches adopted to generate potential solutions for distinct challenges associated with city logistics. We report the patterns we observe in these potential solutions that practitioners and policymakers can use in their decision-making. Third, based on our analysis, we discuss the most recent changes and innovations in city logistics

in terms of barriers and enablers that create potential areas of study for future research. Finally, by adopting a QBL perspective, we collectively consider the four pillars of sustainability to examine the analytical studies in DCL literature. The existing articles that review the DCL literature consider environmental, economic, and social sustainability, overlooking the cultural dimension (e.g., Viu-Roig & Alvarez-Palau, 2020; Lauenstein & Schank, 2022). However, consideration of cultural aspects is also critical for developing effective and sustainable solutions, as neglecting them can lead to conflicts with cultural identities and limit the acceptance and effectiveness of proposed solutions. Thus, we posit that all QBL aspects should be considered while developing sustainable solutions for city logistics. This chapter examines which QBL aspects are considered in the DCL literature.

2.1 Research Background

According to recent data, more than half of the global population resides in urban areas as of 2023 (World Bank, 2023). This percentage is poised to increase due to the migration of individuals to developed cities in search of better opportunities (Hussain & Imitiyaz, 2018). In 1950, only around 30% of the world's population lived in urban areas (Statista, 2018). However, experts predict that in 2050, approximately 70% of people will dwell in cities, increasing to 85%

by 2100 (Savelsbergh & Van Woensel, 2016). Additionally, urban areas account for 80% of the global domestic product, highlighting their significance in the global economy (Calisto Friant et al., 2023). City logistics is critical in driving this economic growth by facilitating the transportation and storage of various goods within urban areas to meet demand most efficiently and sustainably (Savelsbergh & Van Woensel, 2016). Nevertheless, the growing urban population adds complexities to city logistics.

City logistics deals with the inter-urban and intra-urban flow of products (recall Figure 1). Inter-urban flow represents the inflow and outflow movement of goods with either a destination or origin outside the city limits. Product inflow emphasizes transporting demanded goods to the city from external regions. In contrast, the outflow involves the transportation of product returns and waste from the city to external regions. Examples of inter-urban product inflows include but are not limited to, package deliveries associated with business-to-consumer (B2C) e-commerce and the shipment of large quantities of goods in business-to-business (B2B) deliveries. On the other hand, e-commerce product returns and the removal of waste from the cities exemplify the outflow operations. In contrast, intra-urban flow involves transporting goods where both the origin and destination points are within the city limits, such as online food and grocery deliveries (Swamy & Baindur, 2013).

2.1.1 Home Deliveries

The B2C e-commerce and online food and grocery delivery sectors have experienced substantial growth over the last decade and emerged as significant contributors to the city economy. The COVID-19 pandemic, in fact, further accelerated the growth of these sectors as individuals began to spend more time at home (Ozbilge et al., 2022; Viu-Roig & Alvarez-Palau, 2020). Reports indicate that global e-commerce sales reached approximately USD 5.5 trillion in 2023, up from USD 1.3 trillion in 2014 (Statista, 2023a). The online food and grocery delivery sector, too, saw a surge in demand, with its market size estimated at around USD 370 billion in 2019 and growing to over a trillion USD in revenue as of 2023 (Statista, 2024a). This growth and the subsequent impact on the city economy underline the importance of e-commerce and online food and grocery delivery industries, making the audience feel the significance of these sectors.

The delivery process of goods shipped by e-commerce companies involves city logistics. Amazon, Walmart, and Alibaba are the largest e-commerce companies globally. Amazon is the market leader, capturing 37.6% market share in the United States (Statista, 2023b) and generating approximately USD 575 billion in annual net sales revenue in 2023 (Statista, 2024b). As the largest e-commerce company, Amazon's delivery process may represent a typical e-commerce delivery in cities. The delivery process begins with the customers'

online orders, which are picked and packed at Amazon's warehouses. After that, Amazon transports the packages to an urban distribution center located within or near the city, using large trucks and possibly additional modes of transport. Employees organize these packages at the distribution center and load them onto smaller trucks. Finally, the packages depart from the urban distribution center and are delivered to the end customers residing in the city (Rodrigue, 2020). The stages following the arrival of goods to the distribution center are considered last-mile logistics. The last-mile delivery of goods to the end customers is also considered the final of many preceding supply chain stages. B2B commerce is also a vast industry that follows a similar delivery process involving the logistics of large quantities of products.

As an example of an intra-flow city logistics operation, the online food and grocery delivery process differs from the e-commerce industry as it is entirely carried out within the city limits. UberEATS and DoorDash are the leading online food and grocery delivery companies, achieving respective market shares of 23% and 67% in the United States as of March 2024 (Statista, 2024c). These companies and the entire industry are poised to grow further in the following years as demand for food and groceries ordered online becomes increasingly popular among consumers living in urban areas (Ozbilge et al., 2022; Poon & Tung, 2024). To that end, "crowdsourcing" has emerged as a vital concept for city logistics in

catching up with the rampant demand for delivery capacity. Crowdsourced delivery is a method that introduces the enlisting of public drivers as couriers to deliver customers' online food and grocery orders. The couriers are independent contractors who use their vehicles to deliver the goods (Alnaggar et al., 2021), mainly food and groceries.

2.1.2 Product Returns

Product returns are a form of reverse logistics where customers return items to the retailer they originally purchased them. In the context of B2C home deliveries, many customers decide to return their packages delivered to them either immediately or after using them for a certain time. These instances can occur due to various reasons. First, the product they ordered may be damaged during the shipment process or turn out to be defective following its delivery. In such cases, the end customer will most likely request a return for the related item, especially if the damage/defection impacts the item's functionality. Second, the item may not meet the customer's expectations, or they might find they cannot use it as they had hoped. This could lead to a return request if the customer believes the item's value is worth dealing with a return. If the product does not have a high value for the respective customer, they might also decide not to return it despite being dissatisfied with it. Third, the customer can return a product or request a re-shipment because they received the wrong item (the delivered item is completely

different from the one the customer bought). Finally, the customer might find the same product for a better price offered by a competitor and request a refund to buy the cheaper option instead. All cases can lead to dissatisfied customers and impact the retailer company economically in the long term. Therefore, almost all retailers offer a return option to their customers as long as the user does not damage the item, and it is returned earlier than a predetermined time threshold. There is also the possibility of abusive product returns. Some customers may abuse the product return policies by utilizing the product and then returning it just before the last allowed day for a return request (Ülkü & Gürler, 2018).

The method for returning a package varies depending on the retailer company. As the largest B2C e-commerce company, Amazon offers various methods for returning a product to its customers. First, the customers can choose to return their packages from their home addresses which a courier will pick up on a specific date and time. Second, the customer can drop their packages to a nearby PL which a courier will then pick up. This relatively newer package returning method can be more efficient than picking up from customers' home addresses. Finally, the customer can choose to ship the product to the retailer themselves by paying a shipping price. There are also companies such as Hudson's Bay and Sportcheck that allow cross-channel returns and utilize their physical facilities in cities to facilitate package returns (Ozbilge et al., 2023). According to

Ozbilge et al. (2023), allowing cross-channel returns increases both the total demand and returns, therefore having a mixed influence on the firm.

Enabling product returns is important for meeting the city's demand and improving customer satisfaction. However, several sustainability challenges are associated with product returns when the methods of returning a product are analyzed (Ozbilge et al., 2023). A returned product's environmental, economic, and social costs might differ based on the selected returning method. First, when a customer chooses to return their packages from their home addresses, their location will be added to the related/associated courier's route. This can increase the distance courier vehicles travel, increasing fossil fuel consumption. As a result, operational costs would increase, and higher GHGs would be released into the atmosphere. Second, if the customer decides to return their package by shipping it themselves back to the retailer, they are required to carry the package to a designated location. Customers usually handle this by driving to that location and then driving back to their homes to complete their part of the return process. This also increases the use of vehicles, incurring both environmental and economic costs. These environmental and economic implications can be reduced when the customer chooses to return their packages through a nearby PL, which usually already exists on the route of a courier vehicle. In any case, customers (excluding the abusive customers) will spend their time completing the return of their

packages. Considering that it is already inconvenient for customers to return their packages for various reasons, this can create harmful consequences. Based on these, online product returns are highly challenging for retailers and should be managed efficiently (Ozbilge et al., 2023). Solutions that can reduce the impact of product returns on the environment and economy should be developed to achieve greener cities.

All these operations are essential to sustaining cities' livability and meeting urban dwellers' demands. However, there are several sustainability concerns associated with them. In the case of B2C e-commerce, delivering and collecting goods from customers' homes or designated pickup locations instead of retail stores significantly increases freight movements. Conventional vehicles are the primary mode of transportation in city logistics, resulting in a considerable rise in GHGs produced within cities. It also worsens issues such as traffic congestion and air and noise pollution, which are already significant challenges, particularly in densely populated cities. Moreover, many people in cities have started to prefer ordering meals and groceries online from platforms such as UberEATS and DoorDash instead of visiting restaurants or supermarkets. Such shifts in consumers' lifestyles also increase vehicle use, causing significant harm to the environment. Therefore, although these operations play an essential role in cities, they also pressure city logistics and

raise several environmental concerns. Hence, solutions for DCL are required to minimize the environmental impact of these and several other operations concerning city logistics. However, sustainability does not only consist of the environment but also the economy, society, and culture. Thus, consideration of all QBL aspects for any potential solution is essential.

2.1.3 Quadruple Bottom Line Pillars of Sustainability

Environmental, economic, social, and cultural sustainability, which are overall called QBL pillars, are considered in this chapter for the discussion of articles we selected for the review. Four aspects of QBL are provided in Figure 4. We adopt a QBL perspective instead of the commonly used triple bottom line (environmental, economic, and social sustainability) because the real-life applicability of the solutions proposed in the existing DCL literature highly depends on their acceptance by the culture in which they are intended to be applied. The authorities will evaluate a solution based on their area's cultural identity and decide whether to utilize a proposed solution. If a solution contradicts a society's unique cultural characteristics, it may not be applicable or effective. Therefore, it is imperative to consider various cultural aspects while developing an influential solution. Given this, the traditional TBL approach falls short in accounting for cultural factors, making QBL a more comprehensive and

critical approach. Hence, this chapter examines the proposed solutions in the DCL literature through the lens of the four QBL pillars of sustainability.

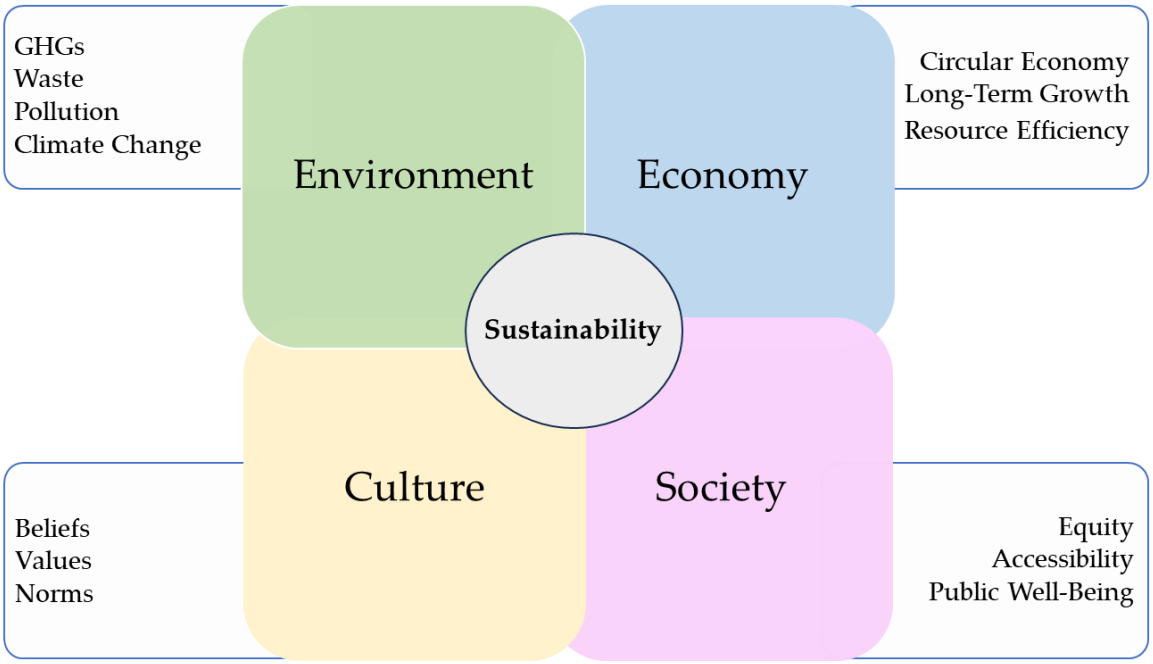


Figure 4. Quadruple bottom line (QBL) pillars of sustainability

2.2 Bibliometric Analysis and Discussion

This section analyzes and reports the selected articles' publication years, journals, and countries, along with the keyword co-occurrence network, presenting the current state of DCL research.

2.2.1 Publication Years

Our initial search on SCOPUS, detailed in Section 1.6, produced 142 articles. Based on this, the oldest article available using our search term was published in 2007, and only four articles were published until 2013. After narrowing our selection to 64 articles, we created Figure 5 to illustrate the yearly distribution of the published articles we selected for review. Although some studies were published between 2013 and 2019, as indicated in Figure 5, the majority (54 out of 64) of the articles were published following 2019. It is important to note that Figure 5 includes articles published before June 2024. Taking Figures 2, 3, and 5 into consideration, we conclude that research efforts have significantly increased in recent years, reflecting the growing interest in DCL to promote sustainable cities and mitigate the severe impacts of CC. This surge may be attributed to city logistics being a significant contributor to CC and the increasingly intense and widespread effects of CC in recent years. The growing urban population and rise in e-commerce and online food and grocery delivery industries pose further challenges in city logistics, such as increased air and noise pollution, traffic congestion, accidents, and various health issues, offering new areas for research. Considering these, despite the plethora of published articles on city logistics, we posit that DCL calls for more research, especially in the face of the climate crisis.

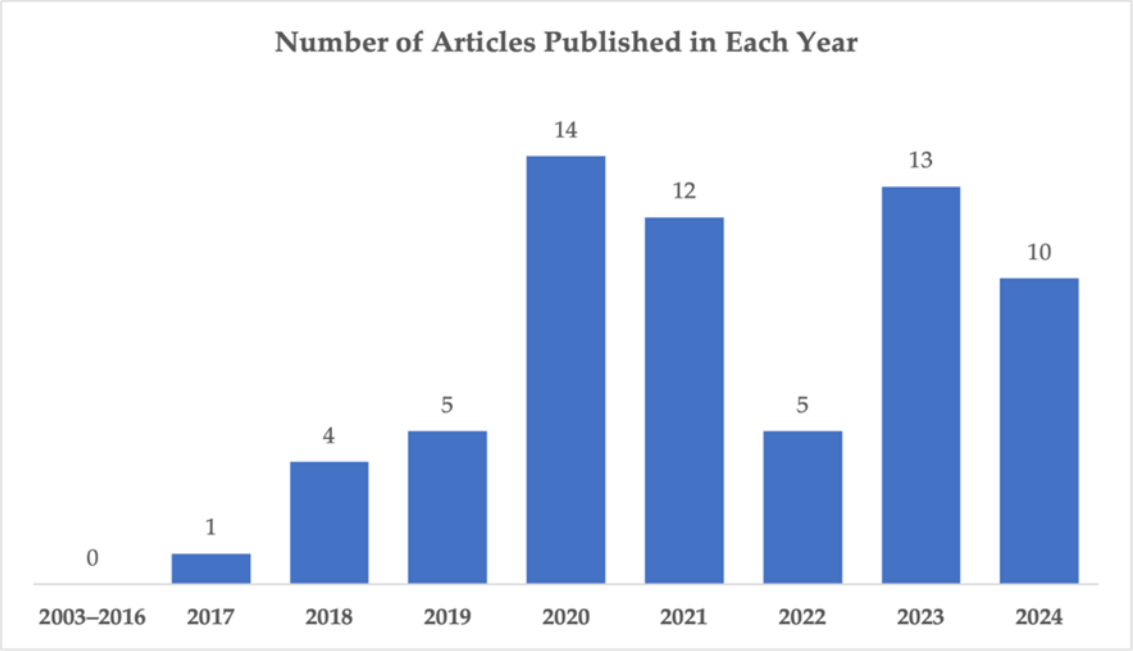


Figure 5. Number of selected articles published in each year

2.2.2 Publication by Journals

The articles we reviewed were published in 33 different journals. Among those, only Sustainability, Energies, Sustainable Cities and Society, and Computers and Industrial Engineering published three or more papers on DCL. Figure 6 demonstrates the top ten journals that published articles on DCL, which considered multiple aspects of QBL. 22% of the reviewed articles (14 out of 64) were published by the journal "Sustainability". The second and third most published journals were "Energies" (6 articles) and "Sustainable Cities and Society" (5 articles).

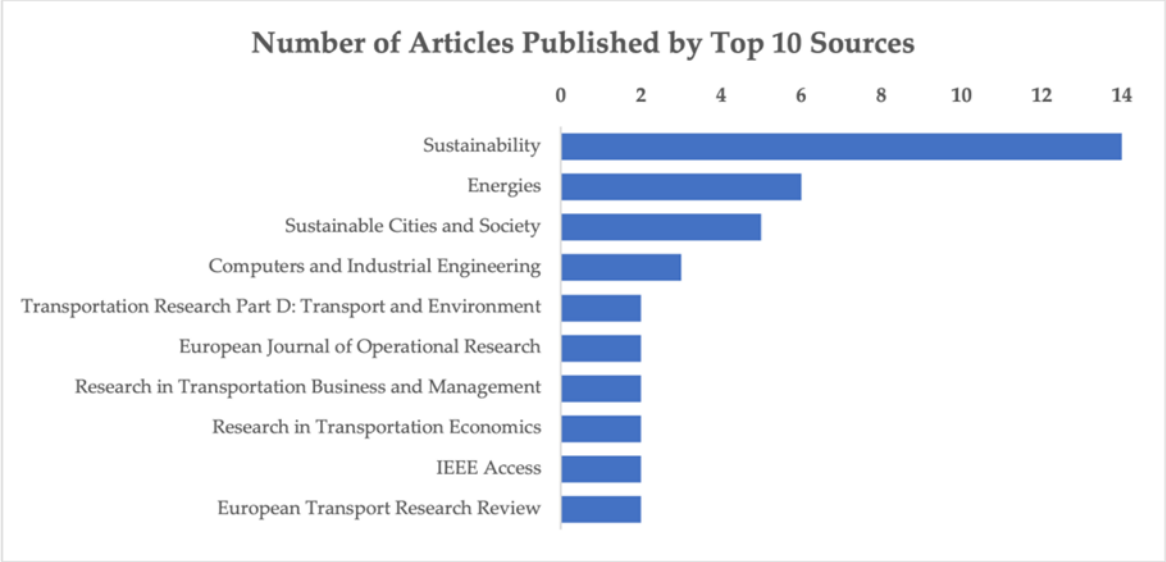


Figure 6. Scholarly journals that published the most on DCL

2.2.3 Publication by Country

We created the graph in Figure 7 by considering the affiliations of the selected articles' authors. Our country-wise classification of the articles reveals that China has published the most studies (12) focusing on the DCL and QBL aspects. As the world's second most populated country with 1.41 billion people (Statista, 2024d) and the most significant global manufacturer, city logistics plays a crucial role in major cities such as Shanghai, Beijing, and Shenzhen. Given that China is the leading emitter of GHGs, air pollution and the climate crisis are critical issues, and city logistics significantly contribute to them. These unique characteristics of China may explain the increased research efforts directed toward DCL to achieve greener

cities and protect public health. Figure 7 also highlights the interest of the United States and various European countries in sustainability and DCL research.

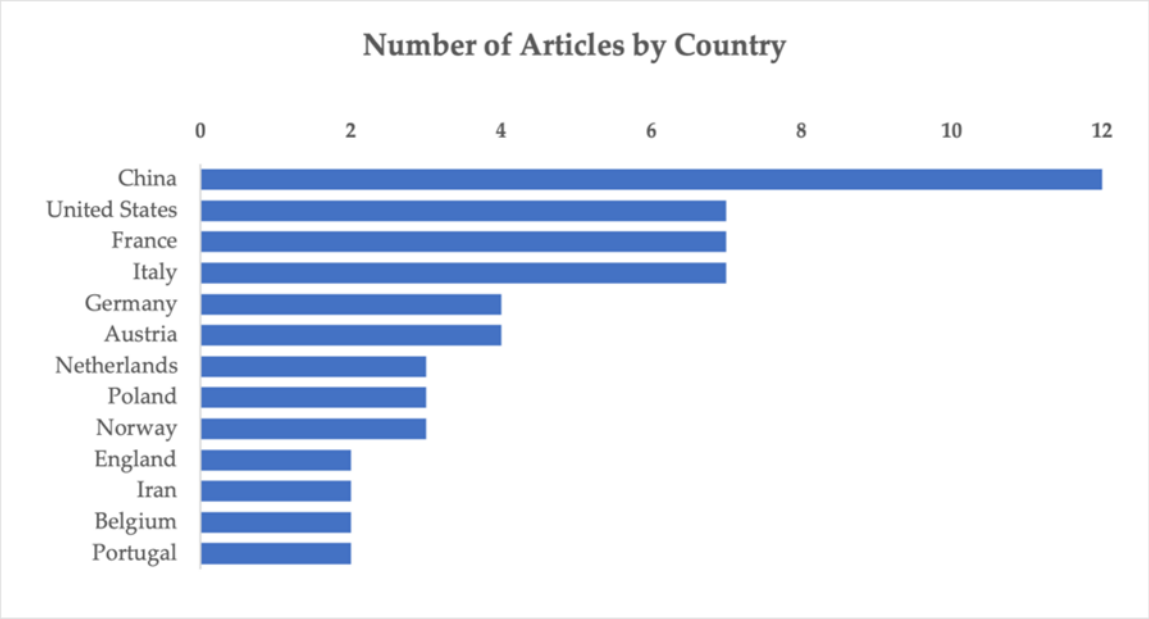


Figure 7. Countries that published the most on DCL

2.2.4 Keyword Analysis

VOSviewer is a tool that can provide the relationships between keywords stated in a set of scholarly articles. Providing a keyword co-occurrence network can help observe the current state of the literature by visualizing the trends and patterns, such as the topics that were studied the most. Therefore, as given in Figure 8, we created a co-occurrence network with the authors' keywords from the selected 64 articles using VOSviewer (version 1.6.20). While establishing the network, we used the complete counting method to tally the total number of keyword occurrences.

The keywords are grouped in a way that each of them belongs to exactly one group. It should be noted that we included keywords used by at least four articles to obtain a more precise visualization. As a result, we obtained a total of 51 key terms and 684 links under four main groups (clusters) given in red, blue, green, and yellow colours. We analyzed the keywords used the most for each cluster and their connections.

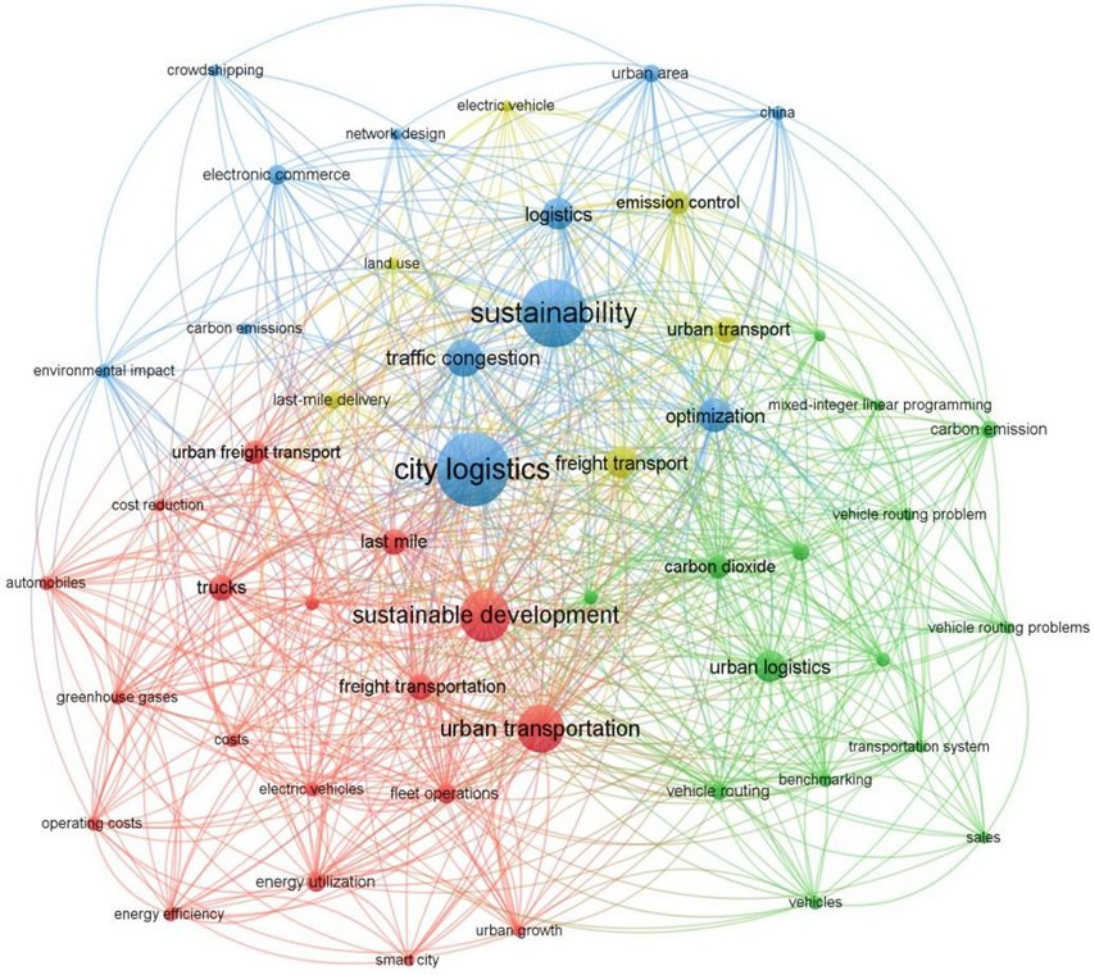


Figure 8. Keyword co-occurrence network via VOSviewer (version 1.6.20)

Analyzing Figure 8, “city logistics” is the central node and stands out the most. There are other nodes such as “urban logistics”, “urban freight transport”, “urban transportation”, “freight transport”, and “freight transportation” that are shown in relatively smaller circles and different colour groups. Based on our analysis, all of these terms referred to (freight) logistics in urban areas, although they were named differently. The terms “sustainability” and “sustainable development” are other prominent nodes that are connected both with “city logistics” and its synonyms, confirming the selected articles’ emphasis on sustainable city logistics.

Cluster 1 is denoted in red colour in Figure 8. “Sustainable development” is the most prominent node with 18 occurrences. It is connected with 45 other key terms from different clusters. The terms “urban transportation”, “urban freight transport”, and “freight transportation” appear around “sustainable development”, and they are synonyms with a total of 34 occurrences combined. Smaller circles connected with these terms are related to vehicles, cost, energy consumption, and greenhouse gases. We observe terms such as “automobiles”, “trucks”, “electric vehicles”, “costs”, “cost reduction”, “operating costs”, “energy utilization”, and “energy efficiency”, showing that the emphasis is on different types of vehicles, cost efficiency, and energy consumption in the context of sustainable city logistics. Our full-text analysis confirms this, as we encountered

several articles that integrated different vehicle types into their optimization efforts to minimize operational costs and energy consumption in city logistics. The term "last mile" also forms a meaningful connection with the nodes "electronic commerce" (cluster 3) and "electric vehicles" as we analyzed several articles that studied the potential use of electric vehicles in the last-mile deliveries of e-commerce products.

Cluster 2 is represented in green colour, where "urban logistics" appears as the central node with 11 occurrences and as a synonym for "city logistics". It relates to the nodes "carbon emission" and "carbon dioxide", which are also connected with the "vehicle routing problem", "vehicle routing", and vehicle routing problems" nodes. These terms are all connected to the "sustainability" term from cluster 3 (blue). These are meaningful connections as CO_2 emissions are highly concerned with environmental sustainability as one of the main drivers of CC, and city logistics is responsible for a significant portion of CO_2 emissions produced. Thus, several articles focused on the reduction of CO_2 emissions. Our full-text analysis revealed that these articles performed optimization and emphasized VRPs to minimize CO_2 emissions and total costs in city logistics. This is confirmed by the key terms and their connections in cluster 2, which are related to the CO_2 emissions in city logistics and vehicle routing problems.

Cluster 3 is represented by blue and includes some of the terms that occurred the most. “City logistics” is the most prominent node in the network, with 26 occurrences and a total link strength of 143. It is followed by the node “sustainability”, which appeared 24 times and had a total link strength of 135.

“Optimization” is another essential term with 12 occurrences. We anticipated this number would be higher, considering that a majority (39 out of 64) of reviewed articles focused on optimization and developed mathematical models. One possible explanation for this inconsistency is that some articles utilized “vehicle routing problem” and its variations as keywords instead of “optimization”. Nevertheless, all studies on vehicle routing problems were centred on optimization. Our full-text analysis and the keyword co-occurrence network demonstrate that optimization is integral to the proposed solutions in city logistics research. Another critical key term, “traffic congestion”, has appeared in 13 articles. Traffic congestion in urban areas is closely linked to QBL aspects. The growing urban population and the rise in e-commerce and online food delivery services exert additional pressure on city logistics and increase traffic congestion, resulting in higher GHGs, air and noise pollution, and reduced accessibility. The terms “electronic commerce” and “crowd shipping” are also connected with “traffic congestion” in cluster 3, supporting this claim. As discussed in Section 2.2.3, China had the highest number of published articles among the selected ones.

China also occurs in cluster 2 and is connected to nodes such as “city logistics”, “sustainability”, and “carbon emission”, highlighting the emphasis on sustainable city logistics and carbon emissions reduction. In summary, cluster 3 underscores the research efforts to optimize city logistics to address associated challenges and achieve sustainable cities.

Cluster 4 (yellow) comprises six key terms: “freight transport”, “urban transport”, “electric vehicle”, “last mile delivery”, “emission control”, and “land use”. As discussed earlier, “freight transport” and “urban transport” refer to the same operation as most articles studied freight transportation in urban areas. Moreover, they relate to “electric vehicle” and “emission control”, further highlighting the objective of reducing emissions in freight logistics in urban areas by utilizing innovative solutions such as electric vehicles. Finally, we realized that the term “decarbonization” does not occur in the network. Our analysis showed that it is not a commonly used keyword, although almost all the selected articles considered emissions in city logistics.

2.3 Proposed DCL Solutions and QBL Aspects in the Extant Literature

Our initial analysis demonstrated that many articles published within DCL literature adopted a quantitative approach, from which we selected 64. These analytical papers employed distinct methods. Many studies (39) performed optimization and developed an analytical model. On the other hand, several studies (25) analytically assessed the cost and effectiveness of various innovative solutions. Regardless of their analytical method, these studies aimed to contribute to city logistics operations while referring to at least two or more QBL aspects. Table 3 presents the QBL aspects discussed, albeit weak or strong, by these studies. It also includes the objective functions of the optimization models proposed in those articles. Table 3 and the information provided in this section address RQ2 and RQ3 by presenting the analytical approaches adopted and the QBL aspects studied.

Table 3. Pointers to the recent DCL literature and its relation to QBL and optimization aspects

Paper	QBL Aspects [2]				Analytical Aspects[3]				Proposition
	EC	EN	SO	CU	CT	EM	TR	SI	
Ahani et al. (2023)	✓	✓			✓				Optimal type and number of vehicles: freight transport
Akbar et al. (2024)	✓	✓	✓						Crowdshipping for inter-urban freight transport
Akkad & Bányai (2020)	✓	✓				✓	✓		Optimization of freight distribution with EVs
Aloui et al. (2021)	✓	✓	✓		✓	✓			Inventory, location, and routing optimization
Anderluh et al. (2021)	✓	✓	✓		✓	✓			Route optimization (2E-VRP) in grey zone deliveries
Arnold et al. (2018)	✓	✓	✓						Cargo bikes for freight delivery
Azad et al. (2023)	✓	✓							E-trikes for delivery
Bi et al. (2020)	✓	✓	✓				✓		Optimal location for crowdsourcing stations
Büttgen et al. (2021)	✓	✓	✓		✓				Optimal route and location with e-vans/cargo bikes
Ceccato & Gastaldi (2023)	✓	✓	✓						Cargo bikes for home deliveries
Chen et al. (2018)	✓	✓			✓	✓	✓		Underground freight transport system
Chen et al. (2023)	✓	✓			✓				Optimal cold chain distribution with EVs
Dupas et al. (2020)	✓	✓	✓				✓		Optimization of freight transport flow

[2] The QBL Aspects here consider qualitative discussion of the four Economic (EC), Environmental (EN), Societal (SO), and Cultural (CU) pillars.

[3] The Analytical Aspects refer to the optimization (quantitative) modeling of the objectives Cost (CT), Emissions (EM), Travel distance and time (TR), and Social Impact (SI).

Dupas et al. (2023)	✓	✓	✓	✓			Optimal location selection for UCC
Enthoven et al. (2020)	✓	✓		✓			Bikes and parcel lockers: optimal delivery (VRP)
Fan (2023)	✓	✓		✓		✓	EVs route optimization
Fan (2024)	✓	✓		✓			EVs route optimization
Fan et al. (2023)	✓	✓		✓			Route optimization: multi-compartment vehicles
Fontaine et al. (2023)	✓	✓		✓			City freighters for two-echelon freight delivery
Fraselle et al. (2021)	✓	✓	✓			✓	EVs and cargo bikes for freight delivery
Gatta et al. (2018)	✓	✓	✓				Crowdshipping using the mass transit network
Gatta et al. (2019)	✓	✓					Crowdsourced delivery
Giordano et al. (2018)	✓	✓	✓				EVs for freight transport
Gruzauskas et al. (2023	✓		✓				Information sharing impact on food delivery
Guo et al. (2019)	✓	✓	✓				Crowdsourced delivery for last-mile logistics
Guo et al. (2022)	✓	✓		✓	✓		Urban logistics enterprise
Hassouna (2022)	✓	✓					EVs for freight transport
Islam et al. (2021)	✓	✓				✓	Hydrogen vehicles/route optimization
Jaegler et al. (2024)	✓	✓	✓				Optimization with inland waterway, EVs
Jiao et al. (2023)	✓	✓				✓	Location selection for urban logistics centers
Jones et al. (2020)	✓	✓					Hydrogen vehicles for freight transport
Kłodawski et al. (2024)	✓	✓	✓				Intermodal terminals for reduced energy use
Kwasiborska et al. (2023)	✓	✓	✓				Delivery: e-scooters and unmanned aerial vehicles

Labarthe et al. (2024)	✓	✓	✓			✓	Joint use of transport modes for freight and passengers
Lee et al. (2020)	✓	✓	✓	✓			Route optimization with mixed fleet
Leyerer et al. (2020)	✓	✓	✓	✓			Optimal locations for refrigerated grocery lockers
Li et al. (2021)	✓	✓	✓	✓	✓		Logistics infrastructure investment options
Liu et al. (2021)	✓	✓		✓	✓		E-grocery delivery: optimal locations and routes
Ma et al. (2024)	✓	✓		✓			EVs: route optimization
Märzinger et al. (2021)	✓	✓					EVs and charging stations
Moll et al. (2020)	✓	✓	✓				Electric trucks for freight delivery
Nocera & Cavallaro (2017	✓	✓					Urban distribution center GHGs assessment
Olapiriyakul & Nguyen (2019)	✓	✓	✓	✓		✓	Warehouse location selection and material flow
Peng et al. (2024)	✓	✓		✓			EVs for dispatching in freight transport
Peppel & Spinler (2022)	✓	✓		✓	✓		Optimal parcel locker location
Perera et al. (2020)	✓	✓	✓	✓	✓	✓	Link toll (a new toll-charging scheme)
Pietrzak et al. (2021)	✓	✓	✓				Rail transport for urban freight delivery
Pilati et al. (2020)	✓	✓					EVs for parcel delivery
Pourmohammad-Zia & van Koningsveld (2024)	✓	✓		✓			Waterway based distribution/EVs in last-mile delivery
Ramirez-Villamil et al. (2022)	✓				✓	✓	Route optimization (2E-VRP): stochastic travel times
Ramírez-Villamil et al. (2023)	✓	✓	✓			✓	Route optimization for parcel delivery

Resat (2020)	✓	✓	✓		✓	✓		Optimal cargo distribution using drones
Saeedi et al. (2018)	✓	✓			✓		✓	✓ Location selection for urban distribution centers
Sayarshad et al. (2021)	✓	✓	✓		✓		✓	Optimal routing and scheduling: EVs
Simoni et al. (2020)	✓		✓					Crowdsourced delivery
Teimoury & Rashid (2024)	✓	✓	✓		✓	✓	✓	✓ Optimal freight transport using drones and trucks
Vajihi, M & Ricci (2021)	✓	✓	✓					Urban rail system for freight distribution
Villa & Monzón (2021)	✓	✓	✓					Metro-based delivery system with parcel lockers
Voegl et al. (2019)	✓							Developed unloading infrastructure to reduce GHGs
Wang et al. (2023)	✓	✓	✓		✓	✓	✓	Location selection for urban logistics centers
Wehbi et al. (2022)	✓	✓					✓	Optimal routes: on-foot porter for last-mile delivery
Wei et al. (2020)	✓	✓	✓		✓			Underground logistics network optimization
Wong et al. (2020)	✓	✓			✓		✓	Route optimization
Zhang & Cheah (2024)	✓	✓					✓	Crowdshipping for freight delivery

Propositions made by optimization articles include vehicle route and inventory optimization for freight transportation and location selection for urban distribution centers and PLs. Many of these articles have integrated various innovative solutions into their optimization models. These include crowdsourcing for food, grocery, and parcel deliveries and various transport modes such as

electric and hydrogen vehicles, cargo bikes, e-scooters, and unmanned aerial vehicles for freight distribution. Additionally, some suggested using inland waterways (where applicable) (Pourmohammad-Zia & van Koningsveld, 2024) and using an underground logistics network for freight distribution in cities.

Many studies have aimed to improve the economic performance of city logistics while reducing the environmental damage it causes. In that sense, a noticeable pattern in these articles' analytical models was their objective functions, which were set to minimize the total costs, GHGs emitted, or both (Islam et al., 2021; Ülkü, 2012; Li et al.,2021). Although several articles did not cast their objective functions, mainly to minimize GHGs/CO_2, almost all claimed an essential reduction in emissions due to their optimization model. There are also several studies with objective functions that minimize the total travel distance/time of the vehicles used for freight transportation. On the other hand, only a few studies minimized social impact in their objective functions.

Our in-depth analysis of the optimization articles provided more specific patterns regarding their analytical models. We observed that many studies emphasize the vehicle routing problem (Chen et al., 2023; Anderluh et al., 2021) and its different variations such as with mixed fleets (Sayarshad et al., 2021), time windows (Wehbi et al., 2022), covering options/locations (Enthoven et al., 2020), multi-depot (Fan, 2024), and multi-compartment (Fan et al., 2023) in city logistics

context. Although their emphasis differs, their solutions are subject to similar constraints associated with city logistics operations. These constraints include but are not limited to the load capacity of vehicles (Lee et al., 2020), supply (Wong et al., 2020), demand (Wei et al., 2020), travel distance of vehicles (Ahani et al., 2023), time window (Akkad & Bányai, 2020), and flow balance (Dupas et al., 2020) constraints. By considering multiple constraints, these studies developed distinct analytical models. Optimization articles that integrated the aforementioned innovative technologies into their analytical models included additional constraints based on the suggested solution. For instance, articles that integrated electric vehicles (EVs), such as e-vans, e-bikes, and e-scooters, in their model included a constraint for battery levels (Akkad & Bányai, 2020).

We also noticed that common analytical modelling approaches include bi-objective/multi-objective programming, which is used mainly by studies that define multiple objective functions such as minimizing total cost and GHGs (Olapiriyakul & Nguyen, 2019), integer/mixed-integer programming (Ahani et al., 2023), and various heuristics/metaheuristics (Li et al., 2021).

Based on our analysis, some aspects were missing in the proposed solutions of the articles we reviewed. These include consideration of uneven roads and missed deliveries, which may significantly influence the amount of GHGs released into the atmosphere during city logistics operations. Although integration of such

aspects can be challenging, they should be considered in order to develop more effective solutions, especially when studying densely populated cities.

Aside from the optimization studies, many articles that studied innovative and practical solutions made an effort to evaluate their implementation. Innovative solutions that were evaluated by these articles include the use of electric (Giordano et al., 2018) and hydrogen (Jones et al., 2020) vehicles, cargo bikes/e-trikes (Azad et al., 2023), inland waterways (Jaegler et al., 2024), crowdsourced delivery (Gatta et al., 2019) and a metro-based delivery system (Villa et al., 2021) for transportation of various goods. Studies highlighted the potential benefits of these solutions, such as the reduction of GHGs (Azad et al., 2023) and air pollution (Jones et al., 2020), as well as challenges associated with their implementation, such as high costs (Fraselle et al., 2021).

Based on our analysis of the selected articles, keyword trends, and the output of the keyword co-occurrence network, we deduce that the term "sustainability" is increasingly appearing. Moreover, we observed that sustainable approaches have been developed and integrated into the analytical models in most optimization studies. On the other hand, studies that did not perform optimization yet analytically analyzed and evaluated potential solutions mostly had a sustainability criterion. We analyzed the articles to see which QBL aspects were

studied, as reported in Table 3. However, we observed that the environmental and economic aspects of QBL were mainly considered.

Albeit weak or strong, all articles we analyzed considered environmental aspects. Studies that developed an analytical model either set the reduction of CO_2 emission as their objective function or argued that implementing their model would help reduce CO_2 emissions based on their case study results. For instance, Akkad and Bányai (2020) minimized GHGs specifically and found that up to 92% emission reduction is possible in some scenarios. On the other hand, Büttgen et al. (2021) did not minimize GHGs in their objective function. Still, they showed that emissions could be reduced by around 96% by minimizing total costs, including operational (travel) and emissions costs. Several studies assessed the environmental implications of various practical solutions (Azad et al., 2023). Such emphasis is crucial for environmental sustainability, and there is a need for further research to achieve greener cities and mitigate the consequences of CC.

In terms of economic sustainability, the articles made valuable contributions. Almost all the articles (60 out of 64) we analyzed considered economic aspects in their proposals. Many optimization studies set their objective functions to minimize the total costs that occur during the operations related to urban freight transport, including operational and environmental costs. These studies aimed to optimize freight transportation by vehicles so that the operations

can be completed with minimum use of resources such as money, time, and fossil fuels. For instance, Enthoven et al. (2020) minimized total travel and connection costs for freight distribution in their analytical model.

Studies that did not conduct optimization analytically assessed the economic impacts or benefits of applying different innovative solutions, as given in Table 3. Thus, these studies frequently referred to the environmental and economic aspects of QBL. These two QBL aspects are also highly related to each other as studies that focused on minimizing costs also found significant reductions in emissions, and vice versa. Nevertheless, more research focusing on cities' environmental and economic sustainability is required to explore ways to minimize the impacts of CC in the most economical way possible.

Only 34 of 64 studies considered social sustainability, unlike environmental and economic sustainability. The solutions proposed in these articles contribute to social sustainability. These include but are not limited to using electric and hydrogen vehicles in urban freight transportation, which may reduce air and noise pollution and provide a healthier environment for city dwellers. Similarly, optimization of routes in logistics operations may ease traffic congestion and save time, creating a more accessible environment. Other innovative solutions, such as crowdsourcing, can create new city job opportunities. On the other hand, applying

proposed solutions may impact society negatively unless social aspects are considered thoroughly.

On the other hand, consideration of the cultural aspect of QBL is scarce in the DCL literature as we have not encountered any studies considering cultural sustainability. This indicates a gap in the DCL literature, as cultural aspects are significant determinants of the applicability of any potential solution. City logistics is a common and indispensable aspect of all urban areas. However, cultural norms and values may significantly vary from city to city. Therefore, additional cultural constraints may be present that can limit the applicability of a solution. For instance, cargo bikes are integrated into the solution proposals made by several articles for last-mile deliveries in cities. Using cargo bikes could be a viable and effective solution in various European countries, like Denmark, where bicycles are already a popular mode of transportation. However, in countries such as Türkiye, where bicycles are not as commonly used, cultural attitudes may hinder the widespread adoption and effectiveness of cargo bikes as a solution. For proposed solutions to be effective, they should not conflict with the related area's culture. This is also crucial for sustaining the cultural identities of these areas (cf. Parmaksız et al., 2024). Thus, studies should consider various cultural aspects throughout the development of a solution. This indicates that all four QBL pillars of sustainability are crucial to consider when addressing the challenges in DCL.

2.4 Evolution of DCL Research and Concluding Remarks

This section addresses RQ4 by presenting enablers, barriers, and future research directions in the context of city logistics. Enablers include the aforementioned innovative technologies, which are expected to be integral to DCL efforts. Based on our analysis, these technologies are increasingly becoming the focus of several studies in DCL literature and emerge as a viable factor integrated into various optimization efforts in the articles analyzed. PLs, crowdsourcing, inland waterways, and underground networks are other innovative solutions for city logistics that produce promising results in terms of QBL aspects.

Some technologies can be greener substitutes for conventional vehicles, which cause more noise and air pollution. For instance, unlike conventional vehicles, electric and hydrogen vehicles do not burn fossil fuel to operate, reducing the GHGs released into the atmosphere. Since city logistics operations account for a significant portion of the total GHGs emitted, transitioning to greener transportation modes from conventional vehicles can significantly reduce GHGs, which may slow down CC. Integrating these technologies into optimization efforts is a significant area of research with the potential to achieve more sustainable cities.

Researchers and practitioners can utilize the findings of this literature review as we provide an overview of the solutions studied in the DCL literature.

However, our analysis shows several barriers exist to employing such technologies. For instance, the upfront cost of electric and hydrogen vehicles is higher than conventional ones. Moreover, a lack of infrastructure for charging/refuelling stations may limit the sustainable use of electric and hydrogen vehicles, especially in developing and underdeveloped countries. The financial burden of high upfront costs and infrastructural limitations would undoubtedly influence the economic sustainability of cities and related organizations. Future studies integrating these technologies into their optimization efforts should consider the barriers since they require adding new constraints, among others, due to possible public-private partnerships.

Analyzing the studies, we observed that the impact of uneven roads on city logistics efficiency is lacking. As conventional vehicles are currently the primary mode of transportation in urban logistics, uneven roads increase fuel consumption, resulting in higher GHGs. Therefore, future studies should consider uneven roads in their emission calculations. Another gap in the DCL literature is the impact of product returns and missed deliveries on supply chain performance, which increases freight movement and, consequently, GHGs. Future studies can emphasize developing analytical solutions to minimize the impact of product returns and missed deliveries in cities by considering QBL aspects.

Based on our findings, most studies emphasize environmental, economic, and occasionally social sustainability, overlooking the cultural aspect of QBL. However, various cultural aspects are crucial determinants of the applicability and effectiveness of a solution. Therefore, future research should consider the unique cultural identities of different cities while proposing a solution. Furthermore, because only about half of the reviewed articles consider social sustainability, we encourage future studies to emphasize it so that life quality and accessibility of city dwellers can be enhanced.

2.5 Chapter Summary

This chapter analyzes the analytical solutions proposed in the DCL literature by considering the QBL pillars of sustainability. First, we found that an increasing number of articles emphasize decarbonization and sustainability of city logistics. However, more research is needed to achieve sustainable cities and mitigate the severe consequences of CC. We demonstrated the current state of the research by presenting the publication years, journals, and countries. Results indicate the increasing interest in sustainable city logistics in the last decade, especially in countries such as China, the United States, France, and Italy. The keyword co-occurrence network shows the topics most emphasized and the keywords commonly used in the DCL literature. Some topics that stand out the most include sustainable development, optimization, and traffic congestion in city logistics.

Second, we discussed the analytical solutions proposed by the articles we reviewed. We reported patterns in their analytical models and calculations. Our findings show that route optimization and location selection are common solution approaches in the DCL literature. Several studies have integrated the aforementioned innovative solutions into their analytical approaches, such as the vehicle routing problem with electric vehicles. Future research can utilize these patterns while developing their solution approaches. Practitioners and policymakers can also utilize these findings to enhance their decisions concerning city logistics. Finally, we discussed the potential benefits and barriers to implementing various innovative solutions that influence DCL's efforts toward greening supply chain logistics.

CHAPTER 3: Problem Formulation and Model

Chapter 2 demonstrated the complex nature of e-commerce home deliveries and product return collection in urban areas. In recent years, the complexity of these operations has further intensified due to growing sustainability concerns. In terms of the environment, the impact of climate change (CC) intensified and became more widespread in various cities around the globe, mainly due to the tremendous amounts of greenhouse gas emissions (GHGs) produced during city logistics. New regulations and economic crises raised economic concerns as operating costs increased and purchasing power diminished in several regions. Societies and their respective cultural values are negatively influenced by increased air and noise pollution and traffic congestion, which threaten public health and force people to adjust their lifestyles. In that sense, effective and sustainable management of city logistics operations has become a significant challenge for the companies involved. E-commerce and last-mile logistics companies deal with many factors, such as the transportation of goods, selection of a vehicle fleet composition, customers' assignments to parcel lockers (PLs) based on their locations, time windows for visiting the customer nodes and managing PLs.

PLs are becoming increasingly common for business-to-customer (B2C) e-commerce deliveries. A PL can be defined as a locked storage that comprises

multiple different-sized containers, as depicted in Figure 9 (Kavus et al., 2022). They are primarily used for unattended delivery purposes where customers can pick up their packages. The packages can be held in a PL until they are picked up by a customer (usually up to three days). PLs offer an easy and quick service for customers' pickup demands (Kavus et al., 2022).

Figure 9. Image of a PL belonging to Amazon

As the largest e-commerce company, Amazon owns several PL facilities in the cities it operates. Customers who prefer to pick up their packages from a nearby PL can select this option within the Amazon mobile application when placing an order. Customers receive a notification on their mobile devices after the package is delivered to the PL. When the customer arrives at the PL, their mobile

device connects to the container where the customer's package is stored. The container is unlocked remotely using Bluetooth technology once the customer selects the "open the locker" option in the app (Amazon, 2024a). After opening the locker, customers simply need to retrieve their packages and manually close the container. This process ensures high security, as only the courier and the customer can open the locker. PLs also facilitate package returns. Instead of shipping items back or requesting a pickup from their homes, customers can return their packages through PLs by following a similar process (Amazon, 2024b). Note that not every PL has to be like the one in Figure 9. Various locations, such as stores and offices, can be used for the same purpose. These locations can be determined as drop-off points where couriers deliver the demand of several pickup customers. They usually involve a dedicated small area inside the store where an employee helps the pickup customers retrieve their packages after confirming their identity. In this study, the definition of PLs includes these drop-off locations too. These locations can be a preferred pickup option for customers who do not want to use the Amazon mobile application. Many customers in cities now choose to pick up their packages through a nearby PL (involving both lockers and drop-off locations) because of the process's security and simplicity, and the availability of many PL facilities.

Many customers prefer PL pick-up because they may not be home when their delivery arrives, such as when they are at work. This is mainly due to the uncertainty of the delivery times and the wide time windows provided by the company. For instance, Amazon usually informs the customer that their package will be delivered by the end of a specific day. Wide delivery time windows increase the likelihood of customers being absent when their delivery arrives. If a customer is not home when the delivery arrives for various reasons, there is a risk of porch piracy if the courier leaves the package at the customer's door. This might result in the loss of the package, harm the company's reputation and reliability, and create economic and social consequences. On the other hand, if company policy prohibits couriers from leaving packages when the customer is absent, the package is typically returned to the depot or a post office. This can also be inconvenient for customers, as they have to travel to the depot to retrieve their package, which might be far from their home. Consequently, picking up packages from a nearby PL has become a preferred option among e-commerce customers.

E-commerce companies such as Amazon also benefit from using PLs as it enables collecting and delivering the packages of several customers to a single location instead of visiting each customer's home. This can potentially decrease the overall distance and time travelled by vehicles, leading to lower fuel and labour costs. Additionally, using PLs can be beneficial for the environment as it

can decrease GHGs resulting from the reduced distance travelled by delivery vehicles (Molin et al., 2022).

This chapter proposes a network designed for B2C e-commerce delivery and pickup operations in urban areas. We developed a two-stage mathematical model. Stage-I involves assigning customers to the nearest PL based on their home location. Stage-II is formulated as a time-definite Vehicle Routing Problem with Variable Capacity and Product Returns (TVRPCR). Note that the integration of missed deliveries to the stage-II model is performed in Chapter 4. This multi-objective mixed-integer non-linear programming (MINLP) model aims to minimize operational costs and CO_2 emissions costs associated with B2C e-commerce operations. We formulated and solved the model using GUROBI Optimizer in Python.

3.1 Problem Description

GHGs produced during e-commerce industry operations must be reduced through sustainable solutions considering the intensifying environmental, social, and cultural consequences. It is also imperative for such solutions to be economically feasible and sustainable for the companies involved in these operations. As this thesis research emphasizes the operations within the city limits, the involved parties would be the end customers and logistics companies responsible for e-commerce deliveries and the collection of customer returns. The

problem consists of two stages. In stage-I, we aim to assign each customer and their demand to a PL. The objective is to complete this assignment so that each customer is assigned to the nearest PL to their home. As a result, customers who prefer to pick up their packages from a PL can obtain them from a nearby location. Stage-II (TVRPCR) is formulated to find the most efficient routes for operating vehicles in terms of economic and environmental costs while utilizing PLs. In Chapter 4, we extend stage-II by integrating missed deliveries. This network would potentially reduce the GHGs and operating costs by ensuring efficient utilization of resources, contributing to environmental, economic, and social sustainability. This problem's formulation necessitates applying a complex MINLP technique to minimize the environmental and economic cost of the delivery and collection process. Implementing the proposed network can enable authorities to decide sophisticated questions such as the type and number of vehicles required for e-commerce delivery and collection, the optimal route for each vehicle, the assignment of each customer to the nearest PL, and time windows in which the customers should be visited. Applying the proposed network in this thesis can help address the environmental, economic, social, and cultural challenges faced by B2C e-commerce operations in cities.

Figure 10 depicts a last-mile distribution network where an e-commerce company provides home deliveries and product return collection to customers

within a city. The company owns a fleet of delivery vans with different capacities and a depot where the customers' packages are stored temporarily. A typical delivery van is depicted in Figure 11. The firm also has several PL facilities inside the city that have been newly opened at specific locations to maximize customer coverage. Each customer is aimed to be assigned to the nearest PL to them with the stage-I model.

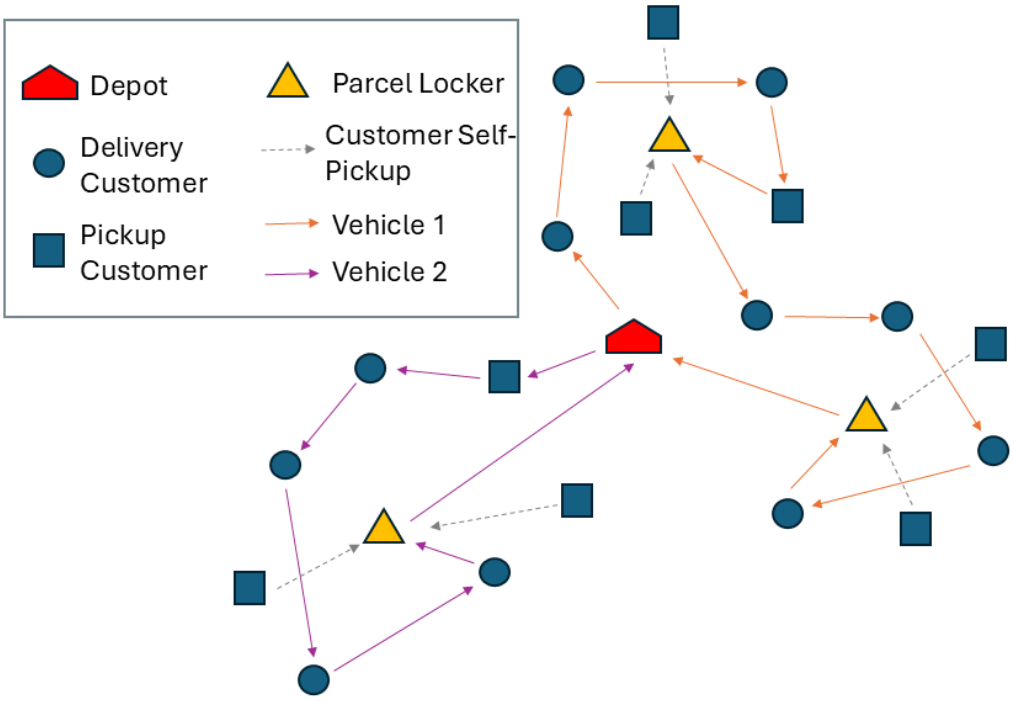


Figure 10. Problem description

Figure 11. A typical delivery van used for e-commerce freight transportation

Source: https://www.steeleford.com/new/commercial.html

The delivery process starts from the depot. Each vehicle departs from the depot carrying the total demand of customers they are scheduled to visit. There are two types of customers based on their preferred delivery options. Delivery customers choose to have their packages delivered to their homes, while pick-up customers request to collect their packages from the nearest assigned PL. Vehicles must service delivery customers if there is a demand for delivery or returns. In contrast, the demand for pick-up customers is fulfilled by delivering packages to the nearest PL, and these customers are only visited if they request a return pick-up from their home location. Similarly, a PL is visited if there is a demand from a pick-up customer assigned to it or if a customer is returning their package through that PL.

Upon visiting a node, the courier unloads the demanded package from the vehicle to complete the delivery and then loads any returned products back onto the vehicle. Each customer is visited only once by exactly one vehicle within a time window determined by the model. We define zones implicitly where each zone consists of a PL and the customers assigned to it. Once a vehicle enters a zone, it must first visit all the customers in that area before proceeding to the designated PL. This is added to realistically manage missed deliveries, which will be integrated in Chapter 4. After completing the delivery and pickup operations within a zone, the vehicle can either return to the depot or move on to the next zone, depending on time constraints and the vehicle's capacity. Finally, each vehicle must return to the depot at the end of its route, carrying the returned items they picked up from visited customers or PLs.

3.2 Model Assumptions

Assumption 1: Customers always prefer the nearest PL.

Assumption 2: All packages are standard (having similar weight and volume).

Assumption 3: The list of delivery and return points are known ex-ante.

Assumption 4: Vehicle capacity is defined by the maximum number of standard, unit-sized packages it can hold.

Assumption 5: For calculating transport emissions, the impact of possible unlevel roads are ignored, without loss of generality.

Assumption 6: All vehicles are assumed to run at an average speed of 20 miles/hour.

3.3 Mathematical Model Formulation

3.3.1 Stage-I Model – DDZCAP (Delivery Demand Zoning and Customer Assignment Problem)

Stage-I aims to assign each customer to the nearest PL and redirect pickup customers' demand to their assigned PL. In doing so, we establish zones, each consisting of a PL and all customers assigned to it. In Tables 4, 5, and 6 we define sets where for a non-empty set A, the expression $|A|$ gives its cardinality.

Table 4. Stage-I model: sets and descriptions

Set	Description	Range
N	Nodes (depot, customers, parcel lockers)	$N = \{0, 1, 2, 3, \dots, n\}$, $\lvert N\rvert = n + 1$
C_D	Delivery customer location	$C_D = \{1, 2, 3, \dots, c_d\}$, $\lvert C_D\rvert = c_d$
C_P	Pickup customer location	$C_P = \{1, 2, 3, \dots, c_p\}$, $\lvert C_P\rvert = c_p$
P	Parcel locker location	$P = \{1, \dots p\}$, $\lvert P\rvert = p$
K	Vehicles	$K = \{1, \dots, k\}$, $\lvert K\rvert = k$

C_{DP}	Union set of DC and PC locations	$C_{DP} = \{1, 2, 3, \dots, c_{DP}\}$, $\lvert C_{DP}\rvert = c_{DP}$
PC_D	Union set of DC and PL locations	$PC_D = \{1, 2, 3, \dots, pc_D\}$, $\lvert PC_{DP}\rvert = pc_{DP}$

Table 5. Stage-I model: parameters and descriptions

Symbol	Description	Measure
d_{ij}	Distance between node i and j	mile
q_i	Delivery demand at node i	Unit-sized package
Q_p	The capacity of the PL	Unit-sized package

Table 6. Stage-I model: decision variables and descriptions

Symbol	Description	Type	Measure
y_{ip}	1, if customer i is assigned to locker p; 0, otherwise	Binary	-
D_p	Demand directed to locker p based on PCs' orders	Non-negative, integer	Unit-sized package

Objective Function

$$\min \sum_{p \in P} \sum_{i \in N} d_{ip}\, y_{ip}$$

The objective function represents the objective function that minimizes the total distance of customers to the PL to which they are assigned.

Constraints

$$\sum_{p \in P} y_{ip} = 1 \,, \forall\, i \in C_{DP} \tag{1}$$

$$\sum_{i \in C_P} y_{ip}\, q_i = D_p \,, \forall\, p \in P \tag{2}$$

$$D_p \leq Q_p, \forall\, p \in P \tag{3}$$

$$y_{ip} = \{0, 1\} \;\forall\, i \in C_{DP} \,, p \in P \tag{4}$$

$$D_p \geq 0 \,, \forall\, p \in P \tag{5}$$

Constraint (1) ensures that each customer is assigned to exactly one PL. Note that both delivery customers and pickup customers are assigned to a PL. This is included to manage missed deliveries, which is discussed in Chapter 4. Constraint (2) redirects the total demand of pickup customers to the PL that they are assigned to. In stage-II, the delivery demand for pickup customers will be set to zero. On the other hand, the delivery demand for PLs will be equal to the total delivery demand of pick-up customers who are assigned to it. In simpler terms, the delivery demand for the PLs in the stage-II model will be determined based on the values decided in the stage-I model (D_p). Constraint (3) ensures that the amount of demand assigned to a PL does not exceed its capacity. Constraint (4) states binary variables, and constraint (5) ensures nonnegativity.

3.3.2 Stage-II Model – TVRPCR (Time-definite Vehicle Routing Problem with Variable Capacity and Product Returns)

Tables 7 and 8 show the additional parameters and decision variables.

Table 7. Stage-II model: additional parameters

Symbol	Description	Measure
Demand Parameters		
q_i	Delivery demand at node i	Unit-sized package
r_i	Return demand at node i	Unit-sized package
Time Parameters		
t_{ij}	Travel time from node i to j	minute
$delay_{ij}$	Delay from node i to j	minute
T_{max}	Maximum completion time of the route	minute
s_i	Service time at node i	minute
Capacity Parameters		
Q_k	Capacity of vehicle k	Unit-sized package
Cost Parameters		
f_k	Fuel cost per mile for vehicle k	$ / mile
F_k	Fixed cost of vehicle k	$
L_c	Labor cost per hour	$ / hour
ε	Calibration coefficient to convert emissions to dollars	-

Emission Parameters		
F_{co_2}	Fuel emission factor	lbs/gal
M_k	The average mileage of vehicle k	mile/gal
P_k	Packing emissions factor	lbs/package
S_{co_2}	Shipping emission factor	lbs/cwt-mile
S_k	The average speed of vehicle k	mile/hour
S_{max}	Maximum vehicle speed allowed	mile/hour
w_p	Weight of the package	cwt
Other Parameters		
M	Large integer	-

Table 8. Stage-II model: additional decision variables

Symbol	Description	Variable Type
X_{ijk}	1, if vehicle k travels from node i to j; 0, otherwise	Binary
a_k	1, if vehicle k is used; 0, otherwise	Binary
V_{ik}	Load of vehicle k after visiting node i	Non-negative, integer
u_i	Position of node i in the route sequence	Non-negative, integer
e_i	Earliest time of arrival at node i	Non-negative
l_i	Latest time of arrival at node i	Non-negative

Stage-II model (TVRPCR) inputs the output of the stage-I model (DDZCAP), which assigns each customer to the nearest PL and allocates the demand of pickup customers to related PLs. TVRPCR aims to minimize the environmental and economic cost of the B2C e-commerce distribution network while deciding on critical factors for the operating company. Equation (6) represents the multi-objective function of the mathematical model where the total cost (TC) is minimized. TC is the weighted sum of the total environmental cost (TEC) and total operational cost (TOC). The weights W_O and W_E are added to enable the adjustment of the trade-off between these two types of costs. Specifically, the condition $W_O > W_E$ indicates higher importance given to the minimization of TOC than TEC, and vice versa when $W_O < W_E$. On the other hand, the condition $W_O = W_E$ indicates that equal importance is given to the minimization of TOC and TEC. Equation (7) converts the total CO_2 emissions that are physically produced into a financial value. This configuration makes the objective function a financial metric that can be minimized. We used the coefficient ε for the conversion of total emissions TE to the total environmental cost TEC. The value of ε was found to be \$0.041 per lb of CO_2 emitted, according to Black et al. (2022).

Objective Function

$$\text{Min } TC = W_E TEC + W_O TOC \tag{6}$$

$$TEC = \varepsilon TE \tag{7}$$

Equation (8) (TE) is adopted from Ülkü (2012) for the calculation of the total CO_2 emissions released into the atmosphere throughout the operation. The calculation considers the total distance travelled, vehicles' fuel consumption and speed, packaging emissions, loads of the vehicles, and weights of the products being transported. This enables a realistic calculation of the total CO_2 emissions produced as the velocity of a vehicle and its total load also influences fuel consumption and, consequently, CO_2 emissions.

$$TE = \sum_{j\in N}\sum_{i\in N}\sum_{k\in K}\frac{F_{co_2}\, X_{ijk}\, d_{ij}}{M_k} + \sum_{k\in K} P_{co_2} V_{0k} +$$

$$S_{co_2}\left(\frac{S_{max}}{S_k} w_p \sum_{j\in N}\sum_{\substack{i\in N \\ i\neq j}}\sum_{k\in K} X_{ijk}\, d_{ij}\, V_{ik}\right) \tag{8}$$

Equation (9) shows how to calculate the total operational costs TOC. It involves fuel cost based on the distance travelled, labor cost based on time, and fixed cost of the vehicles.

$$TOC = \sum_{j\in N}\sum_{i\in N}\sum_{k\in K} f_k\, X_{ijk}\, d_{ij} + \sum_{k\in K} L_c\left(\frac{e_{0k} + l_{0k}}{2}\right) + \sum_{k\in K} F_k a_k \tag{9}$$

Constraints

$$\sum_{j\in N, j\neq 0} X_{0jk} = a_k\,, \forall\, k \in K \tag{10}$$

$$\sum_{j\in N, j\neq 0} X_{i0k} = a_k\,, \forall\, k \in K \tag{11}$$

Constraints (10) and (11) ensure that all vehicles that are selected for use must depart from and return to the depot. On the other hand, if a vehicle is not decided to be used by the model output, it must not depart from and return to the depot.

$$\sum_{k\in K}\sum_{i\in N, i\neq j} X_{ijk} = \left\lceil \frac{q_j + r_j}{M} \right\rceil, \forall\, j \neq 0 \in N \quad (12)$$

$$\sum_{k\in K}\sum_{j\in N, j\neq i} X_{ijk} = \left\lceil \frac{q_j + r_j}{M} \right\rceil, \forall\, i \neq 0 \in N \quad (13)$$

Constraints (12) and (13) indicate that each customer node must be visited and left exactly once by only one vehicle, only if they have a delivery and/or return demand. The ceiling function $\lceil x \rceil$ turns the smallest integer that is greater than or equal to the value of x, e.g., $\lceil 9.6 \rceil = 10$. In Equations (12) and (13), the ceiling function is used because, when divided by M, any sum of $(q_j + r_j)$ will yield a value between 0 and 1. If the result of $(q_j + r_j)$ is different from zero, the ceiling function will ensure the right-hand side equals to one, indicating that node j will be visited once by one vehicle. On the other hand, if the result from $(q_j + r_j)$ is zero, the ceiling function's result will return zero. Therefore, for instance, if a customer has neither delivery nor return demand, constraints (12) and (13) ensure they will not be visited by any vehicle. If another customer has a delivery demand of two packages but no return demand, they will be visited (and left) exactly once by only one vehicle.

$$\sum_{\substack{i\in N,\\ i\neq h}} X_{ihk} = \sum_{\substack{j\in N,\\ j\neq h}} X_{hjk} \ , \forall\ k\ \in\ K, h \neq 0 \in N \tag{14}$$

Constraint (14) ensures the flow continuity for each vehicle by forcing it to leave a node after it is visited (excluding the depot).

$$V_{jk}\ \geq\ V_{ik} -\ q_j\ +\ r_j\ +\ Q_k\, X_{ijk} -\ Q_k\ , \forall\ k\ \in\ K, i, j\ (i\ \neq j) \in N \tag{15}$$

Equation (15) monitors the vehicle's load after each node is visited. It ensures that the delivery demand of a node is deducted, and the return demand is added to the vehicle only if that node is visited. If a node is not visited by the corresponding vehicle, the constraint relaxes the decision variable for that node.

$$V_{ik}\ \leq\ Q_k, \forall\ k\ \in\ K, i\ \in\ N \tag{16}$$

Constraint (16) ensures that a vehicle's load does not exceed its capacity at any given point (including the depot departure).

$$\sum_{j\in PC_D} \sum_{i\in N, i\neq j} X_{ijk}\ q_j\ = V_{0k}\ , \forall\ k \in\ K \tag{17}$$

Constraint (17) ensures that a vehicle must depart from the depot carrying the total delivery demand of the customers scheduled to be visited by that vehicle.

$$u_i -\ u_j + (N-1)\, X_{ijk}\ \leq N-2, \forall\ k\ \in\ K, i, j\ (i\ \neq j) \in N \tag{18}$$

Constraint (18) is the subtour elimination constraint introduced by Miller-Tucker-Zemlin (Miller et al., 1960). It ensures that node visitation is performed in a sequence.

$$e_{jk} \geq e_{ik} + s_i + t_{ij} - M\left(1 - X_{ijk}\right), \forall\, k \in K, i, j\ (i \neq j)(i \neq 0) \in N \quad (19)$$

$$e_{jk} \geq s_0 + t_{0j} - M\left(1 - X_{0jk}\right), \forall\, k \in K, (j \neq 0) \in N \quad (20)$$

$$l_{jk} \geq s_0 + t_{0j} + delay_{0j} - M(1 - X_{0jk}), \forall\, k \in K, (j \neq 0) \in N \quad (21)$$

$$l_{jk} \geq l_{ik} + s_i + t_{ij} + delay_{ij} - M\left(1 - X_{ijk}\right), \forall\, k \in K, i, j\ (i \neq j)(i \neq 0) \in N \quad (22)$$

$$T_{max} \geq e_{ik}, \forall\, k \in K, i \in N \quad (23)$$

$$T_{max} \geq l_{ik}, \forall\, k \in K, i \in N \quad (24)$$

Constraints (19-24) are time-window constraints. Constraints (19) and (20) set the earliest time that a vehicle can arrive at each node if the vehicle is scheduled to visit that node. These times are determined based on the service times at each node and the travel times between them. Similarly, constraints (21) and (22) define the latest arrival times for each node, taking into account potential delays between nodes. Such delays may occur due to factors like traffic congestion, unexpectedly long service times at a previous customer, or vehicle breakdowns. It's important to note that delays significantly impact the latest arrival times, especially for customers who are visited at the end of the route. Earliest and latest arrival times

(time windows) are defined as decision variables. Constraints (23) and (24) state that each customer must be visited within the maximum completion time of the route.

$$\sum_{i\in N, i\neq p} X_{ipk} = \sum_{j\in N, j\neq p} X_{pjk}\,(1 - y_{jp})\ \forall\, k \in K, p \in P \tag{25}$$

$$\sum_{i\in N, i\neq j} X_{ijk}\, y_{jp} \leq \sum_{m\in N, m\neq j} X_{jmk}\, y_{mp} + X_{jpk}\, y_{jp}\ \forall\, k \in K,\ p \in P,\ j \in C_{DP} \tag{26}$$

Constraints (25) and (26) ensure that a vehicle serves all nodes in a zone before moving to the next zone or the depot. (As stated earlier, a zone comprises a PL and the customers assigned to it.) It is also ensured that a zone's PL is visited after meeting the demands of all customers assigned to it.

$$V_{ik}, u_i, e_{ik}, l_{ik}, TE, TOC \geq 0, \forall\, k \in K, i \in N \tag{27}$$

$$X_{ijk}, a_k = \{0, 1\}, \forall\, k \in K, i, j\ (i \neq j) \in N \tag{28}$$

Constraints (27) and (28) are for stating the nonnegative and binary variables.

3.4 Chapter Summary

In this chapter, we developed a two-stage mathematical model for last-mile operations in B2C e-commerce with the aim of reducing CO_2 emissions and operational costs. The stage-I model assigns each customer to the nearest PL to optimize zoning. The stage-II (TVRPCR) considers both home deliveries and package returns while utilizing PLs, addressing a gap in the DCL literature. This

chapter further contributes to the field by defining vehicle fleet composition and time windows as decision variables. In Chapter 4, missed deliveries will also be integrated by extending the stage-II model, which is a significant issue that has been overlooked in the DCL literature.

CHAPTER 4: Integration of Missed Deliveries to TVRPCR

Statistics indicate that 20% of home deliveries fail on the first attempt (Lim et al., 2023). These failed deliveries, referred to as missed deliveries, occur when the customer is not at their home address when the courier arrives to deliver their package. When a missed delivery occurs, the related package is typically loaded back into the delivery vehicle and transported back to the depot or an authorized post office at the end of that day. The package can be picked up by the customer from the depot or a post office on the following days. This increases vehicle usage as the customers are likely to drive to the depot to collect their packages and then return home. The package can also be rescheduled for another delivery in the following days**.** However, this also increases the total distances travelled since the vehicle will visit that customer again for redelivery. In both cases, air and noise pollution and the amount of GHGs will increase as conventional vehicles are mainly used for these operations. This will also increase operational costs due to higher fuel consumption and damage the retailer's brand reputation (Lim et al., 2023). When this occurs for a significant number of customers, such as in metropolitan cities, this process's environmental and economic consequences can become devastating. Therefore, the current way of handling missed deliveries cannot be considered sustainable for both the company and its customers.

4.1 Extended Problem

Research shows that neglecting the existence of missed deliveries in optimization efforts can create an important downward bias in calculating the total costs (Lim et al., 2023). In this chapter, we extend the TVRPCR model developed in Chapter 3 to integrate missed deliveries. In the proposed network depicted in Figure 12, when a missed delivery occurs at a customer node, the vehicle will deliver that customer's package to the PL they are assigned instead of returning the package to the depot. Following this, the customer is required to self-pickup their package from that PL. As a result, the extended network in this chapter will consider package deliveries, returns, and missed deliveries while utilizing PLs, addressing a significant gap in DCL literature.

The occurrence of missed deliveries for each customer is uncertain until the vehicle arrives, as this is only revealed upon arrival. Consequently, missed deliveries should not affect the vehicle's routes since these routes are determined before the vehicle departs from the depot (usually on the previous day). To realistically incorporate missed deliveries into stage-II model (TVRPCR) developed in Chapter 3, we adopt a scenario-based approach. We generate scenarios based on a missed delivery probability for each delivery customer,

which is derived from available statistics. In each scenario, missed deliveries occur at certain customer locations according to the specified probability.

In the extended model, we define a scenario-based parameter for the occurrence of missed deliveries. Since it is defined as a parameter, it could potentially affect the routing decision in the model. However, this is not a realistic situation as the occurrence of missed deliveries cannot be known upfront and, therefore, should not alter the routing decision. The proposed strategy addresses this issue and provides a realistic routing decision as it ensures that a zone's PL is visited only after fulfilling the demand of the customers assigned to it. To illustrate this concept, consider a situation where multiple missed deliveries occur at various customer locations within a single zone (recall that a PL and the customers assigned to it form a zone). The vehicle should not be permitted to travel to the PL before visiting all the required customers. This is important because there may be several missed deliveries at different customer locations, which could lead to the need for additional visits to the same PL.

4.2 Additional Model Assumptions

This model is a variant of TVRPCR where missed deliveries are integrated. In addition to the assumptions in Section 3.2, we include the following assumptions:

Assumption 7: A missed delivery can only occur at a delivery customer node. It cannot occur at a pickup customer because their demand has already been redirected to the PL for customers' self-pickup.

Assumption 8: When the customer is not at home, it is not permitted to leave the package outside. This is a security precaution against "porch pirating," which would result in the loss of packages and dissatisfied customers.

Assumption 9: There is enough capacity at a PL for a potential missed delivery at a customer assigned to that PL.

Assumption 10: Customers whose packages could not be delivered (due to a missed delivery) always pick up their packages from the PL they are assigned to.

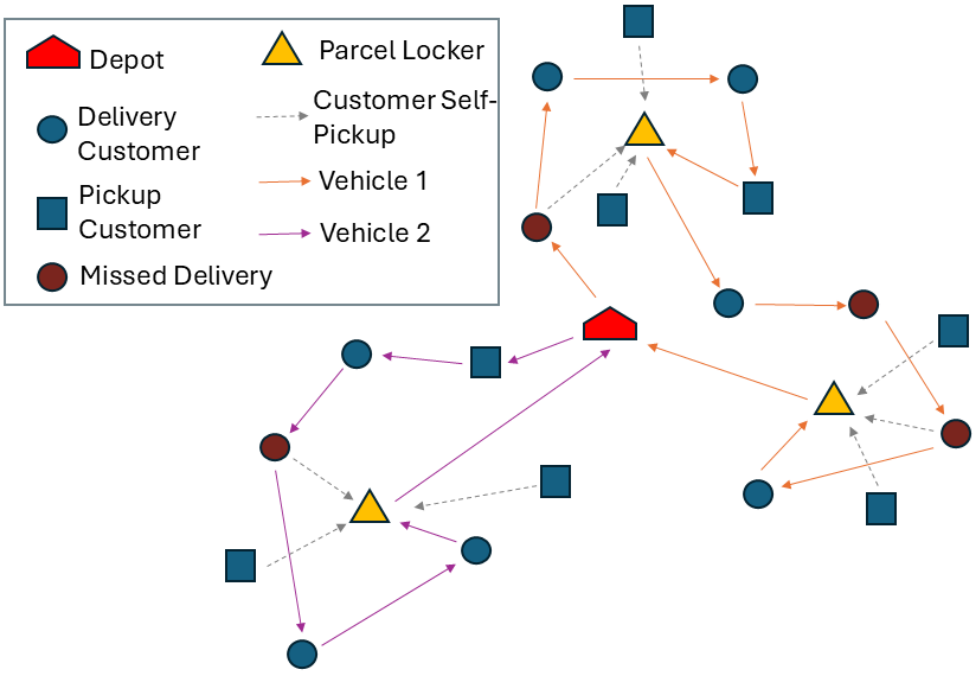


Figure 12. Illustration of the problem in the presence of missed deliveries

4.3 A Variant of TVRPCR: Green VRP with Missed Deliveries (GVRPMD)

Model TVPRCR can be modified by including the following conditions to integrate missed deliveries. We call this new variant of the problem GVRPMD. It is the extended version of TVRPCR, and the results of this study will be based on the output of GVRPMD.

Table 9. Extended model: additional sets

Sets	Description	Range
S	Generated scenarios for missed deliveries	$S = \{1, \ldots, s\}$, $\lvert S \rvert = s$

Table 10. Extended model: additional parameters

Symbol	Description
m_{is}	1, if missed delivery occurred at the customer node i in scenario s; 0, otherwise

Table 11. Extended model: decision variables

Symbol	Description	Variable Type
The following decision variable is removed:		
V_{ik}	Load of vehicle k after visiting node i	Non-negative
The following decision variable is added:		
V_{iks}	Load of vehicle k after visiting node i in scenario s	Non-negative

The objective function of TVRPCR in Chapter 3 is updated as equation (29) for integrating missed deliveries. We minimize the TC across all generated scenarios. TOC calculation is not affected by different scenarios since it does not include any related variables that depend on a set of scenarios. Therefore, only TEC is divided by the number of scenarios.

$$\text{Min } TC = \frac{1}{s} W_E TEC + W_O TOC \tag{29}$$

$$TEC = \varepsilon(TE) \tag{30}$$

Equation (8) from Chapter 3 is removed:

$$TE = \sum_{j\in N}\sum_{i\in N}\sum_{k\in K}\frac{F_{co_2} X_{ijk} d_{ij}}{M_k} + \sum_{k\in K} P_{co_2} V_{0k} +$$

$$S_{co_2}\left(\frac{S_{max}}{S_k} w_p \sum_{j\in N}\sum_{\substack{i\in N \\ i\neq j}}\sum_{k\in K} X_{ijk}\, d_{ij}\, V_{ik}\right)$$

The following equation is added:

$$TE = s \sum_{j\in N}\sum_{i\in N}\sum_{k\in K}\frac{F_{co_2} X_{ijk} d_{ij}}{M_k} + \sum_{s\in S}\sum_{k\in K} P_{co_2} V_{0ks} +$$

$$S_{co_2}\left(\frac{S_{max}}{S_k} w_p \sum_{s\in S}\sum_{k\in K}\sum_{j\in N}\sum_{i\in N} X_{ijk}\, d_{ij}\, V_{iks}\right) \tag{31}$$

Constraint (15) from Chapter 3 is removed:

$$V_{jk} \geq V_{ik} - q_j + r_j + Q_k X_{ijk} - Q_k, \forall\, k \in K, i, j\ (i \neq j) \in N$$

The following constraints are added:

$$V_{jks} \geq V_{iks} - q_j(1 - m_{js}) + r_j(1 - m_{js}) + Q_k X_{ijk} - Q_k, \forall k \in K, i (i \neq j) \in N, j \in C_{DP}, s \in S \quad (32)$$

$$V_{pks} \geq V_{iks} - q_p + r_p - \sum_{h \in C_D} m_{hs} y_{hp} q_h + Q_k X_{ipk} - Q_k, \forall p \in P, s \in S, k \in K, i, \in N (i \neq p) \quad (33)$$

Constraints (32) and (33) ensure the accurate tracking of the vehicle load in consideration of missed deliveries. Specifically, constraint (32) indicates that the delivery demand of a customer is only deducted from the vehicle's load if they are present at their home address (no missed delivery occurred). However, it is only valid for delivery customers who ordered their packages to their home address since a missed delivery can only occur to a delivery customer. There cannot be a missed delivery at pickup customer nodes since their packages will be delivered to the nearest PL, and they are only visited when they request a return from their home address. Also, there cannot be a missed delivery at PL facilities. Therefore, constraint (33) is added to keep track of the vehicle load for pickup customer nodes and PL facilities. It ensures that the delivery demand of an absent customer (missed delivery occurred) is deducted from the vehicle's load at the PL to which they are assigned.

Constraint (29) from Chapter 3 is updated as:

$$V_{iks}, u_i, e_{ik}, l_{ik}, TE, TOC \geq 0, \forall k \in K, i \in N \quad (34)$$

4.4 Data Generation

Due to the lack of real-life data for the specific problem we are considering, we generated realistic data for each parameter defined in the mathematical model based on existing knowledge. We developed a Python code to generate a randomized distance matrix, as shown in Table 12. The distance values accurately reflect and simulate real-life distances, considering that we emphasize the last-mile logistics of the B2C e-commerce industry. The 20 nodes in the distance matrix involve the depot, PLs, delivery customers, and pickup customers. The values in the matrix vary between 0.8 and 2.5 miles (excluding the depot).

Table 12. Distance matrix (20 nodes)

Distance	Depot	C_D	C_D	C_D	C_D	C_D	C_D	C_P	C_P	C_P	PL	C_P	C_P	C_P	C_P	C_P	C_D	C_D	C_D	PL
Depot	0	4	4	4.2	4.2	4	4.2	4.8	4	4.8	4.5	4	4	4.2	4.2	4	4	4.2	4.2	4.5
C_D	4	0	2	1.2	1	2.2	1.8	1	2.2	1.2	1	2.5	1.2	2.5	1	2.5	2.5	0.8	2.5	2.2
C_D	4	2	0	2	2.2	1	2.5	2.5	1	2.5	2.2	1	2.5	1.2	2.5	1	0.8	2.5	0.8	1
C_D	4.2	1.2	2	0	1	2.5	2.5	1.5	2.5	1	1	2.5	1.2	2.5	0.8	2.5	2.5	1	2.5	2.2
C_D	4.2	1	2.2	1	0	2.5	2.5	1	2.5	1.5	1	2.5	1	2.5	0.8	2.5	2.5	1	2.5	2.2
C_D	4	2.2	1	2.5	2.5	0	0.8	2.5	1.2	2.5	2.2	1	2.5	1.2	2.5	0.8	1	2.5	0.8	1
C_D	4.2	1.8	2.5	2.5	2.5	0.8	0	2.5	2.5	1.2	2.2	0.8	2.5	2.5	2.5	1	1.2	2.5	1	0.8
C_P	4.8	1	2.5	1.5	1	2.5	2.5	0	2.5	1	1.2	2.5	0.8	2.5	1	2.5	2.5	0.8	2.5	2.2
C_P	4	2.2	1	2.5	2.5	1.2	2.5	2.5	0	1.2	2.2	1	2.5	1	2.5	0.8	0.8	2.5	0.8	1
C_P	4.8	1.2	2.5	1	1.5	2.5	1.2	1	1.2	0	1.2	2.5	1	2.5	1	2.5	2.5	1	2.5	1.2
PL	4.5	1	2.2	1	1	2.2	2.2	1.2	2.2	1.2	0	2.2	1.2	2.2	1	2.5	2.5	1	2.5	2.2
C_P	4	2.5	1	2.5	2.5	1	0.8	2.5	1	2.5	2.2	0	2.5	0.8	2.5	1	1.2	2.5	0.8	1
C_P	4	1.2	2.5	1.2	1	2.5	2.5	0.8	2.5	1	1.2	2.5	0	2.5	0.8	2.5	2.5	1	2.5	2.2
C_P	4.2	2.5	1.2	2.5	2.5	1.2	2.5	2.5	1	2.5	2.2	0.8	2.5	0	2.5	1	0.8	2.5	0.8	1
C_P	4.2	1	2.5	0.8	0.8	2.5	2.5	1	2.5	1	1	2.5	0.8	2.5	0	2.5	2.5	0.8	2.5	2.2
C_P	4	2.5	1	2.5	2.5	0.8	1	2.5	0.8	2.5	2.5	1	2.5	1	2.5	0	1	2.5	1	0.8
C_D	4	2.5	0.8	2.5	2.5	1	1.2	2.5	0.8	2.5	2.5	1.2	2.5	0.8	2.5	1	0	2.5	1	0.8
C_D	4.2	0.8	2.5	1	1	2.5	2.5	0.8	2.5	1	1	2.5	1	2.5	0.8	2.5	2.5	0	2.5	2.2
C_D	4.2	2.5	0.8	2.5	2.5	0.8	1	2.5	0.8	2.5	2.5	0.8	2.5	0.8	2.5	1	1	2.5	0	0.8
PL	4.5	2.2	1	2.2	2.2	1	0.8	2.2	1	1.2	2.2	1	2.2	1	2.2	0.8	0.8	2.2	0.8	0

The travel time matrix is correlated with the distance matrix, as travel times are directly proportional to distance. To calculate realistic travel times between each node, we use the formula ($X/V = t$), where X is the distance, V is the vehicle's speed, and t is time. However, these travel times do not account for potential delays between nodes. To address this, we generated a delay matrix, which incorporates delays that may arise from factors such as traffic congestion. The values in the delay matrix are less than those in the travel time matrix, as we assume that the delay duration between two nodes should logically be shorter than the travel time itself. Consequently, we divided each value in the travel time matrix by 5 to create the delay matrix. We assigned service times for each node, giving customer nodes a service time of 1.5 minutes, while PLs have service times ranging from 3 to 4 minutes.

For the delivery demand data, we assumed that delivery and pickup customers could order a maximum of three packages online. In contrast, research indicates that return demand is significantly lower than delivery demand. Consequently, in the model, the values for return demand are limited to a maximum of one package (excluding PLs).

The delivery vehicles commonly used for e-commerce operations in urban areas are typically medium-sized cargo vans, such as the Ford Transit Cargo and the Mercedes Sprinter Cargo Van, as shown in Figure 11 (Car and Driver, 2024).

The proposed model involves three delivery vehicles with different sizes, capacities, and types. While these vehicles may have slightly different specifications, we have gathered values for several vehicle-related parameters based on a typical delivery vehicle used in B2C e-commerce operations.

As of October 2024, one litre of gasoline in Canada costs $1.75 (GlobalPetrolPrices, 2024). Since one gallon of gas is approximately 4.5 litres, the price of one gallon is about $7.88. Considering that a typical delivery vehicle can travel approximately 7 miles per gallon of gasoline (M_k), the fuel cost of travelling one mile for this type of vehicle is approximately $1.125 (U.S. Department of Energy, 2024). The fixed cost of this type of delivery van is assumed to be around $4 per hour.

According to the United States Environmental Protection Agency, the combustion of one gallon of gasoline emits approximately 23.3 pounds of CO_2 (F_{co_2}) (EPA, 2014). A typical urban delivery truck emits 0.14 lbs of CO_2 per cwt-mile (S_{co_2}) (Ragon & Rodriguez, 2021). For the purposes of this analysis, we assume that the maximum allowed speed within city limits is 31 miles per hour, while the average speed of delivery vehicles is around 20 miles per hour (Wikimedia Foundation, 2024). All packages considered in this problem are assumed to be identical in weight and volume. It is estimated that the corrugated

box needed to package an average-sized e-commerce product weighs around 0.5 pounds, leading to a packaging emissions factor (P_{co_2}) of approximately 0.848 pounds of CO_2 per package (Ülkü, 2012). Lastly, the hourly wage for a courier is estimated to be about $21.10 (Indeed, 2024). These parameters will be used to calculate CO_2 emissions and operational costs in the proposed model. Table 13 summarizes the values assigned to each parameter.

Table 13**.** Parameter values

Symbol	Description	Measure
Distance Parameter		
d_{ij}	The distance matrix is generated randomly between the values 0.8 to 2.5 (except the depot)	mile
Demand Parameters		
q_i	Delivery demand can take values from 0 to 3	Unit-sized package
r_i	Return demand can take values from 0 to 1	Unit-sized package
Time Parameters		
t_{ij}	The time matrix is proportional to the distance matrix	minute
$delay_{ij}$	Delay matrix is proportional to the time matrix	minute
T_{max}	120	minute
s_i	1.5 to 4	minute

Capacity Parameters		
Q_k	22	Unit-sized package
Cost Parameters		
f_k	1.125	$ / mile
F_k	3 - 4	$ / hour
L_c	21.10	$ / hour
ε	0.041	-
Emission Parameters		
F_{co_2}	23.3	lbs
M_k	7	mile
P_{co_2}	0.848	lbs
S_{co_2}	0.14	lbs/cwt-mile
S_k	20	mile/h
S_{max}	31	mile/h
w_p	0.02	cwt
Other Parameters		
M	150	-

4.5 Chapter Summary

Chapter 4 defined and discussed missed deliveries in B2C e-commerce operations. In this chapter, we develop GVRPMD by adding new constraints and adjusting existing ones to integrate missed deliveries into TVRPCR. To achieve this integration, we adopted a scenario-based approach, generating different scenarios based on a missed delivery probability for each customer. The objective function has also been updated to minimize the TEC and TOC across all scenarios. It is proposed that when a missed delivery occurs at a delivery customer location, their package will be redirected to the assigned PL. The model ensures that the PL for a given zone is visited only after all assigned customers in that zone have been served. This way, missed deliveries and packages for customer pickup will be delivered to the nearest PL, which serves as the final stop in the zone. Customers can then pick up their packages from the PL. This ensures that the developed model is practical and considers the worst-case scenario. Consequently, GVRPMD employs PLs to develop a last-mile logistics network that addresses e-commerce home deliveries, customer returns, and missed deliveries, filling a significant gap in the DCL literature.

CHAPTER 5: Results and Discussion

This section presents and discusses the results of the proposed last-mile logistics network (GVRPMD) for B2C e-commerce operations in cities. By developing a mathematical model, this study proposes a sustainable network that can reduce these operations' environmental and economic impact while benefiting society and culture. The model's outcome involves crucial operational decisions such as customer assignments to PLs, vehicle fleet composition, time windows, and optimal routes for delivery vehicles. Based on the model's results, the GVRPMD is evaluated in terms of its feasibility, sustainability, and effectiveness. The insights drawn from the results can guide practitioners and policymakers in managing last-mile logistics in urban areas.

5.1 An Illustrative Case: Optimal Network Design for GVRPMD

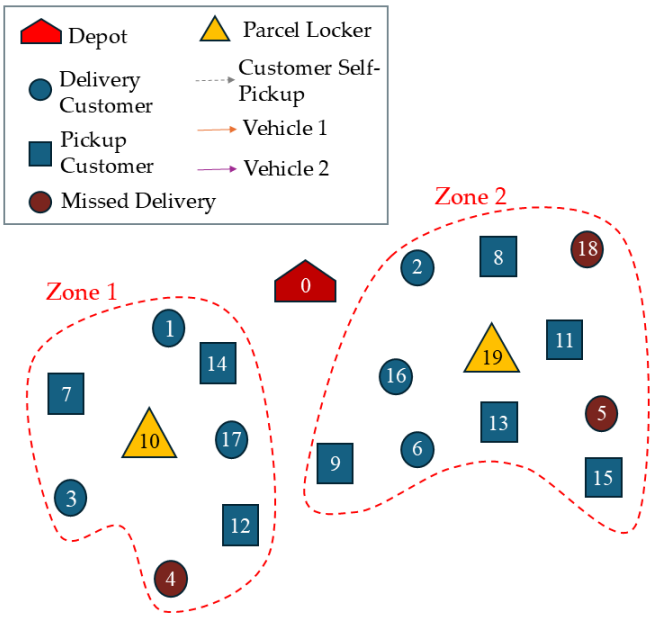
Given the challenges associated with B2C e-commerce last-mile operations, improving sustainability in terms of all QBL aspects is crucial. The optimal design of this distribution network is the key to achieving sustainability. In that sense, this study aimed to propose a sustainable network by developing a two-stage mathematical model. In this section, we present and analyze the results of the proposed model through an illustrative example.

Consider that Amazon, the largest e-commerce company in the world, decided to implement GVRPMD proposed in this thesis for its last-mile operations in a certain city. For operations in that city, assume that Amazon has a depot, three available vehicles and two PLs.

After receiving online orders and requests from 17 customers, Amazon transported customers' packages to the depot from off-city limits. The department responsible for the last-mile operations used the customers' addresses to generate the distance matrix, which involves the distances between each node (including customers, PLs, and depot). The customers are divided into two groups: Delivery customers and pickup customers. Delivery customers choose to have their package delivered to their home address. On the other hand, pick-up customers requested to self-pick up their package from the nearest PL. For that specific day and area, there are nine delivery customers and eight pickup customers to be served by Amazon. Some customers also requested to return a package they ordered in the previous weeks. Upon checking the details of the return requests, the department manager observed that some customers asked for their package return to be picked up from their home location. In contrast, some of them had already dropped off their return package to the PL that they are assigned to (assuming Amazon offers these services in that region).

By executing the stage-I model (DDZCAP) proposed in Chapter 3 using all the required input, the department manager assigned each customer to their nearest PL. Additionally, the demand from each pickup customer was allocated to their assigned PL. The output generated from this stage-I model will serve as input for the stage-II model. Consequently, in the GVRPMD, the delivery demand of the pickup customers will be recorded as zero because their delivery will be handled directly by their assigned PL.

Figure 13 illustrates the designation of each node as either a delivery customer, pickup customer, PL, or depot, along with the zones formed by the assignment of each customer to the respective PLs. Note that although only pickup customers pick up their packages from the PLs, delivery customers are also assigned to a PL. The reason for this is to manage missed deliveries as in the proposed network (when a missed delivery occurs to at a customer, their package will be delivered to the PL that they are assigned to).



Customer Assignments to Parcel Lockers		Parcel Lockers	
		10	19
Delivery Customers	1	✓	
	2		✓
	3	✓	
	4	✓	
	5		✓
	6		✓
	16		✓
	17	✓	
	18		✓
Pickup Customers	7	✓	
	8		✓
	9		✓
	11		✓
	12	✓	
	13		✓
	14	✓	
	15		✓

Figure 13. Customer assignments to the parcel lockers

After completing the customer assignments to PLs and obtaining the finalized demand data from the stage-I model, the manager inputs all necessary information and runs the GVRPMD. The manager checks the output of the model, observing the decided vehicle route composition, routes for each vehicle decided to be used, and the time windows for visiting each customer.

The manager uploads the delivery time windows determined by the model to Amazon's system. This ensures that each customer receives a notification on their mobile device informing them of the time window for their package delivery. Notifications are sent to customers the day before their package is scheduled to be delivered. Tables 14 and 15 show the time windows for each node to be visited.

The route's total completion time when two vehicles are used is around 50 minutes. However, in practice, a daily operation tends to last much longer. This is because the small-scale example discussed in this section involves 20 nodes to show the mechanics of the GVRPMD rather than solving it for large instances.

Table 14. Time windows for nodes visited by vehicle 1

Visited Nodes (Vehicle 1)	Time Window	
	Earliest Arrival	Latest Arrival
Node 1	09:12	09:14
Node 17	09:16	09:18
Node 12	09:20	09:23
Node 4	09:25	09:29
Node 3	09:29	09:34
Node 10 (PL)	09:34	09:39
Depot	09:49	09:56

Table 15. Time windows for nodes visited by vehicle 2

Visited Nodes (Vehicle 2)	Time Window	
	Earliest Arrival	Latest Arrival
Node 16	09:12	09:14
Node 2	09:16	09:18
Node 18	09:20	09:23
Node 5	09:24	09:27
Node 6	09:28	09:32
Node 19 (PL)	09:32	09:36
Depot	09:48	09:54

Subsequently, the manager uploads the routes for two delivery vehicles selected for use by GVRPMD. On the next day, both vehicles depart from the depot, carrying the total delivery demand of the nodes they are scheduled to visit. The routes of both vehicles 1 and 2 are shown in Figure 14. Vehicle 1 begins its

route by entering Zone 1 and visiting Node 1, a delivery customer, at 09:13 AM. Following this stop, Vehicle 1 proceeds to Node 17 and then Node 12, where it delivers packages and collects any return requests from customers, if applicable.

When Vehicle 1 arrives at Node 4 (the customer's delivery address) at 09:27, the courier notices that the customer is not home. As a result, the courier loads the package back into the vehicle. The package for the customer at Node 4 will now be delivered to the assigned PL assigned to them (Node 10), where they can easily collect it. After visiting Node 3 and serving the customer, vehicle 1 travels to the PL (Node 10) as the final node of that zone before returning to the depot. Upon arriving at the PL at 09:36, the courier collects the package returns dropped off by the customers who chose to return their products through this PL. The courier then loads these returned packages onto the vehicle. Next, they unload several packages intended for multiple pickup customers, including the package of Node 4, which belongs to a customer who missed their delivery and is assigned to this PL. The courier organizes each package into the designated containers and updates the order statuses to notify customers that their packages are ready for pickup. Finally, vehicle 1 returns to the depot at 09:53, carrying only the package returns collected from the pick-up locations and customer nodes. Vehicle 2 follows the same process simultaneously despite having a different route and serving zone

2. This finalizes the day, and the department can evaluate the results of the network proposed in this study.

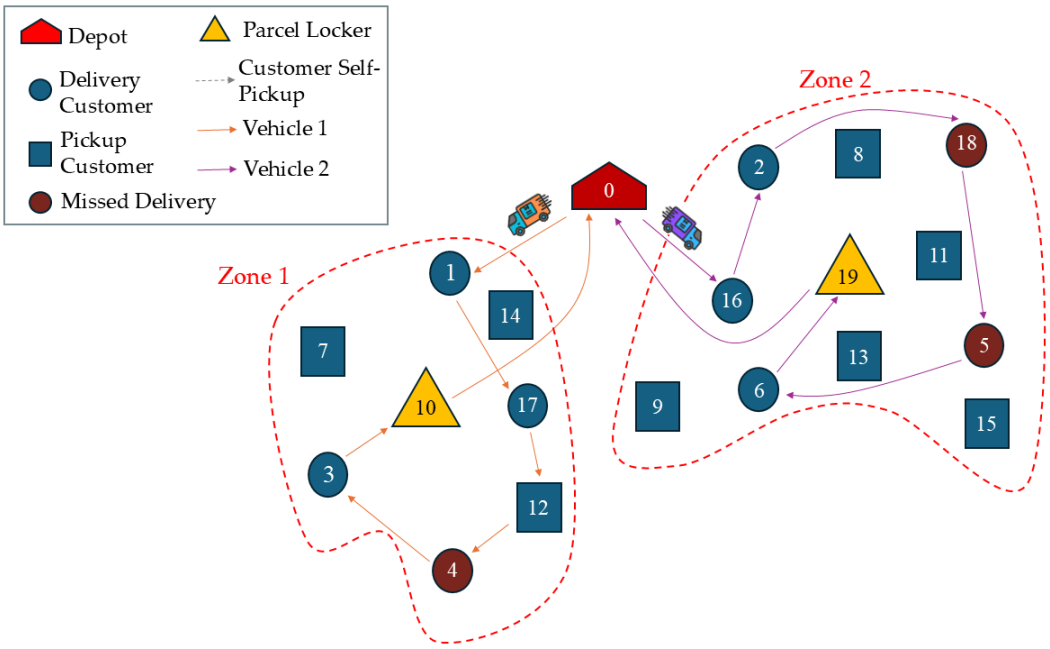


Figure 14. Routes of vehicles 1 and 2 based on GVRPMD

5.2 Economic Evaluation

To assess the sustainability of GVRPMD, an additional mathematical model was created for benchmarking the results. In this section, we compare the economic outcomes of both models. Figure 14 illustrates the vehicle routes generated by the GVRPMD presented in this thesis, while Figure 15 displays the routes for the benchmark model. The benchmark model represents the operations where missed delivery packages are returned to the depot as in current practice. Therefore, in

the benchmark model, when a missed delivery occurs, the customer travels to the depot to retrieve their packages.

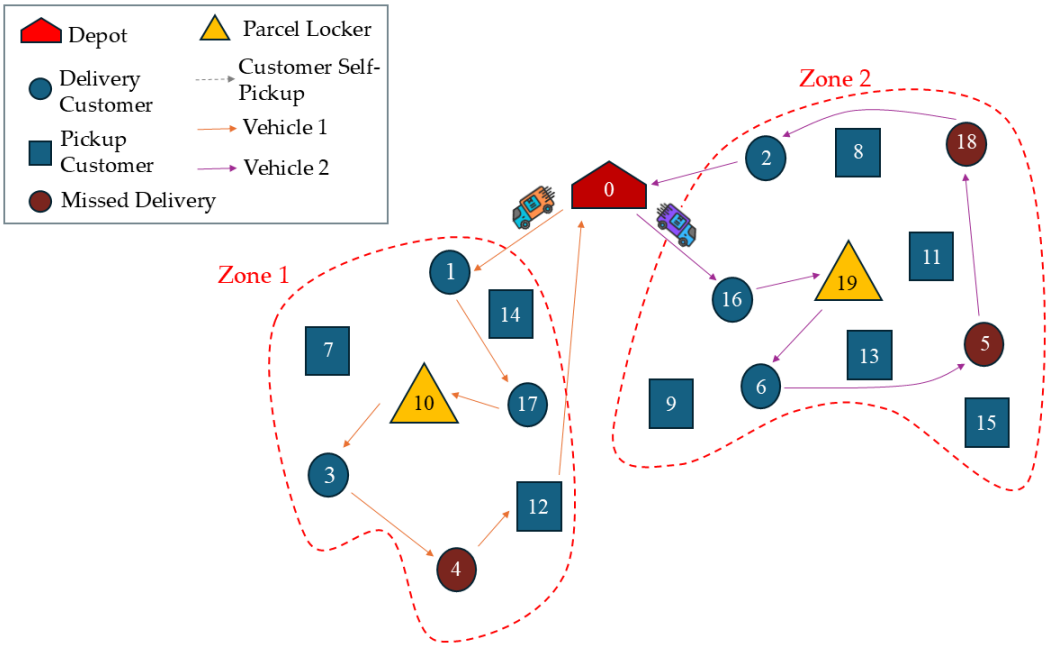


Figure 15. Routes of vehicles 1 and 2 based on benchmark model

The models produce daily results. We converted these results into annual values to provide a more meaningful observation. Figure 16 shows the comparison of the two models in terms of TOC. Based on the routing decision illustrated in Figure 14, the results of GVRPMD show that the expected total operating cost (TOC) is $247,105. This amount is comprised of three different sources of costs. The annual fuel cost is calculated at $92,710, which is determined by the total distance travelled and the vehicle's average mileage. Labour cost was found to be

$132,495, where each courier has an hourly wage of $21.10. Finally, the total fixed cost of the vehicles was $21,900. On the other hand, the TOC of the benchmark model, where the vehicles follow the routes given in Figure 15, is $271,670. This indicates that GVRPMD can potentially reduce the TOC by 9%. Figure 16 shows that fuel cost is higher in the benchmark model, mainly due to the increase in the total distances travelled by the vehicles. Considering these, the proposed network is more economically sustainable. Note that TEC and TOC calculations of the benchmark model involve missed delivery customers' travel to the depot to retrieve their items. We considered that customers' passenger vehicles use less fuel than delivery vehicles. The difference between GVRPMD and the benchmark model is how they handle missed deliveries. This comparison quantifies the benefits of integrating missed deliveries.

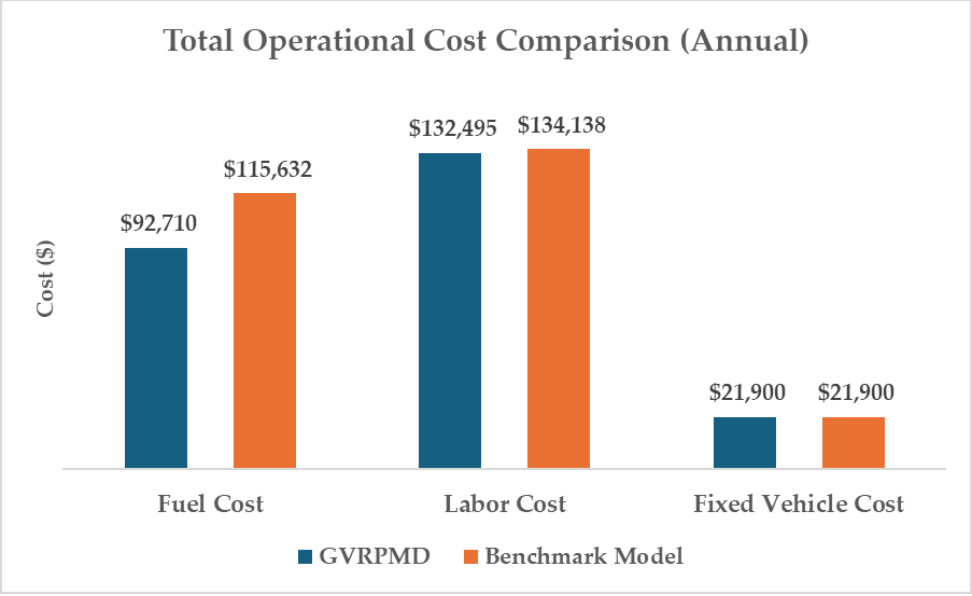


Figure 16. Total operational cost comparison of two models

5.3 Environmental Evaluation

This thesis highlights the importance of DCL in the face of the climate crisis. For that reason, one of the objectives of the proposed model is to minimize TEC. To evaluate the GVRPMD regarding environmental sustainability, we compared its result with the benchmark model. Figure 17 demonstrates the expected total of CO_2 emitted as a result of each model.

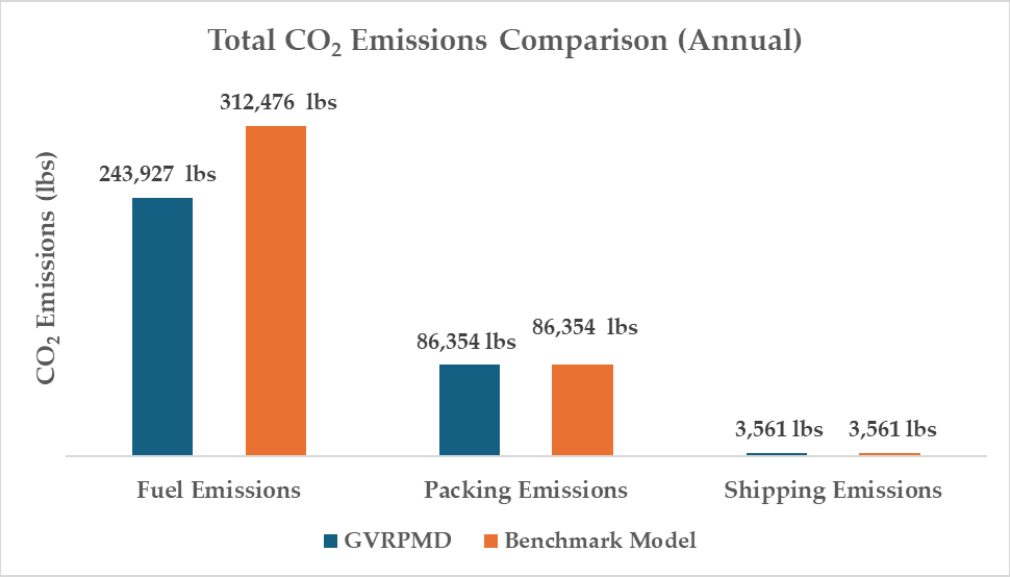


Figure 17. Expected total CO_2 emitted in GVRPMD and Benchmark models

According to Figure 17, the anticipated annual total of CO_2 emissions by applying GVRPMD is 333,841 pounds. The total CO_2 emissions depend on three factors, with the fuel burned by the delivery vehicles contributing 243,927 pounds of CO_2. It can be observed that fuel emissions account for the majority of the emissions and depend primarily on the total travel distance. The production of the

corrugated boxes used for packing the delivery items is expected to emit 86,354 lbs of CO_2. This indicates that finding a more efficient way of packing the products can potentially reduce the emissions. Finally, the distance travelled by the vehicle while loaded with the customers' packages (shipping emissions) is expected to emit 3,561 lbs of CO_2 throughout the year.

On the other hand, the total expected CO_2 emissions when the benchmark model is implemented (GVRPMD not utilized) is 402,390 lbs. Recalling that this amount was 333,841 lbs with GVRPMD, this indicates a 17% reduction in CO_2 emissions. Fuel consumption accounts for most of the CO_2 emissions and depends on the total distance travelled by the vehicles. Considering that this is only the result of a small-scale problem involving 20 nodes, implementing GVRPMD can significantly improve the overall environmental sustainability of B2C e-commerce operations worldwide.

5.4 Social Evaluation

In developing the mathematical model, we also aimed to promote social sustainability. As a result, the GVRPMD has significant potential benefits for people living in urban areas. Reduction in CO_2 emissions can improve air quality, an important issue threatening public health. According to the World Health Organization, air pollution can cause various health issues, including cancer

(WHO, 2024). Thus, the proposed model can potentially improve the well-being of society.

The impacts of CC are intensifying and becoming more widespread. Extreme temperatures around the world negatively influence city dwellers' well-being. Solutions such as those in this study can pace down CC and its consequences by reducing GHGs. Freight transportation in city logistics increases traffic congestion and noise pollution. Traffic congestion impacts the accessibility of the public by increasing travel times and giving rise to accidents. GVRPMD can potentially reduce traffic congestion and noise pollution.

The proposed network can also improve the service provided to the customers. They are offered two options (home delivery or self-pickup from the nearest PL). They can also return their packages by either requesting them picked up from their home or dropping them off at the nearest PL. This gives the customer enhanced flexibility for their delivery and return demands. Furthermore, if a delivery customer is not at home when their delivery arrives, their package is delivered to the nearest PL to them, from which they can pick up when they are available. This prevents the customer from having to travel to the depot or a post office to collect their packages, which can be much farther than the PL. Considering these, GVRPMD can provide a more socially sustainable environment for city dwellers.

5.5 Cultural Evaluation

While developing the mathematical models, this study considered the different lifestyles of individuals associated with their cultures. In the context of B2C e-commerce operations, the cultural aspects of the customers have a significant influence and are crucial to consider (Toktaş et al., 2024). For instance, customers in different regions might reside in townhouses or apartments, reflecting their cultural lifestyles. In Canada, townhouses are highly common, influencing the operational decisions of e-commerce companies. When a customer living in a townhouse is absent at the time of package delivery, the courier typically either leaves the package in front of the door or returns it to the depot. Leaving the package outside raises safety concerns due to the risk of porch piracy and potential loss. This relates directly to the culture of a region, as porch pirating may be a significant problem in some neighbourhoods, whereas, in others, it may be rare. On the other hand, returning the package to the depot results in inconvenience for the customer, who either must travel to retrieve it or wait longer for a rescheduled delivery. In either scenario, customer satisfaction is negatively influenced. However, implementing the network proposed in this study can potentially address these issues by ensuring that a missed package is delivered to the nearest PL for the customer. Therefore, GVRPMD considers cultural factors and aligns with people's values.

In some cultures, people may prefer to spend more time outdoors than at home, which varies between cultures. These preferences can be related to cultural norms. From the perspective of B2C e-commerce operations, if customers in a particular area tend to be outside more often, it can lead to more missed deliveries since they may not be home to receive their packages. Additionally, the likelihood of missed deliveries may be higher, say in living areas, where working in an office is more common than remote work. The demographic structure of a region can also impact missed deliveries. In cultures with low birth rates and a higher proportion of older adults than younger individuals, the number of missed deliveries might be lower, as older and retired people tend to spend more time at home. All these factors are essential to consider when developing solutions (Liu et al., 2023). GVRPMD effectively manages missed deliveries and reduces their impact by acknowledging and respecting cultural differences. Thus, practitioners and policymakers can consider the implementation of this network, especially in these areas, to effectively manage missed deliveries.

One of the novelties of this thesis lies in integrating the package returns, which is a gap in the DCL literature. Enabling package returns is an essential service offered to customers, but it has an impact on the environment and economy. As discussed in Chapter 2, customers can return items for various reasons. The amount and reason for the return demand in an area can be related

to some cultural aspects. For instance, customers living in a specific region might be culturally more meticulous about the items they own. In that case, it is more likely that they will return an item they ordered if it has any defects or does not meet their expectations. On the other hand, customers living in another area can be more careless and may choose not to return an item although it has a minor defect or does not entirely satisfy them. These were considered in the development of the proposed solutions, which allow customers to return their packages flexibly from their homes or through the nearest PL.

The acceptance of new technologies may also vary depending on cultural norms and the mindset they create. People belonging to a particular culture may be more open to emerging technologies, leading to easier adoption. On the other hand, individuals from other cultures may not be receptive to changes in their lives, such as using new technologies. For example, cultures with an older population may struggle to adapt to new technologies, whereas cultures with a younger population may find this adaptation easier. The proposed network in this study involves the use of PLs by e-commerce companies and their customers. However, if the people living in an area of operation do not have a positive attitude toward new technologies due to their culture and mindset, the proposed network may not be as effective as expected. Therefore, we also included drop-off points such as stores in our PL definition. This would enhance the service provided to

individuals who do not prefer to engage with new technologies. We advise practitioners and policymakers in the e-commerce industry to consider these factors while making decisions.

5.6 Sensitivity Analysis

Understanding the sensitivity of critical factors in B2C e-commerce operations is essential for making effective decisions when designing an optimal network. In this section, we perform a comprehensive sensitivity analysis to examine how changes in these critical factors affect the sustainability (QBL) of the suggested network. Our goal is to provide valuable insights that can support practitioners and policymakers in this industry.

We examined the TOC and TEC with varying numbers of customers, as given in Table 16. In a scenario with a total of 20 nodes, which includes nine delivery customers, eight pickup customers, two PLs, and the depot, the total amount of CO_2 emitted is 91.5 lbs. On the other hand, when 15 and 10 nodes are defined in the network, the total amount of CO_2 emitted is 73.7 lbs and 60.2 lbs, respectively. Figure 18 illustrates the breakdown of the CO_2 emissions for each case. The comparison between 20-node, 15-node and 10-node cases indicates that the number of customers visited influences total emissions, mainly due to the total distances travelled and packing emissions. Note that the calculations are based on

a small number of customers visited within less than an hour. In reality, an e-commerce delivery vehicle serves approximately 180 customers each day and 65,700 customers annually, which would result in significantly higher CO_2 emissions. However, we cannot examine the scenario of serving 180 customers due to the computational complexity of the GVRPMD, which will be discussed in section 4.7.

Table 16. Number and type of nodes served

Number of Nodes	Number of Nodes Served			
	Delivery Customer	Pickup Customer	Parcel Locker	Depot
20 Nodes	9	8	2	1
15 Nodes	6	6	2	1
10 Nodes	3	4	2	1

Figure 19 demonstrates the expenses associated with the fuel, labour, and fixed vehicle costs for each case examined. When 20 Nodes are defined, TOC is estimated at $58. On the other hand, when analyzing 15 and 10 nodes, the TOC is expected to be $47.73 and $37.68, respectively. As the travel distance and working hours increase with the number of nodes visited, fuel and labour costs become higher.

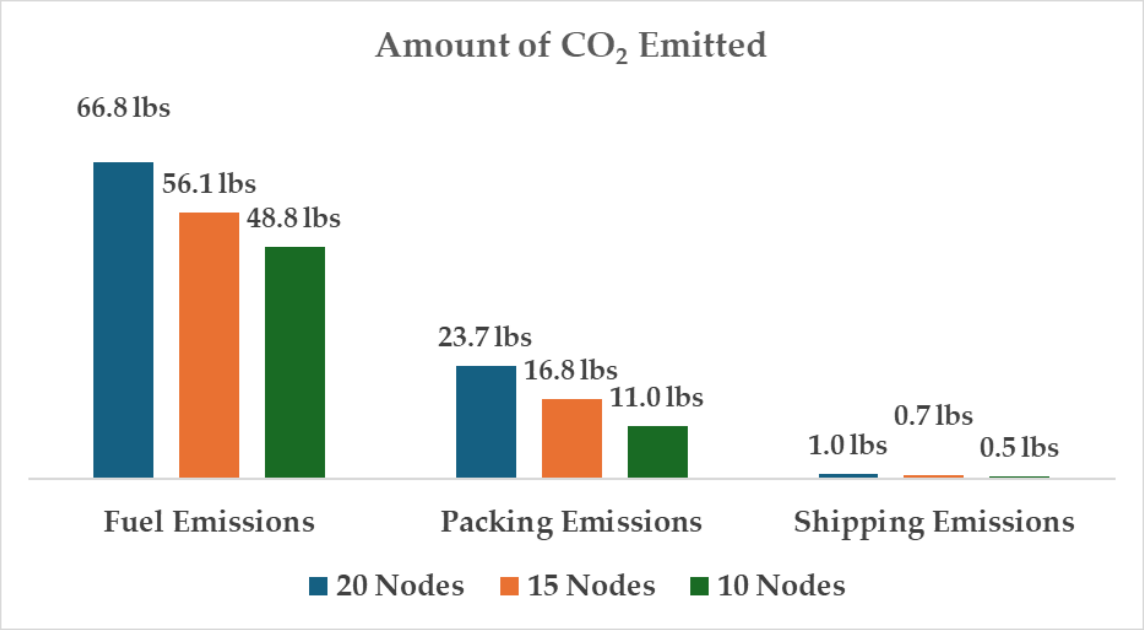


Figure 18. CO_2 emissions in models with different numbers of nodes

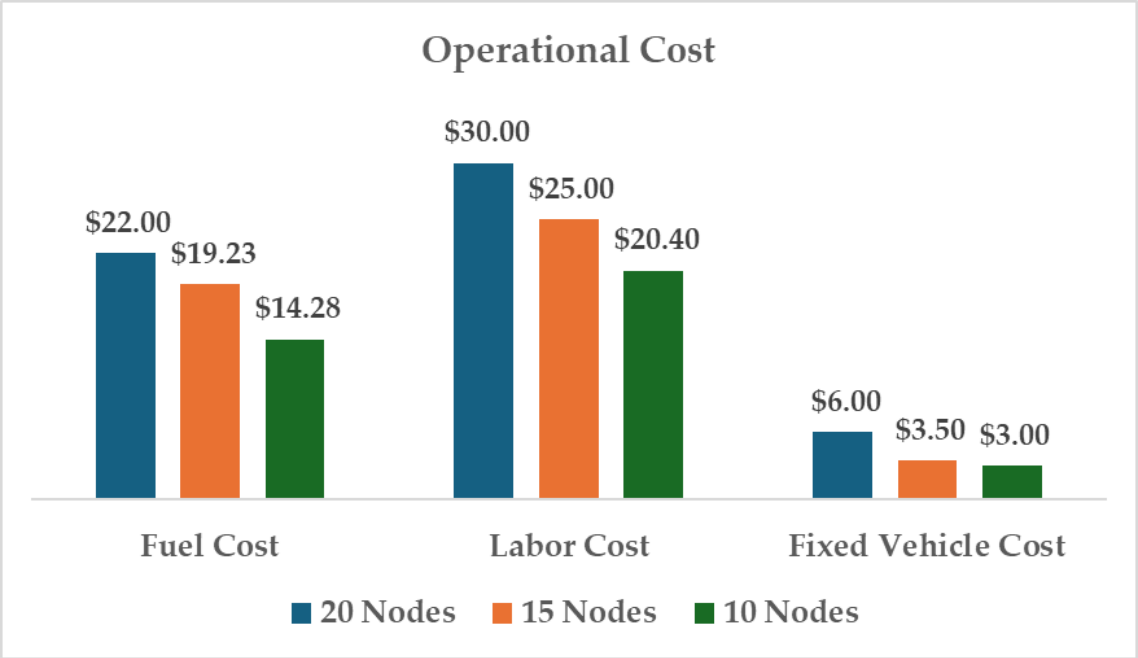


Figure 19. Breakdown of TOC in models with different number of nodes

The network involves three available vehicles with package capacities of 22, 18, and 18 packages. The results indicate that when there are 20 nodes, two vehicles

with an 18-package capacity are required. For 15 nodes, one vehicle with 22 package capacity is sufficient, while for 10 nodes, a single vehicle with 18 package capacity can meet the total customer demand. The costs mentioned are calculated for a smaller number of customers than typically exists in reality. For instance, when 20 nodes were defined in the system, the operation took approximately 50 minutes (for each vehicle), whereas a typical daily operation lasts around 700 minutes. Therefore, the annual operational costs and CO_2 emissions will increase significantly as the problem size increases.

The capacity of the vehicles is a key factor in determining the vehicle fleet composition. Using a network with 20 nodes, we examined how using one or two vans affects the outcome. Figure 20 shows that using one vehicle with a higher capacity is more beneficial regarding environmental sustainability. Using two vehicles also incurs higher operational costs than using one, as shown in Figure 21. Note that in the proposed model, CO_2 emissions are converted to an environmental cost of $0.041 per pound. (Black et al., 2022). This causes the model to make decisions mainly to minimize TOC. Therefore, when the capacity of one vehicle is adequate for the delivery, the model finds it optimal to complete the operation with one vehicle, incurring smaller operational and environmental costs. However, in problems with greater size, an essential trade-off between CO_2 emissions and operational cost could occur. Accordingly, we expect that the

selection of a vehicle fleet composition will be a critical decision made by the model in networks involving higher number of nodes.

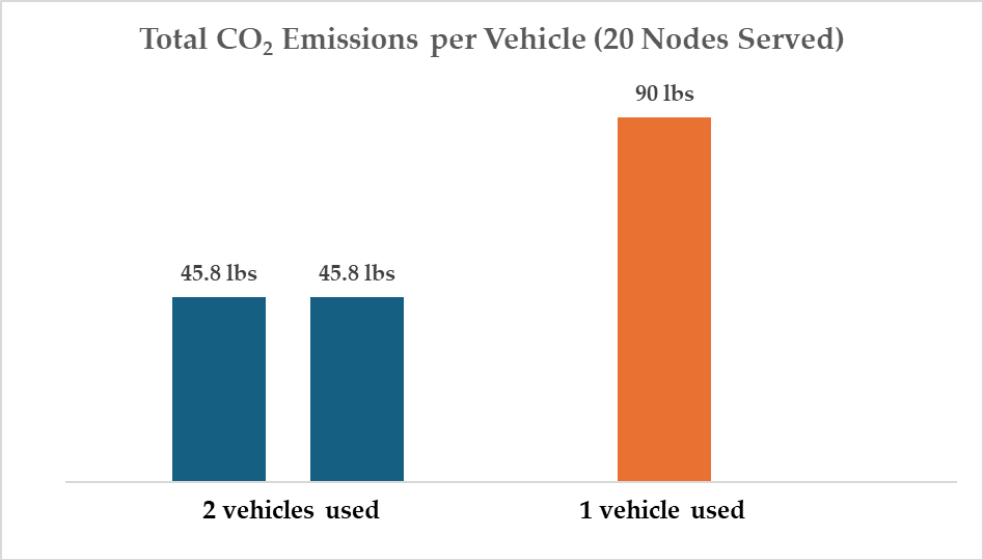


Figure 20. CO_2 emissions based on the number of vehicles used

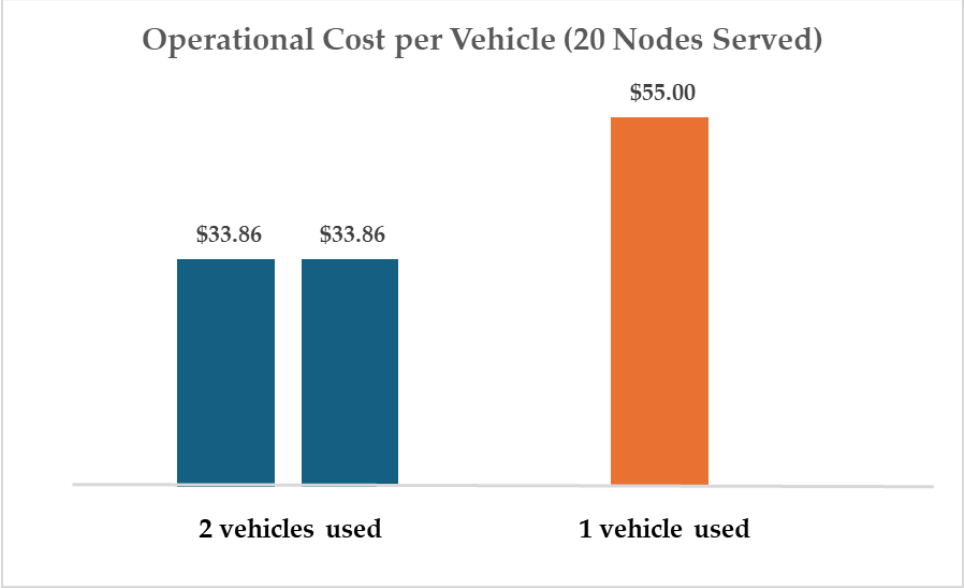


Figure 21. TOC based on the number of vehicles used

Using one vehicle significantly increases route completion time compared to using two vehicles. The results indicate that a tour with 20 nodes takes 84

minutes with one vehicle and 50 minutes with two vehicles. Using one vehicle may result in longer wait times for some customers, while two vehicles can provide much faster service. Considering these, a vehicle fleet consisting of two vehicles can be more socially sustainable for the customers.

As discussed in section 5.5, the number of missed deliveries in a certain area can be related to cultural norms and people's lifestyles. Considering the significant impact of missed deliveries on the environment, economy, and society, we examined the changes in the model results under different missed delivery probabilities. One of the purposes of GVRPMD was to minimize the impact of missed deliveries (aside from package returns). In this regard, we expect the results of the model not to be influenced by the number of missed deliveries. On the other hand, we estimated that the model created for benchmarking, which represents the current way of conducting B2C e-commerce operations in most regions, would be influenced by the increasing probability of missed deliveries. Figure 22 illustrates the total CO_2 emissions resulting from GVRPMD compared to the benchmark model, considering missed delivery probabilities of 0.2, 0.3, and 0.4. Note that this analysis was performed using the model with 20 nodes. According to Figure 22, the total expected CO_2 emissions from implementing the GVRPMD are 91.46 lbs, 91.49 lbs, and 91.51 lbs, given the probabilities of missed delivery at 0.2, 0.3, and 0.4, respectively. On the other hand, in the benchmark

model, total emissions are expected to be 110.24 lbs, 129.27 lbs, and 138.29 lbs using the same set of probabilities. This indicates that GVRPMD is not sensitive to the number of missed deliveries, whereas CO_2 emissions significantly increase in the benchmark model. Therefore, GVRPMD can be effective in regions or cultures where the missed delivery probability is relatively higher. Accordingly, practitioners and policymakers in these regions may consider implementing this model.

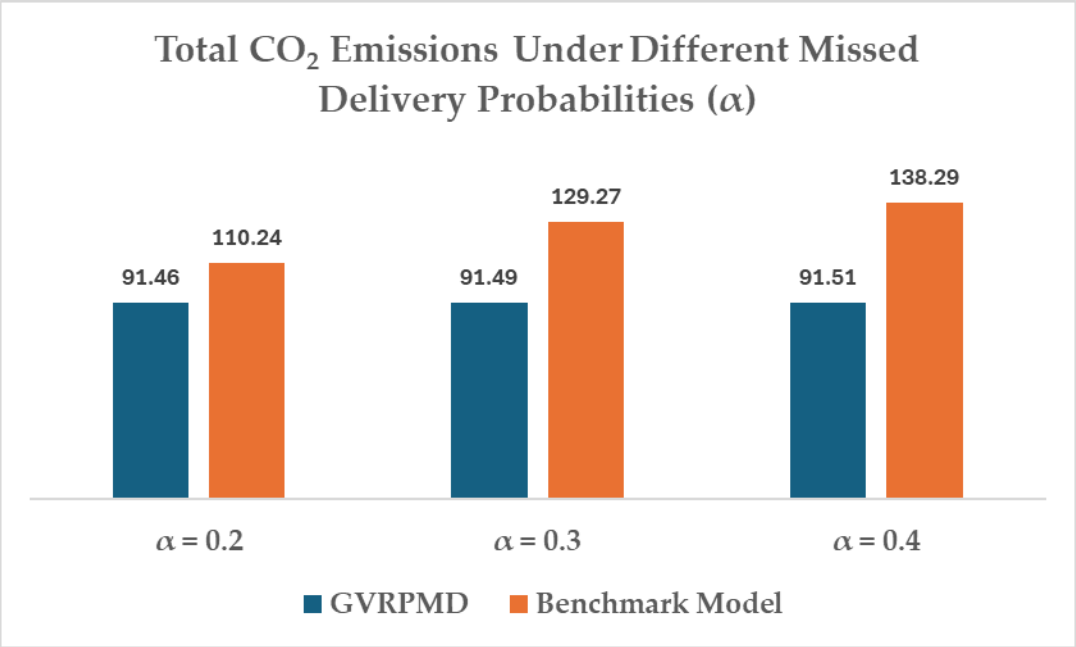


Figure 22. Comparison of GVRPMD and Benchmark models based on (α)

5.7 Computational Complexity

This section discusses the complexities involved in solving GVRPMD. The model was formulated in Python, a high-level programming language that can handle

complex calculations. GUROBI optimizer (version 11.0.3) is used to solve GVRPMD on a Windows 11 computer equipped with an Intel® Core™ i7- 10875H central processing unit (CPU) with 2.30 GHz (16 CPUs) clock speed. The first problem setup included 20 nodes and was tasked with finding a solution with 1,652 decision variables. Although it is a highly complex computational task considering the number of variables, GUROBI Optimizer found a solution in 132 seconds utilizing a powerful CPU. On the other hand, the stage-I model (DDZCAP) used for customer assignments is a small problem with only a few decision variables, producing results almost instantly.

The proposed model is a variant of the VRP, and our test results indicate that the computation time significantly increases with the number of nodes visited. In a network consisting of 20 nodes, Figure 23 shows that when 12 nodes are visited by one vehicle (8 pickup customers are not visited), the computation time is 12.5 seconds. When 15 nodes are visited by one vehicle, it takes 1678 seconds for GUROBI to find a solution. We also tried 16 visitations but terminated the panel after the waiting time reached 9000 seconds. As given in Figure 23, the solution times are even higher when two vehicles are considered (7151 seconds for 15 visited nodes). This behaviour may indicate the NP-hardness of the proposed model.

Travelling salesman problem (TSP), is known to be NP-hard (Cordeau et al., 2007). Given this, we can demonstrate that a problem formulated as a variant of the VRP is also NP-hard by reducing it to the TSP. To achieve this, we removed the time window, capacity, and vehicle load constraints along with related variables and reduced the number of vehicles to one. Through this approach, we found that the GVRPMD can be simplified to the TSP, showing that it is also NP-hard. This result aligns with the findings in Figure 23, where the solution time increases exponentially as the size of the problem grows. Note that when there are more than 16 nodes to visit, GUROBI is unable to find a solution within a reasonable timeframe.

Our analysis of solution times as a function of the number of nodes visited demonstrated an exponential growth pattern. Figure 23 also shows the equations that approximate the growth in computation time. The R^2 values of 1 confirm that the exponential models fit the data well (Desmos, 2024). Based on these findings, we conclude that the time complexity of the proposed model is exponential, which can be expressed as as $O(e^{kn})$ or $O(2^n)$. When we evaluated other time complexities, such as linear time complexity (O(n)) and logarithmic time complexity (O(logn)), we found that our data on solution times better aligns with exponential time complexity than with these other types.

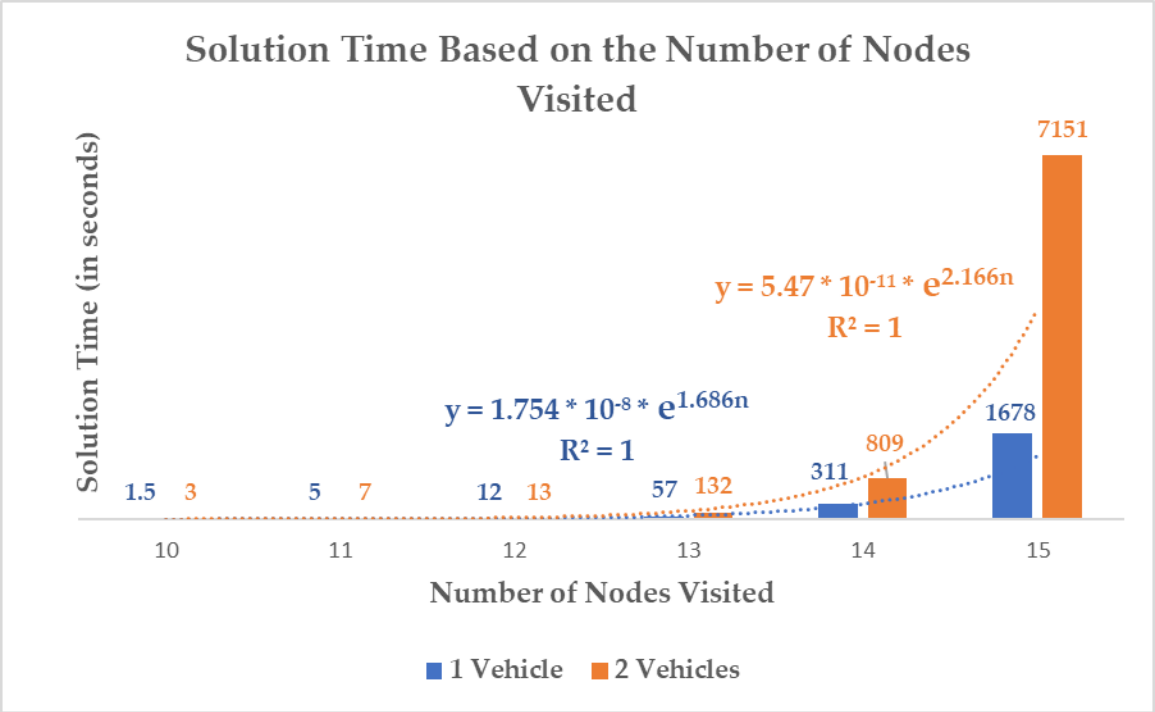


Figure 23. Computation times for different instances

We generated the graph presented in Figure 24 by applying a logarithmic transformation to the original dataset, allowing us to examine the relationship on a logarithmic scale. Figure 24 shows a linear relationship, indicating that the growth of solution time in the original data set may be exponential with respect to the number of customers. This is because the logarithmic transformation has linearized the exponential growth in the original dataset. The functions that approximate the growth in logarithms of the solution times (in Figure 24) are linear, with R^2 values of 0.97 and 0.94, showing a good fit. These findings further support that the time complexity of the GVRPMD is close to exponential. Thus, finding a solution for large instances, such as those involving 180 nodes, is

extremely challenging for solvers like GUROBI. However, various heuristics can be applied to produce results that are close to optimal for larger sizes.

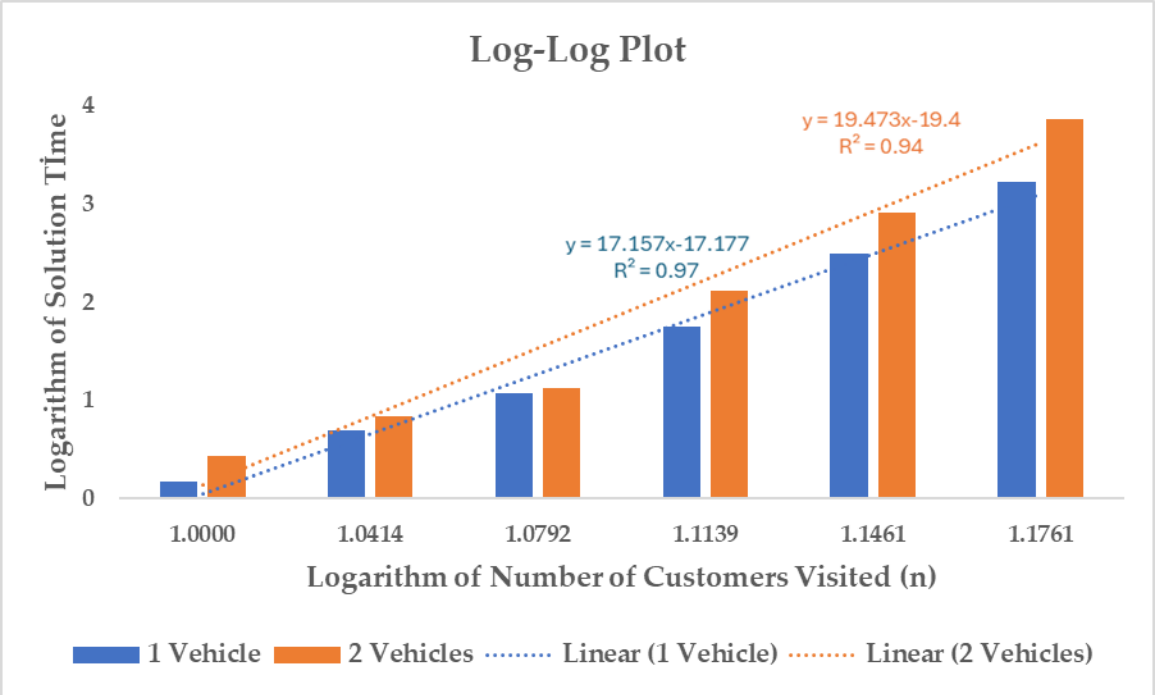


Figure 24. Growth of solution time with logarithmic data

Recall that the proposed network ensures that a vehicle must serve all customers and PL in a zone before moving to the next zone or the depot. We observed that the optimal zoning of the customers significantly reduces the computation time. To demonstrate this, we ran the same model with and without the related zoning constraints. The results indicated that the solution time is significantly shorter when zoning is applied while visiting the same number of customers. Specifically, GUROBI was able to solve the model that included zones and 13 node visitations within 132 seconds. On the other hand, the model without

zones (also with 13 node visitations) was terminated after 3000 seconds of waiting. This demonstrates that optimal zoning allows the proposed model to handle larger instances.

5.8 Chapter Summary

In this chapter, we presented and discussed the results of the proposed models. First, an illustrative example is described based on the model's output. This includes the optimal zoning, determination of the number and type of vehicles needed, and time windows for each node. Second, we evaluated the economic and environmental sustainability of GVRPMD by benchmarking it to a model. The results show that CO_2 emissions can potentially be reduced by 17%, while operational costs are expected to be reduced by 9%. This finding represents a significant contribution of this study. We also discussed the social and cultural benefits of the proposed network. Third, we conducted a sensitivity analysis to examine how variations in the inputs affected the results. Finally, we reported our findings on the computational complexity of GVRPMD.

CHAPTER 6: Conclusion and Future Research

In the face of the climate crisis, various sustainability issues have emerged across multiple industries. City logistics is a key sector that is accountable for CC. This study focuses on e-commerce last-mile operations in urban areas, where conventional vehicles are extensively used and generate significant amounts of GHGs globally.

A comprehensive literature review on DCL is conducted to examine the current state of the research and the analytical approaches. A literature review on DCL was conducted to examine the current state of research, the analytical approaches adopted and to identify gaps. The literature review results showed that optimization is the dominant solution approach in DCL literature. Several studies integrated innovative technologies such as EVs, hydrogen vehicles, drones, and PLs into optimization efforts for last-mile logistics. Their results showed that these technologies could significantly enhance operations. However, despite the increasing number of studies, the integration of package returns and missed deliveries remains a critical gap in the literature. This comprehensive literature review also motivated this study to propose a network for B2C e-commerce operations that integrates home deliveries, package returns, and missed deliveries while utilizing PLs. In doing so, we address an important gap in the DCL

literature. We also evaluated the proposed network in terms of QBL pillars of sustainability. A two-stage mathematical model is developed. In stage-I, customers are assigned to PLs and zones are defined. Stage-II is formulated as TVRPCR in Chapter 3, and extended to GVRPMD in Chapter 4.

An illustrative example is provided in Section 5.1 to describe the results of the proposed network design. To evaluate and benchmark this network's results economically and environmentally, we developed another model that represents the current way of handling B2C e-commerce operations. The results revealed that the GVRPMD can reduce CO_2 emissions by 17% and operational costs by 9%. Considering the scale of e-commerce operations worldwide, these reductions in emissions and costs are crucial, highlighting the practical impact of this research.

The social and cultural implications of this network are also discussed. Reducing emissions and travel distances can enhance accessibility and public health, contributing to a more socially sustainable environment. Moreover, GVRPMD can be particularly effective in cultures where missed delivery probabilities are higher due to various cultural factors. Specifically, sensitivity analysis on missed delivery probabilities indicated that the results from the GVRPMD were almost unaffected by increases in these probabilities. In contrast, both emissions and costs significantly rose in the benchmark model. Therefore,

practitioners and policymakers in such cultures can consider implementing GVRPMD to manage missed deliveries effectively.

Sensitivity analysis revealed that the number of nodes visited is a key factor influencing CO_2 emissions and operational costs. This aligns with expectations, as visiting more customers increases the distance travelled by delivery vehicles. Moreover, for the case with 20 nodes, it was found that using one high-capacity vehicle is more efficient than using two medium-capacity vehicles in terms of CO_2 emissions and operational costs. However, we also observed that using one high-capacity vehicle significantly increases the completion time of the route. Therefore, regarding customer service quality, using two medium-capacity vehicles is more beneficial. Practitioners and policymakers can implement the proposed network and evaluate the results to enhance their decisions regarding vehicle fleet composition, particularly when multiple vehicle options are available.

In the proposed network, we assume that customers are responsible for picking up their packages from a PL. Future studies could extend this service by offering home delivery from the PLs through a crowd-sourcing business model. For instance, if a missed delivery occurs, customers can request their packages to be delivered to their homes from the PL. In this case, the crowd-sourcing method can be utilized to find a delivery person from the public via mobile applications like Uber to perform such a delivery. Instead of using delivery vans, these delivery

personnel can utilize bikes, e-bikes, e-scooters, or even walk to deliver the packages. Offering such a service would create new job opportunities and benefit individuals who are unable to pick up their packages from PLs, such as older people, disabled individuals or those who are simply unavailable. This approach could enhance the social sustainability of the delivery process. Future studies can contribute to the literature and practice by integrating this service into their optimization efforts.

Future studies can adopt a systematic approach to design a network for the problem studied in this thesis. Specifically, random customer locations can be selected using a map of a certain city, and their real-life distances can be obtained to generate realistic data for the distance and time matrix of the given network. Using this updated data, DDZCAP and GVRPMD can be solved again.

One of the limitations of the solution developed in this thesis is the small problem size. The number of nodes defined in the network is considerably lower than what is typically encountered in practice. The reason behind selecting a small-scale problem is the computational complexity of GVRPMD. As discussed in section 5.7, the solution time of the problem grows exponentially as the number of nodes visited increases. Future studies should aim to solve this problem for larger instances so that the results may more accurately represent the current practice. A

heuristic approach can be implemented to find a close-to-optimal solution to solve the GVRPMD for larger instances.

In the proposed network (GVRPMD), we assumed two PLs are located. However, for problems with a larger number of nodes, the number of PLs can be defined as a decision variable and determined by the mathematical model. This would be a more generic approach and provide more control over the network. Future research may consider such an extension by determining the optimal number of PLs using the customer data. This can be done by developing a p-center problem under the location theory.

The literature review revealed that few studies on DCL take regional topography into account. However, factors such as uneven roads can significantly influence emission levels by increasing fuel consumption. Therefore, future research should incorporate topographic characteristics into their optimization efforts to achieve more accurate and unbiased results.

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