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A Simulation Model for Urban Logistics

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Abstract

Recent technology advancements have aided the rapid expansion of e-commerce. Online shopping and home delivery have largely supplanted traditional trade. The rivalry among various firms has changed from being just about the products to being about the quality and speed of the delivery service. However, this expansion and paradigm shift in business transactions was accompanied by other variables, such as an exponential increase in transportation movements. The stage that happens within the cities, known as the last-mile, is the most alarming.

Several solutions emerged as ways to address the inefficiency and sustainability issues associated with last-mile logistics. Even though some of them have already started being implanted, they are still not widely distributed or globally accepted. More research is also needed to fully comprehend the benefits that they would bring to our society.

The purpose of this dissertation is to develop a simulation-based model to aid in the planning of last-mile delivery logistics within a city. The model will generate routes using various heuristics, allow the user to select the type of vehicle used and its characteristics, and, most importantly, support the use of parcel lockers. The benefits of this solution can then be evaluated and quantified.

The model was created with FlexSim software, which enabled a thorough examination of each proposed scenario. The relevant indicators that were measured and compared were the total cost, package delivery lead time, and CO_2 emissions to the atmosphere.

When parcel lockers were used, the results showed improved performance in all the analyzed parameters. They also demonstrated that various types of vehicles behave differently. There is then a need for someone to conduct an analysis and study the trade-offs that can be made in order to make the best vehicle choice.

Resumo

Nos últimos tempos, os desenvolvimentos tecnológicos permitiram o crescimento abismal do comércio eletrónico. A tradicional deslocação às lojas foi substituída por compras online com entregas ao domicílio. A competição entre as várias empresas e negócios deixou de existir somente a nível dos produtos disponíveis, mas também na qualidade e velocidade do serviço de entrega. No entanto, este crescimento e mudança de paradigma nas transações comerciais não vieram sós. Com ele, também a quantidade de transportes comerciais aumentou exponencialmente, distinguindo-se aqueles que acontecem dentro das cidades, vulgarmente conhecidos como *last mile*. São estes os mais alarmantes.

Várias soluções foram consideradas para combater a falta de eficácia e de sustentabilidade associadas a este fenómeno. Apesar de algumas das medidas já terem começado a ser adotadas, ainda não se encontram completamente difusas na sociedade. Um estudo mais aprofundado das vantagens que tais soluções trariam à nossa sociedade é então necessário.

O objetivo desta dissertação passa por criar um modelo de um cenário baseado em simulação e que sirva de suporte ao planeamento à logística envolvida na *last mile* das entregas. O modelo vai recorrer a diferentes heurísticas para criar as rotas de transporte, vai permitir a escolha do tipo de veículo e respetivas características e, mais importante, vai permitir o uso de cacifos de modo a que as vantagens desta solução possam ser avaliadas e quantificadas.

O modelo foi desenvolvido com recurso ao *software* de simulação FlexSim, que permitiu fazer uma análise detalhada de cada cenário proposto. Os indicadores medidos foram o custo total, o *lead time* da entrega de todas as encomendas e as emissões de CO_2 para a atmosfera.

Os resultados obtidos demonstraram a redução em todos os parâmetros analisados quando os cacifos eram utilizados. Também mostraram que diferentes tipos de veículo possuem comportamentos diferentes. Surge então a necessidade de haver alguém responsável por fazer a análise e estudar os compromissos que são possíveis de efetuar, de forma a em cada situação a melhor escolha ser efetuada.

Acknowledgements

To begin, I want to express my gratitude to Professor Jorge Pinho de Sousa and Engineer Romão Santos for the chance and all of their assistance with my dissertation. It has been a challenging journey, and I am confident their guidance was critical in steering me in the right direction and ensuring that I completed this project. I would also like to thank INESC TEC, particularly the CESE (Center of Enterprise Systems Engineering), for the excellent environment provided.

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Gonçalo Ramos

"And I knew exactly what to do.
But in a much more real sense, I had no idea what to do."

Michael Scott

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Abbreviations and Symbols

B2C	Business to Consumer
GHG	Greenhouse Gases
KPI	Key Performance Indicators
LMD	Last-mile Delivery
MCDM	Multi-Criteria Decision-Making
VRP	Vehicle Routing Problem

Chapter 1

Introduction

This first chapter will introduce the theme of the dissertation. Initially, section 1.1 will contextualize the topic, and then the primary justifications for its proposition will be discussed in section 1.2. Section 1.3 outlines the goals this dissertation seeks to accomplish, while section 1.4 briefly summarizes the chosen methodology and the adopted scientific approach. Finally, section 1.5 will reveal the organizational structure of this dissertation.

1.1 Contextualization

In recent years, e-commerce has exploded in popularity [1]. Global sales surpassed $5 trillion in 2021, with projections of a total of over $7.5 trillion by 2025 [2]. The benefits it offers can explain this phenomenon over traditional commerce. These are all-time availability, home delivery, ease of comparing offers, attractive rates, a significant amount of product information, a more extensive selection than traditional retailers, and the ability to return purchased items [3]. Furthermore, the recent COVID-19 epidemic and ensuing lockdowns significantly impacted the acceleration of the preference of customers for obtaining goods online rather than getting them physically [4].

It is also worth noting that, in the year 2021, roughly 56% of the population of the world lived in cities [5], with forecasts produced by the United Nations in 2018 pointing that this figure would rise to 68% by 2050 [6]. According to the World Bank, cities create more than 80% of the global gross domestic product [7], implying that industrial and commercial operations are concentrated there [3]. As a result, metropolitan areas enable the growth of an open market in which items may be acquired from anywhere, and goods can travel throughout the world [8].

The factors above, as well as the rapid globalization facilitated by everyday technology advancements, set the stage for exponential growth in the number of goods that move across the globe. Consequently, transportation has also increased, which created several issues for delivery companies. The main one was increased logistics complexity. The expansion of business-to-consumer (B2C) e-commerce has simplified the buying process so much that the conditions under which it is done are easy to compare to direct rivals, and the value chain has become intangible. The immediate result is that competition has intensified significantly. Logistics becomes, then, one of the most critical differentiators between rivals in a market. Efficiently managed delivery to the final consumer frequently wins out and determines the retailer of choice [3]. Consequently, organizations must thoroughly plan to reduce costs and maximize resource utilization.

Last-mile delivery (LMD) refers to the transportation of items from a transit hub/retailer to the end customer. It is the last stage in the logistic process but is the most inefficient and costliest one. In addition, since it frequently is not a sustainable process, the ramifications for cities in terms of economic, social and environmental impacts, laws, and infrastructure development can be severe [9].

1.2 Motivation

As mentioned before, LMD corresponds to the most expensive stage of delivery logistics, as it accounts for up to 41% of the total delivery costs [4]. Additionally, it contributes to several environmental problems, such as the atmospheric emission of about 25% of all greenhouse gases (GHG). The consequent rise in air pollution has a detrimental effect on human health, leading to diseases, and it harms the environment. Since GHG emissions are the primary cause of climate change, it is also a severe problem [8].

Traffic caused by heavy truck use in the city drastically lowers the effectiveness of the transportation system, costing time and money. The auditory issues caused by vehicles impact human and animal life. Additionally, the transit and parking of vehicles, particularly those used for moving freight, are to blame for taking up more space and damaging the infrastructure. A crucial problem for LMD is reducing negative externalities while providing citizens with quality service [8].

Urban logistics have been improved via the implementation of numerous projects and technologies. The main objectives were to lessen motorized traffic and, as a result, urban GHG emissions, reduce social consequences, and boost profitability. The improvements can be divided into three categories: regulation (which is typically concerned with restricting certain types of activity by time of day, size/type of vehicle); consolidation of product flows within the urban area, achieved through a new organization or new concepts like consolidation centers; or the use of low polluting vehicles [10].

The academic community has recently begun to pay more attention to LMD efficiency. It is possible to separate the papers into two primary categories. The first group discusses ways to improve the standard delivery method (directly to the homes of the consumers). The so-called VRP (Vehicle Routing Problem), which entails determining the best path to deliver a collection of packages to scattered destinations, has been the subject of numerous proposals by authors. Other studies specify adjustments to the structure of the distribution network. The second set of articles focuses on innovative ways to improve the effectiveness of LMD. By including novel elements, businesses can get beyond established barriers, like the likelihood of unsuccessful deliveries or the inability to saturate the transport mean. This second field of study is more recent than the first, meaning it has received less research. Additionally, even though practitioners have already made numerous attempts in this regard, there is still much space for improvement in terms of efficiency [11].

Parcel lockers are a possible solution to LMD problems. They provide flexibility in collection hours and ease in collecting. Rather than delivering items directly to clients, parcel lockers work as locations where customers may pick up their parcels. Depositing numerous packages in parcel lockers will save transportation costs and ultimately enhance LMD efficiency [12]. Parcel lockers started being used in Western countries in 2014. La Poste in France, Correos in Spain, UPS in the USA, Australia Post in Australia, and CTT in Portugal, are significant examples [13].

1.3 Objectives

The primary goal of this dissertation is to present a simulation-based decision-support tool to improve the efficiency and sustainability of the last stage of the delivery of goods within a workday. Several LMD scenarios will be studied from a multiobjective perspective by proposing and assessing a simulation model and changing its parameters.

The main aspects under focus will be the total cost of the deliveries, the lead time, and the emissions of the vehicles. In turn, these indicators are affected by other parameters, such as the distance covered in the routes, and the number of routes needed. Hence, different test scenarios will be conducted for a specific set of distributor and receiver locations. This will allow a better understanding of the nuances of last-mile logistics. FlexSim, a potent discrete-event simulator, will be employed to do so.

The FlexSim GIS module will be used to design a model of an LMD situation that closely reflects a real-world scenario. The routes will be created, and vehicles with specific characteristics will perform the deliveries. Posteriorly, it will be investigated how the model alters behavior and outcomes by changing certain elements.

The proposed tool will then assess the performance of LMD scenarios while trying to minimize its key concerns. It will do so by implementing various actions, such as modifying the type and choosing the number of vehicles utilized and determining the criteria for developing the delivery routes. The utilization of parcel lockers, however, will be the most relevant metric, as it is the primary goal of this dissertation.

Lastly, it is fundamental to validate the project to ensure the sustainability of the system.

1.4 Methodological Approach

The current topic serves as an introduction to chapter 3 that discusses the methodological approach in greater depth and aims to achieve the goals set in section 1.3.

In the initial phase, a simulation model must be constructed in FlexSim, using the capabilities of the GIS module. The points will represent the distributors and delivery destinations, and routes must be drawn between them.

Afterward, the complexity of the model will increase as different types of vehicles, with different characteristics, will be introduced. The option to replace traditional home delivery for parcel locker stations will be highly significant for the fulfillment of the objectives. Additionally, various procedures for constructing the routes will be provided. These will follow heuristics that seek to find good solutions from different perspectives, hence enhancing the robustness of the solutions discovered.

After running the different scenarios, the outcomes will be registered and later analyzed to understand the aspects of LMD that make it inefficient, unsustainable, and costly.

1.5 Dissertation Organization

The dissertation that follows is broken up into six chapters. The current chapter aims to introduce the document, explain its context, purpose and objectives, and lay out the methodology used.

The literature study in Chapter 2 begins with an overview of logistics and transportation logistics before focusing on the most recent developments in LMD, the primary subject of this dissertation. Discrete-event simulation is also covered.

The description and characteristics of the issue, as well as the approach taken to solve it, are covered in Chapter 3.

A more thorough explanation of the case study will be provided in chapter 4, and the outcomes will be covered in chapter 5.

Finally, chapter 6 presents the conclusions of the dissertation and some suggestions for future work.

Chapter 2

Literature Review

The next chapter presents the topics and concepts that resulted from the bibliographical study and will be covered in the dissertation.

Initially, section 2.1 will provide a general overview of logistics. The logistics of transportation will be considered next (section 2.2), with an emphasis on the modes of transportation (subsection 2.2.1), what a transportation network is (subsection 2.2.2), transportation routing (subsection 2.2.3), and lastly customer service (subsection 2.2.4).

The definition of last-mile delivery (LMD) will be covered in section 2.3, as it is the topic of interest in this dissertation. The externalities, described in subsection 2.3.1, will present the key factors that will be monitored during the following chapters. Additionally, numerous innovative techniques for improving LMD efficiency will be presented (subsection 2.3.2), with a greater emphasis on parcel lockers in subsection 2.4. They will be of special interest in the approach taken.

In section 2.5, several simulation-related concepts will be examined, and the process behind the implementation of a functional simulational model explained.

Finally, section 2.6 highlights the most essential notions covered, which will serve as the foundation for the subsequent chapters.

2.1 Logistics Overview

Logistics corresponds to the management and handling of resources and product distribution by transporting them from the origin point to the point of consumption. As a subset of supply chain systems, it can broadly be described as the processes involved in material flow within these systems [14]. The Council of Supply Chain Management Professionals (CSCMP), a non-profit association that thrives on connecting, educating, and developing supply chain management professionals worldwide, defines logistics management as "that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption to meet the requirements of the customers" [15]. Supply chain management is distinct in that it encompasses all the preceding tasks as well as all manufacturing operations and coordination of procedures across marketing, sales, finance, and information technology. A popular way to describe the goal of logistics is "getting the right product in the right quantity in the right condition at the right place at the right time to the right recipient at the right price" [15]. The supply chain system is detailed in figure 2.1.

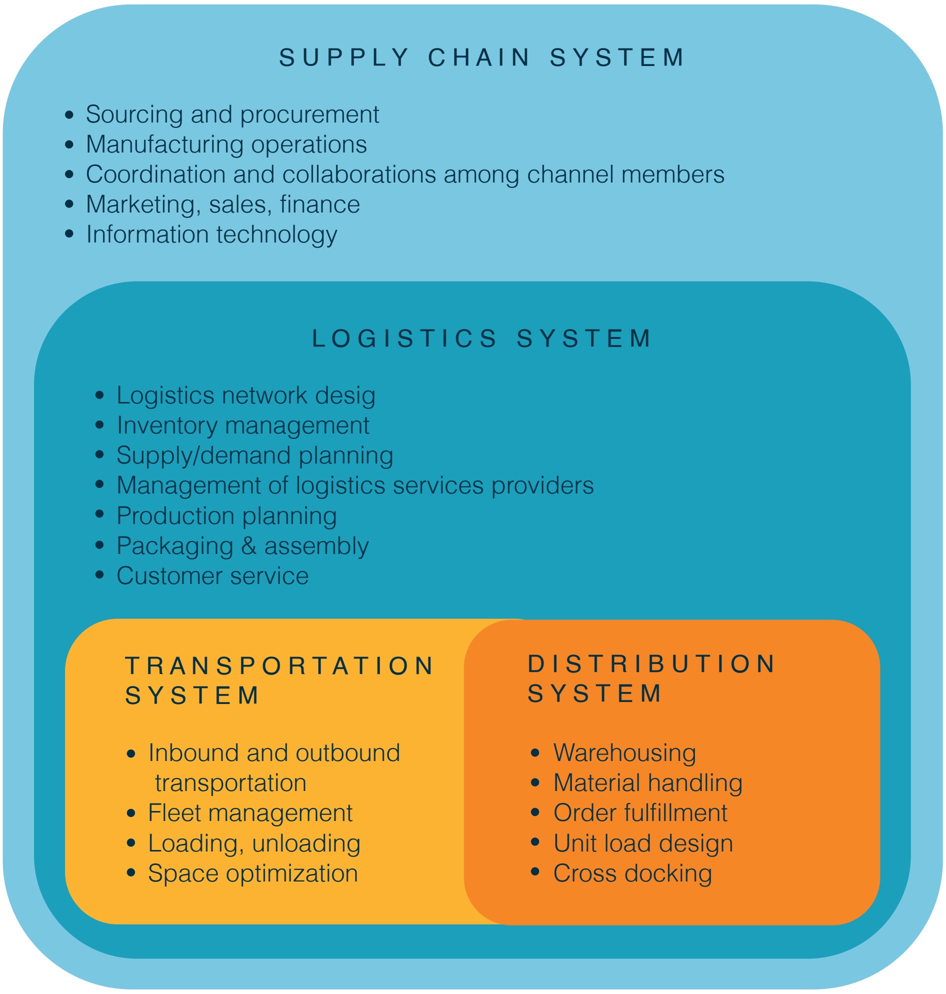

Figure 2.1: *The supply chain system, adapted from [16]*

Some significant functions that are associated with logistics are transportation and distribution. The latter entails processes such as warehousing, outsourcing services, and reverse logistics. Transportation is concerned with the flow of commodities through the supply chain, and the best possible mix of modes of transportation determines its efficiency. Receiving, storing, and delivering products between sites are part of warehousing. The outsourcing services can be of two kinds, third- or fourth-party logistics. Reverse logistics refers to transporting items to recuperate some of their value or fully dispose of them [16].

The planning, execution, and later optimization of the physical movement of goods is a crucial part of logistics and is known as transportation management. Some of its key objectives include ensuring a timely reaction to client orders and market changes, decreasing inventory to decrease costs, maintaining a high level of quality and striving for continual improvement, and providing support throughout the product life cycle [16].

Transportation, handling, inventory, order processing, and lot quantity costs are five of the main components that sum up the total logistics costs. Transportation expenditures are made up of line haul, which is the process of transporting products to their final destination, as well as pickup and delivery, handling, and collection. On the other hand, handling costs include sorting, packaging, loading, and unloading. Inventory costs include rent, salary, perishability, insurance, and the cost of holding unsold products. Figure 2.2 shows the relationship between transportation costs and storage and inventory costs. Finally, order processing costs are connected with setup costs and wait time, while lot quantity costs are associated with setup costs. Because they are all intertwined, a trade-off must be made between them all, which will impact performance. As a result, the scope and efficacy with which orders may be delivered become a competitive differentiator [16].

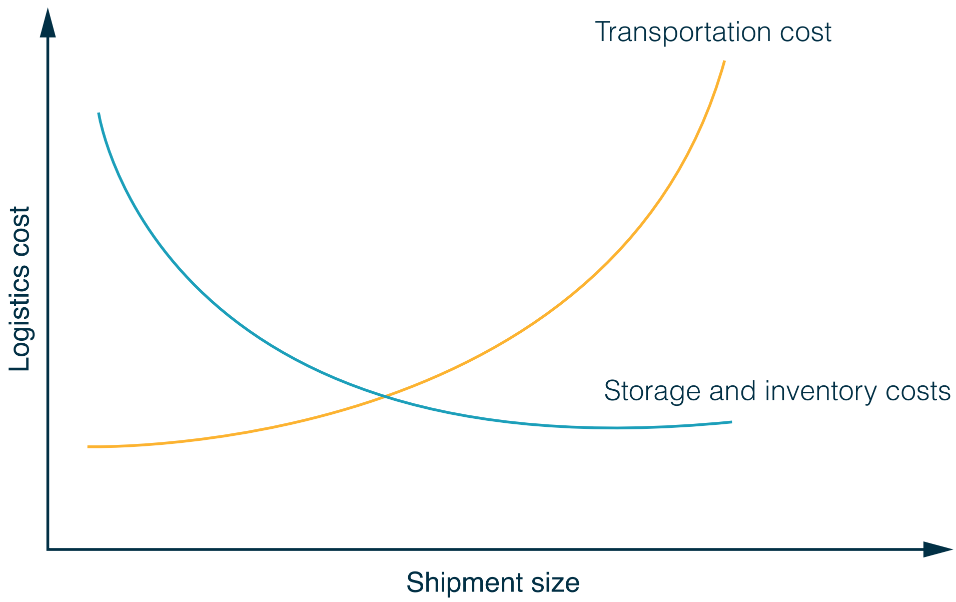

Figure 2.2: *Relationship between transportation costs, and storage and inventory costs, adapted from [16]*

Finally, figure 2.3 shows how the supply chain costs are distributed.

2.2 Transportation Logistics

Transportation is one of the most critical drivers of global economic growth. Indeed, the advancement of transportation systems enabled the exploration of new markets for expansion. Furthermore, formerly isolated markets began to be able to participate in the global market, bringing greater competition and contributing to globalization. These developments benefited economies of scale enormously because access to more markets meant access to more clients, which suggests

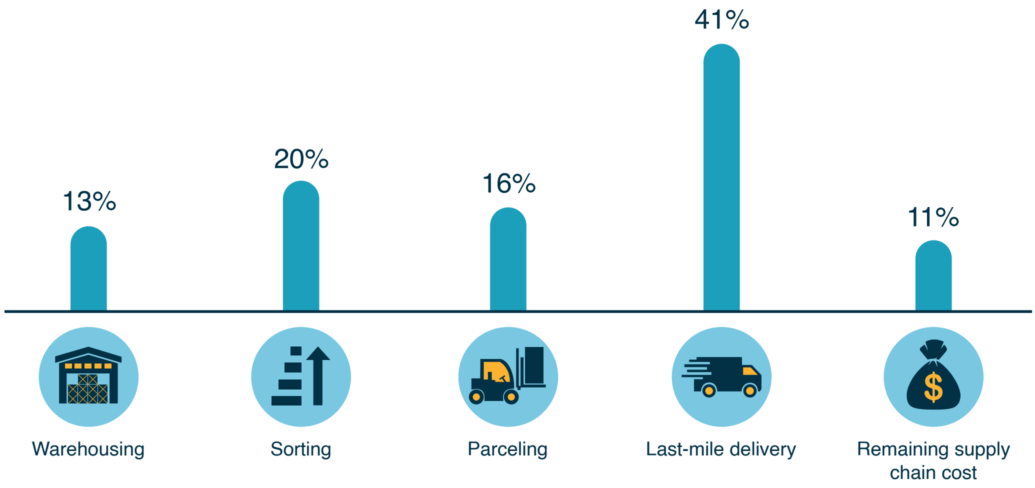

Figure 2.3: *Distribution of supply chain costs, adapted from [17]*

more items. As a result, the increase in product volume results in a reduced price [16]. Table 2.1 compares some of the characteristics of the existing transportation modes.

Table 2.1: *Comparison between Transportation Modes, adapted from [16]*

	Road	**Rail**	**Maritime**	**Air**	**Pipeline**
Speed	Moderate	Slow	Slow	Fast	Moderate
Availability	High	Moderate	Low	Moderate	Low
Consistency	High	Moderate	Low	Moderate	High
Loss and damage	Low	High	Moderate	Low	Low
Flexibility	High	Low	Low	Moderate	Low
Operational cost	Moderate	Low	Low	High	Low
Capacity	Low	Moderate	High	Low	High
Competition	High	Low	Low	Moderate	Low

2.2.1 Transportation Modes

Transportation systems have both positive and negative societal, environmental and economical consequences. Therefore, depending on the sort of products handled by the firms, it is critical for them to analyze which transportation mode (or combination of modes) is most suited for their businesses. The primary modes of transportation are road, rail, maritime, air, and pipeline [16].

Road Transportation

Trucks are typically used for this manner of transportation. Its advantages are the overall low cost, as a consequence of the competition in the trucking industry, the consistency and punctuality in the deliveries, and the great flexibility. On the other hand, the high fuel consumption, which has severe environmental consequences, the traffic congestion, the liability for traffic accidents, and the stringent regulations that they are subjected to compose the main disadvantages of this mode [16]. In addition, the infrastructure and vehicle maintenance expenses for road transportation systems are expensive [18].

Rail Transportation

This means of transportation is inexpensive, efficient, and ecologically benign. It is, however, limited to set routes and scheduled services, and goods handling must take place at train terminals. Massive expenditures are required to build railroads and improve connectivity between freight hubs. Because gradients during travel have a negative impact on fuel consumption and transit time, it is also limited by physical terrain [16].

Maritime Transportation

It is also referred to as water transportation. While it can transport heavy volumes of material, its reach is restricted. Despite this, it remains the most effective way of moving large quantities of cargo over long distances. In fact, over 80% of the amount of international commerce in products, and much more so for the majority of developing nations, is attributed to it, according to the United Nations Conference on Trade and Development (UNCTAD) [19]. However, it entails high costs since both the ships and the required infrastructures are pretty expensive to develop, maintain and operate [18].

Air Transportation

Although it is quite expensive, this mode of transportation is quick, dependable, and allows flexibility. It may happen either through specialized air freight businesses or by shipping excess space on conventional aircraft. It is typically saved for expensive, perishable, or time-sensitive goods with far-off final consumers [16].

Pipeline Transportation

It is often used for oil and gas, making it a fairly specialized means of transportation. The rigidity of the design and the high investment requirements are its primary drawbacks. However, its usefulness comes from having a specific supply and demand location [16]. Since pipelines may be placed both on land and underwater, the potential routes are almost limitless [18].

Multimodal and Intermodal Transportation

Multimodal transportation is a term used to describe a form of freight shipping that combines two or more modes of transportation. This approach is especially helpful for long-distance shipments [16]. According to the Organization for Economic Co-Operation and Development (OECD), intermodal transportation goes a step further. It entails the movement of commodities in a single loading unit that utilizes two or more modes of transportation without handling the actual items when they change modes. This approach aims to make it easier to move standardized shipping units between transportation types [20]. This way, the main distinction between multimodal and intermodal transportation is that in the first one, one carrier manages all of the transportation, i.e., only one contract or Bill of lading exists. In contrast, in the latter, the shipper enters into separate contracts with various carriers to handle each leg of the transportation [16].

Businesses must concentrate on delivery times and costs to remain competitive. Setting the shipping and handling price too high or too low might harm revenue. Customers will perceive phantom costs if firms charge too much, and their cart abandonment rates may increase. The bottom lines of businesses might swiftly evaporate if they overcharge since they must absorb some of the transportation charges. Phantom cost is a shipping fee that a client must pay that is higher than the actual shipping expenses incurred by the vendor, while absorption costs are when the vendor absorbs some of the transportation costs associated with delivering the items in an effort to win the business of the customer [16].

2.2.2 Transportation Network

A transportation network comprises the lines, nodes, and links that make up the supporting structure of the transportation system. Links serve as the connecting points, or pathways, between nodes, which are locations where goods are picked up and delivered or handled in other ways along the supply chain. Transportation network analysis is used to ascertain how goods move across the network. Hence, it is essential to any community because it ensures the smooth movement of both people and goods [21].

A transportation network can be categorized as either a direct or hub-and-spoke network (figure 2.4). The former involves moving goods directly from their point of origin to their final destination. All deliveries are made straight from the provider to the address of the buyer. Direct networks have the benefits of not requiring an intermediary warehouse and being straightforward to coordinate. However, they have more extensive inventories and sizable receiving costs. In a hub-and-spoke network, the liner services between regional terminals and the hubs are the spokes. The transport units are switched from one liner service to another at the hub, which connects it to the final destination terminal. Hubs should ideally be placed close to the point where transportation demand is most significant as a way to reduce the detour length and the travel time between the origin and destination terminals. Due to the additional distance for the call at the hub and the time spent in the hub itself, the terminal-to-terminal trip time is increased. A hub-and-spoke network combines minor flows that are coming and departing from several directions [16].

Hubs serve as switching points, combining cargo flows between numerous origins and destinations. The significant consolidation of goods that occurs there results in lower costs, greater use of the transportation system, and better service while using fewer resources. It also helps to distribute the demand pattern and offers different routes for moving freight. They do, however, also have some drawbacks. They incur some operating expenses related to facility and handling

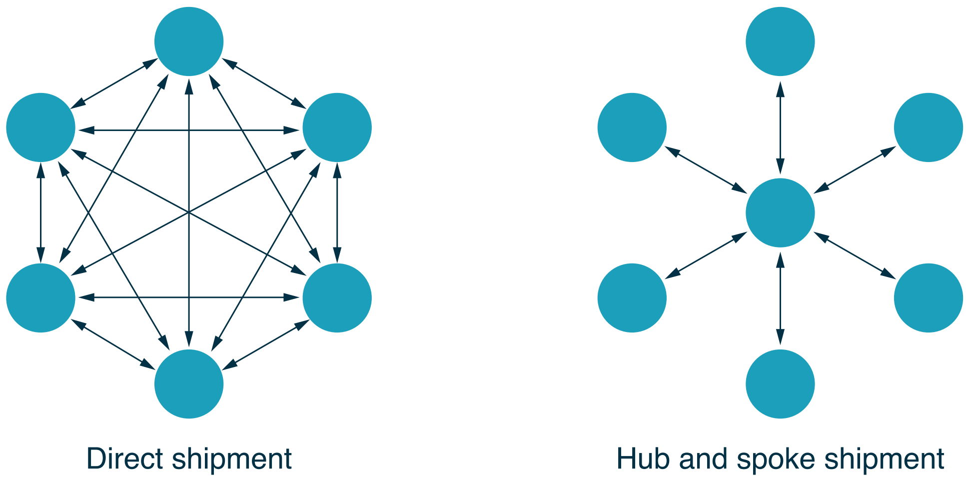

Figure 2.4: *Direct shipment and hub-and-spoke shipment, adapted from [16]*

expenses, such as unloading, loading, and sorting, as well as expenditures for theft, misrouting, and damage. They are highly rigid and have an impact on services and traffic. In essence, the hub acts as a network bottleneck [16].

2.2.3 Transportation Routing

Routing of the transportation network attempts to reduce costs and improve customer service. In fact, routing frameworks support lesser mileage, less fuel consumption, lower carbon emissions, and better resource usage. The frequency of proposed truck capacity variations must be considered when selecting a route planning system. Fixed routes and timetables should be maximized while continuous optimization is being performed. Live vehicle tracking, central scheduling, taking into account uncommon circumstances, and appropriate reporting are additional important instruments to enhance the transportation process and generate better outcomes [16].

Several issues might arise while attempting to route vehicles throughout a network. When the origin and destination points are distinct and have single locations, the goal of the system is to determine the shortest travel time between two sites while still satisfying the requirements of an associated transportation. However, sometimes other factors must be considered, such as tolls and road construction. When there are multiple origin and destination locations, it is necessary to identify the best origin point and network paths. Taking into account customer demand, travel routes, and supplier production capacity is also crucial. Finally, when the origin and destination points are coincident, the goal then shifts to figuring out the best order of places to visit to reduce the overall route time or distance [16].

A VRP builds upon fundamental routing concepts. It takes into account practical factors, including volume, weight constraints, the maximum amount of time drivers may drive, pickup and delivery considerations, and driver breaks. Since the ideal answer frequently does not exist, businesses must develop a best-case scenario that satisfies most of their requirements. There are eight typical procedures used [22]:

- Load trucks with stop volumes that are the closest proximity to each other;
- Stops on various days should be scheduled to create compact clusters;
- Create routes starting with the stop that is furthest away from the depot;
- The stops in the truck route should be placed in a teardrop pattern;
- The largest trucks are used to design the most effective routes;
- Instead of placing pickups at the tail end of routes, delivery routes ought to include them;
- A halt that is far from a cluster of routes is an excellent option for an alternative delivery method;
- Avoid placing limits on a small stop time frame.

As previously mentioned, a VRP has several restrictions, making it challenging to develop a decent solution. One strategy to solve it can be by making the most of vehicle capacity and planning the stops of each route to be as close together as possible. This is called the sweep method. Another tactic, known as the savings technique, entails attempting to minimize the total distance traveled by all vehicles while trying to reduce the number of vehicles used. In addition, it is essential for the routes to be clustered as a way of maximizing truck capacity [22].

Freight consolidation emerged as a technique to lower the overall transportation cost per unit weight, and it can be carried out in several ways. Inventory consolidation can be accomplished by stocking up on inventory items in accordance with observed demand; vehicle consolidation entails picking up and delivering items from multiple locations when the capacity of the vehicle is lower; warehouse consolidation is based on the idea that smaller shipments are sent over short distances while larger shipments are routed over longer distances; temporal consolidation entails keeping track of customer orders so that larger shipments can be sent out at a later time [16]. One of the most crucial ways to achieve the rationalization of distribution activities is to combine loads from various shippers and carriers onto the same vehicles along with some kind of coordination of operations within the city [23].

2.2.4 Customer Service

The outcome of all supply chain or logistical operations is customer service. It depends on how quickly and effectively the product is made available after being ordered and delivered, starting with the order entry of the goods from the inventory and ending with the conveyance of the finished product to the intended location. Customer service is broken down into three stages. The operating staff is given a road map for the tactical and operational aspects of the customer service activities of the company through pretransaction elements. Transaction elements consist of the entire process from receiving an order to delivering it to the consumer. Post transaction elements are a collection of services required to handle returns, complaints, and claims, as well as to support the product in the field, safeguard consumers from defective products, and provide for package returns. The four most crucial aspects of logistics customer service are the order fill rate, product condition, on-time delivery, and accurate documentation [16]. This is supported by figure 2.5.

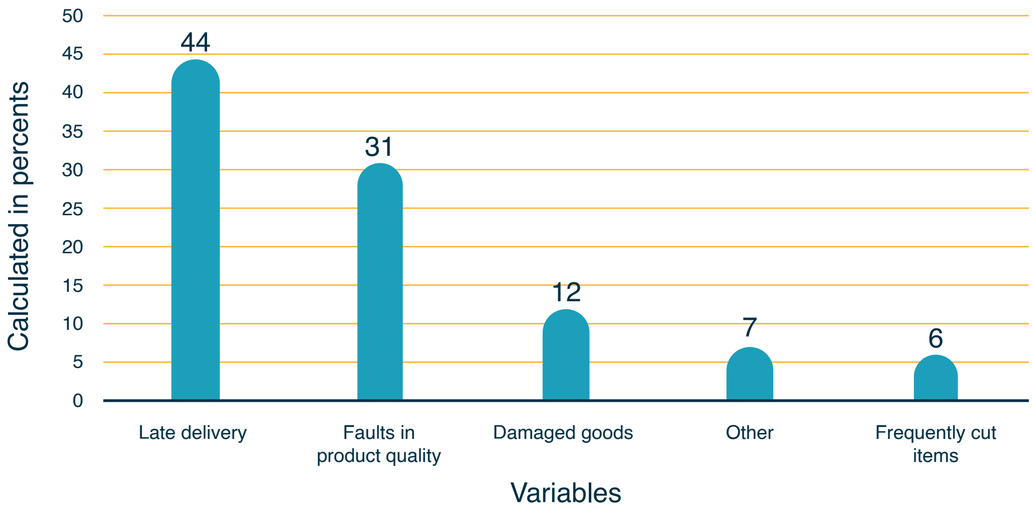

Figure 2.5: *Common customer complaints, adapted from [16]*

In the context of e-commerce, adopting a customer journey perspective to engineer customer experience becomes a problematic endeavor. Customer behavior is not as clear when they are unable to be observed. As a result, tracking client behavior on-site is necessary to construct a detailed consumer profile. However, developments in the retail environment have also caused modifications in consumer satisfaction methods. Customers see their e-commerce experience as a whole without explicitly identifying who of the market participants is in charge of each procedure. Therefore, a poor delivery experience will impact overall customer satisfaction and endanger the future of the relationship between the customer and the e-retailer [24].

2.3 Last Mile

Last-mile delivery corresponds to the final leg of shipments, which occurs between the last processing location and the customer. It accounts for between 40% and 50% of shipping expenses in a B2C context, and it has negative consequences on the environment, and public safety [17]. The reason for the low efficiency of urban last-mile logistics is that carriers must move through and operate in an increasingly complicated urban environment that is not designed for their needs. Compared to other legs of the transport chain, the last-mile distribution uses a lot more resources due to low cruising speeds in metropolitan areas, vehicle size restrictions, and temporal route limits. Lowering the number of first-attempt delivery failures, which happen when the carrier arrives at the residence of a customer but no one is available to receive the package, is one of the primary issues in the specific scenario of B2C e-commerce. In fact, it is estimated that around 20% of the attempts will fail [25].

For the firms to be successful, they must excel in three critical dimensions related to last-mile deliveries. Cost-effectiveness, which is directly related to the margins used by shipping services, comes first. There are various methods to improve it, such as increasing the number of packages delivered at each stop, as well as bundling them, which reduces the amount of fuel used, the amount of time it takes to deliver them, and the distance traveled [4]. Utilizing the advantages provided by digitalization and the consequent automation is another option. By replacing conventional home delivery with innovative, resource-saving delivery methods, automation offers a viable replacement for an aging workforce [26].

Additionally, technological developments enable improved optimization both in routing and in processes at sorting centers. Processing time is an additional dimension. The demand from customers for same- or next-day delivery is growing, making it necessary for shipping services to improve their product distinction between express and conventional deliveries. To provide these services, businesses must thus design highly adaptable and durable processes. This suggests a trade-off between delivery speed and expenses. The final dimension is quality. In addition to lost or damaged packages, how personal data is handled these days also impacts service quality. This will influence if it remains competitive or not. Eco-friendly delivery services are desired by clients and may boost economic performance [4].

2.3.1 Externalities

Because LMD exacerbates a number of societal issues, experts are looking into sustainable approaches to improve it. Sustainability encompasses three dimensions, as shown in Table 2.2. Financial stability and expansion are primarily tied to the economic dimension. The improvement of the local environment and customer satisfaction are two common ways to measure the social dimension. The dimension that recently has caused the most alarm, though, is the environmental one [27].

In contrast to other polluting sectors that show a constant downward trend in GHG emissions, the road transport sector has increased global emissions since 1990. Moreover, urban transport is responsible for a quarter of the total carbon dioxide emissions to the atmosphere [29]. Besides that, it creates health problems, noise pollution, traffic jams, and a loss of open space, which is detrimental to the general livability of a city [30].

Humans face an issue with the air pollution because it contributes to a number of diseases and irreparable harm. In addition, building surfaces, particularly old ones, are deteriorating due to air and fine dust pollution. A result of the high levels of GHG emissions is climate change. Scientists are searching for advances that could contain the connected impacts while the phenomenon is still developing. In residential locations, noise pollution is extremely detrimental. It has been

Table 2.2: *Sustainability framework, adapted from [28]*

Dimension	Objective	Indicator
Economic	Economic productivity	Capital costs Annual operational costs Return of investment after analyzed period
Environmental	Air pollution prevention	Annual CO emissions Annual NO_X emissions Annual PM10 emissions Annual SO_2 emissions
	Climate stability	Annual GHG emissions
	Energy efficiency	Transport annual energy consumption Share of renewable energy in the annual energy consumption
Social	Community development	Land devoted to transport facilities Employment turnover
	Equity	Share of potentially excluded users due to technological exclusion
	Noise minimalization	Noise level of a vehicle passing by
	Safety and security	Number of accidents and near misses

related to a number of problems, including hypertension, overall discomfort, and sleep disturbances. Congestion in metropolitan areas increases travel times, traffic, fuel consumption, and public transportation inefficiency and delays. Accidents can result in fatalities, material and medical costs, lost wages, and other costs. Multiple cars using transportation infrastructures and an increase in the frequency of trips lead to infrastructure wear and tear, notably when heavy trucks are involved [8].

Numerous studies indicate that by improving the usage of freight trucks, optimizing routes, and attributing GHG emissions to specific shipments, it is possible to minimize GHG emissions from the supply side without making significant financial expenditures. In addition, the demand side also has been requesting ways to make more conscious and sustainable selections at the time of purchase. By taking into account not only economical and financial factors but also environmental sustainability implications on their purchase decisions, consumer behavior has become crucial in this context for improving the sustainability of the supply chain. So, it is thought that if customers had access to more environmental sustainability information at the time of purchase, they would use it as a guide to making educated, sustainable selections. As a result, they would lessen the environmental effect of their purchase orders [31].

A strategy to achieve more environmental-friendly transportation is to change the type of vehicle. Switching to electric trucks was a huge step made by carriers, although they have certain drawbacks, including high purchase costs, restricted range, and lengthy recharging periods [32]. A cargo bike is another option for transportation due to its efficiency, which results in less traffic, shorter travel distances, quicker deliveries, and the use of less energy. In addition, it costs less money, uses less fuel, and emits fewer greenhouse gases. However, it has a constrained capacity, slower speeds, and shorter delivery distances [30].

2.3.1.1 Multi-Criteria Decision-Making

Following the description of the primary concerns surrounding LMD, it becomes crucial to define multi-criteria decision-making (MCDM). MCDM is a process employed when deciding on complex situations that include numerous criteria and numerous stakeholders that the outcomes and decisions may significantly impact. MCDM enables users to balance several aspects and give relative weights to each alternative. The objective outcomes can then be debated and compared, and a choice can be reached by making trade-offs [33].

The decision maker should examine financial, environmental, and social considerations concurrently in the framework of a sustainable supply chain. This dilemma turns decision-making into an MCDM. According to existing literature, researchers mostly focus on a few criteria in their methods. Only a few indications might be included in multiple-criterion decision-making procedures, since modeling many criteria might be quite difficult [34].

Two or more aims typically clash in LMD-related publications. Their distinct nature, however, makes quantification difficult. Tools are employed in this context to give a variety of solutions that illustrate the trade-off between different objectives [35].

2.3.2 Innovative Solutions

As previously explained, customers are looking for quick, affordable and sustainable ways to get their items delivered to them. This paved the way for the introduction of cutting-edge solutions aimed at improving LMD effectiveness [11].

Commercial fleet electrification has tremendous possibilities for lowering the air pollution and noise produced by regular freight shipments in urban areas. Despite the optimistic view of electric cars among logistics firms, adopting electric vans and trucks in the last-mile sector appears to be proceeding very slowly. Adapted to LMD and urban space constraints, non-motorized vehicles such as electric cargo bikes, bicycles, and trolleys have also been developed in recent years in part due to environmental concerns. Developments have also been instigated by the freight sector in containers that hold goods for ease of movement. In addition, there has been a current enthusiasm for autonomous technology that can reduce both the operating costs and externalities of the carrier. This is explained by the fact that around 80% of the overall operational costs of the vehicle are incurred during last-mile operations due to personal expenses [25].

The following sections will concentrate on some of the fresh approaches suggested to lessen some of the difficulties that LMD faces. Table 2.3 presents some of the main effects each innovation has on LMD.

Reception Boxes

Slow picking and ineffective home delivery can be reduced by placing boxes at the residences of customers where packages will be delivered [11]. However, the buyer will experience a lengthy and expensive installation. A delivery box that can be safely fastened to the building wall and recovered empty later or the next day could help reduce some expenditures [36].

Pick-up Points

These are places that offer storage and delivery services. Customers are welcome to go there to pick up their orders after they have been delivered. They are frequently shops or kiosks. The benefits of this approach are a reduction in the likelihood of a botched delivery and a decrease in the trip time of the carrier from delivery to house [11]. However, the accumulation of orders from many consumers at the same place can contribute to the increase in client density. Therefore, building a network of pick-up locations might be difficult because the location and number of points need to be considered [37].

Parcel Lockers

These are boxes used by different customers but owned by a retailer or a logistics service provider. They are typically arranged in buildings in public spaces like supermarkets and post offices. The distribution of a specific locker to a particular customer is dynamic and changes based on the issued orders and available lockers. Customers can retrieve their packages by scanning a barcode or a QR code or using a one-time password. Similar to the pick-up locations, they reduce the likelihood of missed deliveries and the delivery distance to homes while increasing client density. They also provide delivery automation [11].

Crowdsourcing Logistics

It consists of outsourcing LMD activities to a network of "common" people who can transport a package from the point of origin to the point of destination [11]. These businesses adhere to the principle of involving many people in the delivery process, both professional and non-professional, who are already on the road, have spare capacity, and are willing to detour to consumer locations rather than hiring fixedly employed delivery employees. The existence of a digital platform and a linked smartphone app is a key component of crowdshipping. When posted on a site, a delivery request is offered to registered crowdshippers. These individuals can select one or more tasks, pick up the shipments, and deliver them to the addressee. They can be paid for their services in two ways: either a fixed amount based on their journey time and distance or a system of bids [26].

Drones

They are Unmanned Aerial Vehicles (UAVs) that can transport packages from one location to another while utilizing the onboard GPS. The container is left behind when it has arrived at its desired location, and the drone returns to the warehouse or a truck that changes location. There, an employee swaps the battery and loads the new container. The fact that they fly, avoiding traffic and other barriers in this way, the automation attained in both transportation and delivery, and the reduction in resource use are the key benefits [11]. However, the delivery range is not that great, and they cannot carry many items, which translates into a low return per item delivered [38].

Robots

They are autonomous road vehicles that travel along predetermined and controlled routes until they reach the consumers, who then unload the vehicle and retrieve their packages. It boosts transport automation while using fewer resources [11]. However, it has a questionable safety record, a small cargo capacity, and a low maximum parcel weight and demands significant capital investment [28]. Since they travel at walking speed, it is recommended that the robot be moved by vehicle to overcome its narrow ranges [39].

Table 2.3: *Summary of the main impacts of innovative solutions*

	Reception boxes	Pick-up points	Parcel lockers	Crowdsourcing logistics	Drones	Robots
Probability of failed delivery	-	-	-	X	X	X
Customer density	X	+	+	X	-	-
Traffic / obstacles	X	X	X	X	-	X
Transport automation	X	X	X	X	+	+
Delivery automation	+	X	+	X	+	+
Resource consumption	X	X	X	X	-	-
Delivery-home distance	X	+	+	X	X	X
Driver specilization	X	X	X	-	X	X

2.4 Parcel Lockers

This section will delve deeper into what parcel lockers are, as well as the advantages and disadvantages they provide.

Parcel lockers are a self-collection service. They offer a round-the-clock automated and streamlined parcel receiving and unloading operation that benefits both customers and carriers. After making an online purchase, the buyer can select from one of the numerous automated parcel stations where he wants the merchandise to be delivered by the courier. The courier must verify his identity to perform the delivery in a digitally interfaced locker. The customer then receives a message containing the collection password. After obtaining the information, the customer may travel to the pick-up location and retrieve the package by inputting the verification code at a convenient time. It must take place within a specific timeframe, though; otherwise, the shipment will be returned. It also can perform the inverse operation [40]. The consumer benefits from this approach since it offers privacy, convenience, and flexibility in collection times. Additionally, carriers can benefit from it since it efficiently lowers the mileage of their delivery vehicles and improves delivery efficiency [13]. Song et al. predicted that implementing a self-collection service could result in savings reaching 70% [41].

One of the challenges this method faces is the design of a parcel locker network. To optimize the overall profit from the income from clients who utilize the service less the fixed and operational expenses of the chosen facilities, the number, locations, and sizes of the facilities must be decided [12]. Since customers generally prefer closer parcel locker stations, they must be within a certain threshold distance [42]. Figure 2.6 shows how a parcel locker network works, while figure 2.7 shows a client can choose what parcel locker station they want to retrieve their products from. Therefore, the companies aim to position the stations to ensure maximum coverage without causing facility overlap [13]. By doing so, companies can decrease total expenditures, which include setup costs and procurement prices, while increasing customer satisfaction and parcel locker use rates [42].

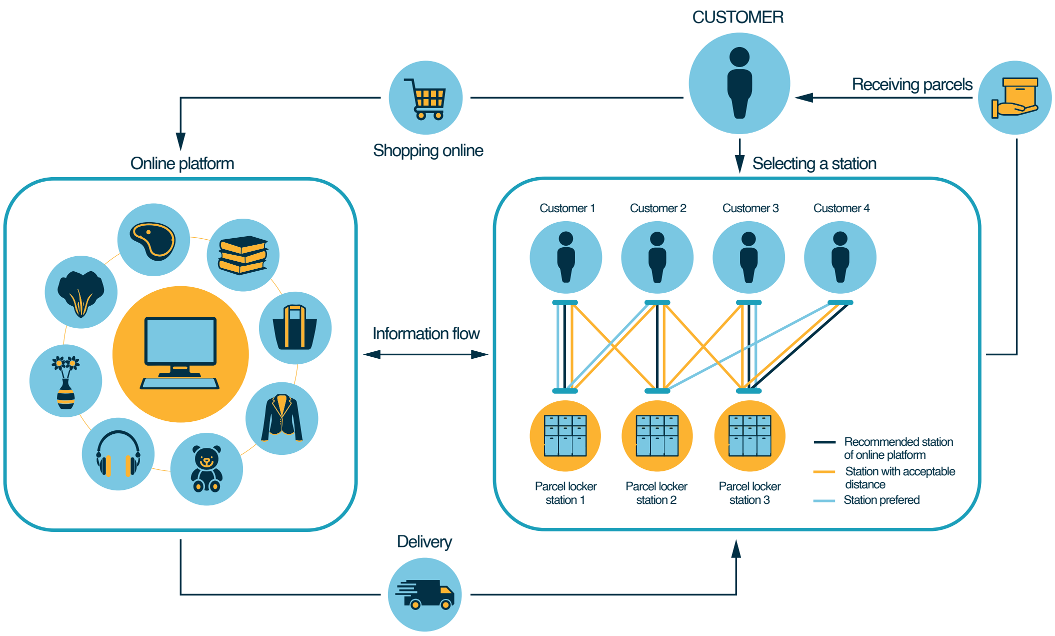

Figure 2.6: *Sketch of a parcel locker network, adapted from [42]*

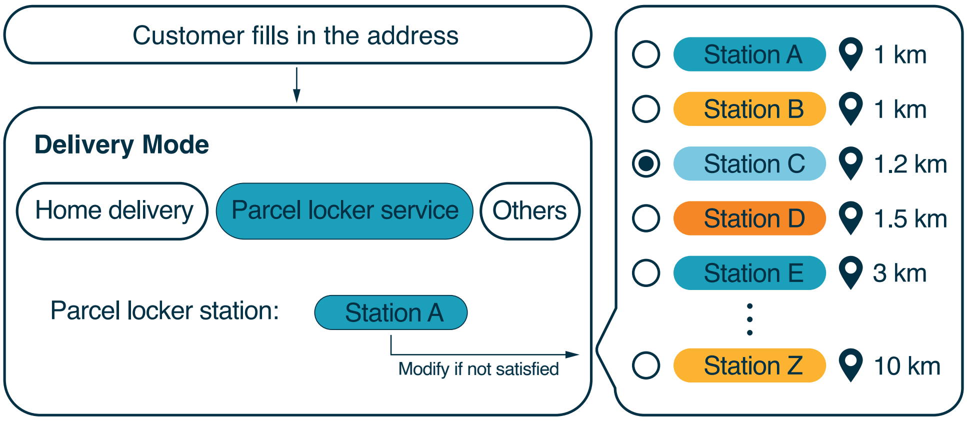

Figure 2.7: *Illustration of the recommendation of parcel locker stations to customers, adapted from [42]*

The dependence on constant demand and the impossibility of adjusting to seasonal changes is one of the drawbacks of parcel lockers. Modular lockers were suggested as a remedy since they can adapt to changing demand [43]. More recently, mobile lockers have been studied as a way to help offset some of the losses brought on by the high starting costs of stationary parcel lockers and the reluctance of consumers to utilize them [44].

The level of the preparedness of a customer to participate in the creation and delivery of a service is known as consumer participation readiness (CPR) [45]. It becomes essential when installing parcel locker stations because using them requires more of a consumer than conventional package delivery services. Customers play a crucial role in coproducing the service, molding the results, and learning new behaviors. They must also be willing to do so [46].

2.5 Simulation

Models are valuable tools that aid in decision-making and help us understand how things function in the real world. Virtual models are created because they offer a risk-free environment when real-life experiments are frequently too expensive or even impossible to do. Given the variety of modeling tools and methods available, simulation modeling stands out due to its ability to include dynamics in models.

2.5.1 Simulation Overview

Every simulation model undergoes a continuous or discrete state change over time due to rules governing the system [47]. Simulation becomes incredibly valuable when [48]:

- New organizational or operational methods are being studied without interfering with ongoing operations;
- Testing new physical layouts or hardware designs without needing to make a purchase commitment;

- The validity of theories on how or why specific events occur is taken into consideration;
- Understanding the interactions between variables is desired;
- Work in progress, information, and materials are being delayed, i.e., where the bottleneck is;
- Attempting to provide answers to suppositions while developing new models;

On the other hand, building models involves experience and skill, simulation findings can be hard to interpret, and simulation modeling can be time- and money-consuming. In addition, it is essential to understand when analytical solutions are feasible and preferable [48].

A system is a collection of items that work together to achieve a specific goal through regular interactions or independence. Changes taking place outside of it frequently have an impact on it. Depending on the purpose of the study, the boundary between the system and its surroundings must be chosen when modeling systems [48].

Three frameworks exist when simulation modeling a system. System dynamics is mainly used for strategic modeling and operates at a high abstraction level. A stock, which is a digital representation of a modeled object, and a flow, which are the interactions between stocks, are the fundamental components of system dynamics. Discrete event simulation is a process-centric method that supports medium and medium-low abstraction. Systems are viewed as a series of processes carried out by several entities. In agent-based modeling, the system behavior is a compilation of the individual activities of each agent [47].

2.5.2 Discrete-Event Simulation

The modeling of systems where the state variable changes only at a discrete collection of points in time is known as discrete-event systems simulation. Instead of analytical approaches, numerical methods are used to analyze the simulation models [48].

The key simulation-related concepts are [48]:

- **System** - A group of entities that work together over time to achieve one or more goals;
- **Model** - An abstract illustration of a system, typically including mathematical, logical, or structural relationships that define the state, entities, sets, processes, events, activities, and delays of the system;
- **System State** - Set of variables that may be used to describe it at any moment;
- **Entity** - Any object or component in the system that needs explicit representation in the model;
- **Attributes** - The properties of a particular entity;

- **List** - A group of connected entities that are arranged logically;
- **Event** - An immediate event that modifies the state of a system;
- **Activity** - A period of a specific length, which is known when it begins;
- **Delay** - A period of indeterminate unlimited length, which is unknown until it ends;
- **Clock** - A variable that represents simulated time.

A set of instructions for model builders is shown in figure 2.8 for conducting thorough and reliable simulation studies.

Every study should start with a problem statement. Setting the goals and determining whether simulation is the best tool for solving the problem comes next. If so, it is necessary to build the system model while simultaneously gathering the input data. Since real-world systems demand too much information, the model must be entered into a program that computers can recognize. In the experimental design phase, the alternatives that are to be simulated must be decided if the computer program is operating correctly and the model is calibrated. Performance measures for the simulated system designs are estimated using production runs and the following analysis. Both the program and the progress must be documented if additional runs are not required. Finally, the outcomes can be put into practice. The effectiveness of implementation is directly related to how well the previous steps were carried out [48].

2.6 Final Remarks

Throughout this chapter, it was discussed some of the most important topics regarding LMD and its problems and solutions. The background in which the subject of this dissertation inserts itself was provided, beginning with a definition of logistics and continuing with an overview of the transportation and distribution systems inside. Drawing some conclusions becomes crucial.

The main concerns surrounding LMD are making it a cost-efficient and sustainable activity. In this sense, it is advantageous to quantify the impacted parameters, such as costs and CO_2 emissions, in relation to other factors, such as route creation criteria and the type of vehicle being utilized. A deeper analysis is required in addition to improving these parameters as a whole. A MODA becomes necessary as the trade-offs between these factors allow for better solutions for LMD scenarios that are personalized to the surrounding environment and delivery conditions.

Parcel lockers stand out among the potential solutions discussed in this chapter for easing some of the issues that occur in LMD. Because of how easily this method can be put into practice and the benefits it provides, it is conceivable that it will be more widely embraced in the actual world. The ability of a discrete event simulation to accurately represent this circumstance makes this technique very pertinent as well. For these reasons, they gain particular interest, and they will be an object of study in the following chapters.

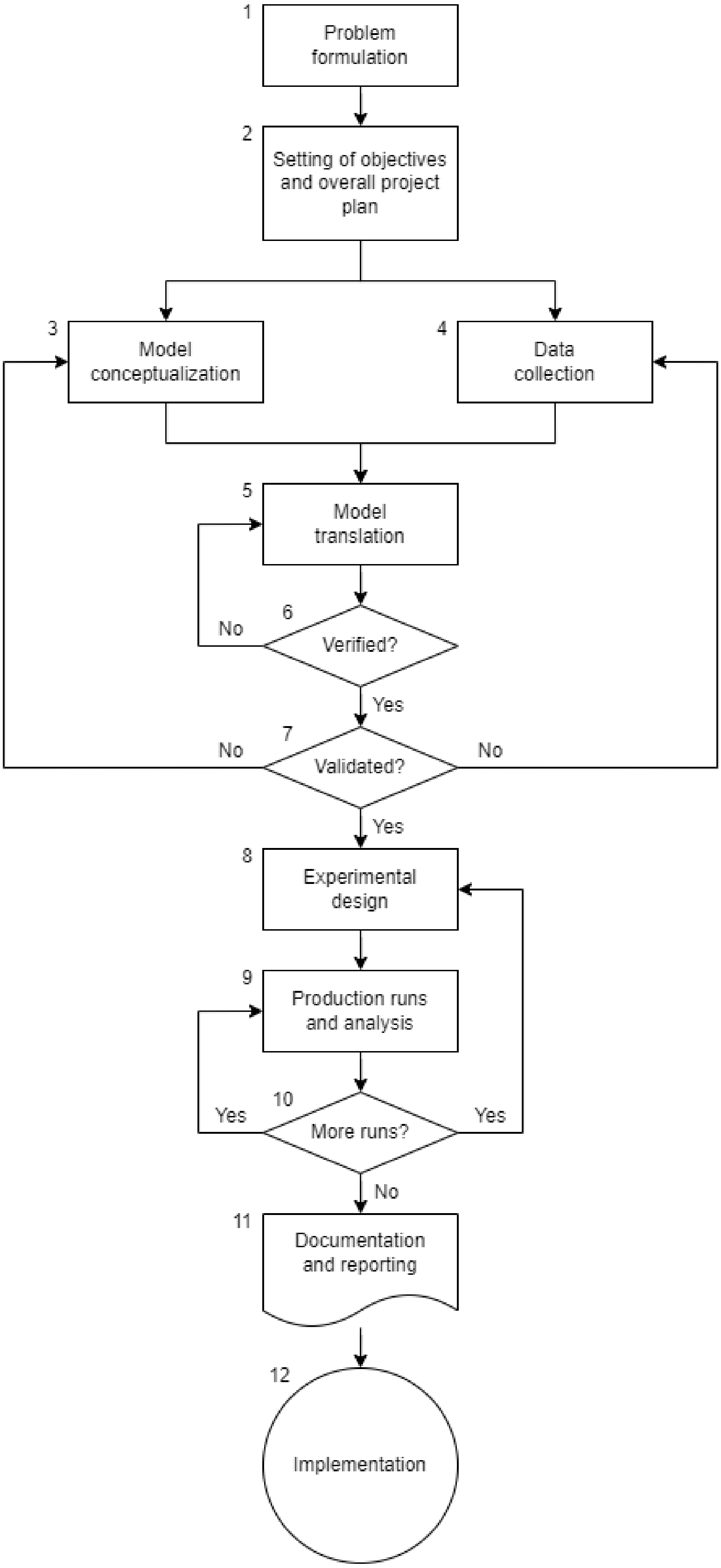

Figure 2.8: *Steps in a simulation study, adapted from [48]*

Chapter 3

Problem Description and Adopted Methodology

The general description of the problem that this dissertation aims to solve will be first presented in this chapter (section 3.1), followed by an explanation of some aspects of the simulation model (section 3.2). Finally, the methodology adopted will be characterized (section 3.3).

3.1 Problem Description

The goal of this dissertation is to provide a decision-support tool for planning the last-mile delivery (LMD) logistics of a city or metropolitan region within the confines of a workday. The key performance indicators (KPIs) will be registered and assessed using a simulation model, allowing conclusions about the efficiency and sustainability of the LMD to be drawn.

The workday was based on the hours of operation of the Portuguese company CTT. It provides a wide range of postal services, including mail and package delivery. It performs the deliveries between eight in the morning and seven in the evening [49]. The simulation will then run between these hours.

The model will employ synthetic addresses for the distribution centers, clients, and parcel locker stations, based on real-world locations. The sites will be chosen at random from the Porto metropolitan area. In addition, the list of orders resulting from the demand of the consumers will also be fictitious. In fact, an app will be created to produce orders that are identified by an identity number, a delivery location, and the weight and volume of the shipment.

User selection will affect some model inputs. In fact, there will be different types of vehicles, each with specific characteristics, as well as different criteria when creating the routes of the vehicles, and the parcel locker stations can or cannot be used. In case they are used, they have a 32% chance of being chosen in place of the traditional home delivery [50]. In addition, the user will still be able to select the maximum number of vehicles used for the deliveries.

The total expenditures, the amount of CO_2 emissions, and the lead time of the deliveries will be the KPIs assessed in this simulation. If some orders cannot be fulfilled, the service level, or the proportion of successful deliveries, will be considered rather than the lead time.

There will be several simulated scenarios. Actually, all possible combinations of the aforementioned elements will be tested. Furthermore, the number of existing orders will also change, resulting in additional simulation runs. Following the KPI evaluation, some conclusions will be drawn about the benefits and drawbacks of the various vehicle types, as well as how parcel locker stations actually help to increase delivery efficiency and lessen the issues that LMD poses.

One additional point to mention is that in each scenario, only one type of vehicle is used at a time. The fundamental reason for this is that the duration of a journey is defined as a parameter of the route and is unrelated to the vehicle that is traveling it. As a result, if two distinct vehicles traveled the same route simultaneously, they would be unable to travel at different speeds. Even though there are ways to counter this problem, it is already an issue that the developers hope to address in future versions of the software [51].

3.2 Test Case

The section that follows will detail some of the characteristics of the test case that was utilized to address the problem in hand. Considering the task of creating a tool to help improve LMD efficiency, it will describe how the simulation model was constructed.

Initially, to create the simulation model, it was necessary to know the locations of the distribution centers, the clients, and the parcel lockers. All of these locations had to be placed on the map using the component point, and each one is characterized by identification number (ID), name, longitude (X coordinate), latitude (Y coordinate), and function, as shown in table 3.1. It is vital to note that all of the sites are fictitious and were created only for the sake of this dissertation.

3.2.1 Vehicle Characteristics

The features of the various vehicle kinds are another essential piece of information. Trucks, diesel and electric vans, and cargo bikes are the vehicles used in this model. Each has unique average speeds, weight and volume capabilities, CO_2 emission rate, and fixed, per time unit and per distance unit associated costs, as shown in table 3.2.

Average Speed

One simplification made in the model is that vehicles travel at a constant pace. Instead of characterizing them using an acceleration equation, they can be associated with an average speed that changes depending on the kind of vehicle. The average speed of an electric van was not identified in any relevant literature, although it is said not to be different from a diesel van.

Table 3.1: *Locations of the relevant points*

ID	Name	X	Y	Function
1	Point1	-8.55233	41.21758	Warehouse
2	Point2	-8.65965	41.18883	Point
3	Point3	-8.62306	41.19189	Point
4	Point4	-8.59786	41.18669	Point
5	Point5	-8.55761	41.17292	Point
6	Point6	-8.55506	41.15629	Point
7	Point7	-8.57022	41.14721	Point
8	Point8	-8.59664	41.16405	Point
9	Point9	-8.59664	41.14629	Point
10	Point10	-8.61493	41.14782	Point
11	Point11	-8.62347	41.16313	Point
12	Point12	-8.63445	41.17935	Point
13	Point13	-8.65437	41.17904	Point
14	Point14	-8.67673	41.17415	Point
15	Point15	-8.67754	41.16129	Point
16	Point16	-8.66941	41.15119	Point
17	Point17	-8.65518	41.15915	Point
18	Point18	-8.64461	41.20107	Point
19	Point19	-8.61046	41.17262	Point
20	Point20	-8.57631	41.16772	Point
21	Point21	-8.62312	41.17347	Point
22	Point22	-8.57324	41.15826	Locker Station
23	Point23	-8.66412	41.16956	Locker Station
24	Point24	-8,65079	41.13594	Point
25	Point25	-8,62987	41.13079	Point
26	Point26	-8,59602	41.13451	Point
27	Point27	-8,58271	41.12420	Point
28	Point28	-8,60477	41.11216	Point
29	Point29	-8,65193	41.12420	Point
30	Point30	-8,60819	41.12391	Locker Station
31	Point31	-8,64167	41.11532	Point
32	Point32	-8,62721	41.10844	Point
33	Point33	-8,57587	41.11044	Point
34	Point34	-8,63976	41.15112	Point
35	Point35	-8,65650	41.11130	Point
36	Point36	-8,65574	41.14883	Point
37	Point37	-8,69453	41.19436	Point

Capacity of the Vehicle

The capacity of the electric van was chosen to be equal to that of the diesel van, as is common in the literature. It is worth mentioning, however, that for both types of cars to have the same payload, the electric vehicle must be significantly heavier, as electric batteries are far heavier than a diesel combustor. This could pose another issue, which is related to the maximum vehicle weight restrictions, but the vans included in the model are acceptable [65]. One model simplification was that the shape of the packages was not taken into consideration. This meant that a vehicle could be filled until the weight or volume capacity limits were reached, regardless of how the parcels were

Table 3.2: *Vehicle characteristics*

	Cargo bike	Diesel van	Electric van	Truck
Average speed [km/h]	18 [52]	38.8 [53]	38.8 [54]	32 [55]
Capacity [kg]	250 [56]	1300 [57]	1300 [52]	2500 [57]
Capacity [m^3]	1.5 [56]	10 [57]	10 [52]	34 [57]
CO_2 emissions [g/km]	3 [56]	159 [58]	77 [59]	307 [60]
Fixed cost [€]	15 [52]	30 [52]	40 [52]	103 [57]
Cost per kilometer [€/km]	0.04 [61]	0.4 [61]	0.04 [52]	0.74 [57]
Cost per minute [€/min]	0.33 [52]	0.33 [52]	0.33 [52]	0.33 [52]
Depot service time [min]	10 [52]	16.4 [62]	16.4 [62]	30 [52]
Customer service time [min]	2 [52]	4 [52]	4 [52]	8 [63]
Range [km]	80 [52]	500 [52]	200 [52]	564 [64]

arranged in the vehicle or size incompatibilities between separate items.

Associated Costs

Various price parameters are associated with an automobile [66]. First, when acquired, it has an upfront cost. Then it needs energy to move, which means it requires some form of fuel, either electricity or diesel, which has a price. It also requires a driver. When it comes to deliveries, usually someone is employed to operate the vehicle, which results in operating expenditures (wages). It also requires maintenance because it deteriorates with time. Furthermore, a tax on CO_2 emissions has been established to reduce GHG emissions in certain countries. Finally, part of the money spent can be recovered if the car is resold.

To simplify the model, three parameters are evaluated for the cost of the route, depending on the type of vehicle. The cost per distance unit traveled corresponds to the cost of the fuel. Aside from that, it was assumed that all drivers would be paid identically, resulting in an equal cost per time unit for the various types of vehicles. The fixed cost is a fictitious representation of the other charges, namely amortization and maintenance costs.

Emissions

One thing to consider is that CO_2 emissions are linked to energy use. While diesel vans and trucks burn fuel and emit greenhouse gases into the environment, electric vehicles do not. However, they must be charged, and in most regions, electricity is not produced solely from renewable sources. Hence, neither cargo bikes nor electric vans have zero CO_2 emissions in table 3.2.

Another point to consider is that when it comes to adverse environmental repercussions, only CO_2 emissions are included. Other gases, such as CO, NO_X, and others, are, nevertheless, released into the environment. Furthermore, noise pollution and traffic congestion caused by automobiles are also relevant factors. These variables ultimately influence the existing parameter that measures the environmental impact, simplifying the model.

Service Time

Depot service time is the amount of time a truck spends in the depot, where it gets loaded with more packages, and the driver may take a break. This parameter is frequently overlooked in VRPs. Another vital criterion is customer service time, which is the time it takes the driver to deliver the item from the moment the truck stops until it begins moving. It is influenced by vehicle size in the sense that the larger the car, the more difficult it is to park to let the driver serve the client.

Covered Distance

The distance that a vehicle can transit before running out of fuel corresponds to its range. It is affected by the type of vehicle used, as diesel allows a longer range than electric batteries. Additionally, a battery takes far longer to be recharged than a car to fill up its tank. However, to simplify the model, the recharge time, in the case of electric vehicles, or the time taken to fill in the tank will not be considered. As a consequence, and since the time window used in the simulation is one day, battery deterioration will also not be taken into consideration.

3.3 Simulation-Based Approach

As previously indicated, the behavior of the system will be evaluated using a discrete-event simulation model. They are instruments that can simulate real-world scenarios without posing any real risks. This section will first describe the software utilized, followed by an explanation of the relevant components and how they will be used.

3.3.1 FlexSim

FlexSim will be the software used in the simulation. It is a cutting-edge simulation modeling application used to investigate, illustrate, and improve real-world processes. It combines process flow logic with a 3D simulation environment, assuring a critical degree of validation while also providing a high-level knowledge of the system and the ability to observe what is going on [67].

Numerous simulation projects, including those for material handling, logistics and distribution, and transportation, can use FlexSim. It even has a simulation package that focuses on healthcare. In this dissertation, the Geographic Information System (GIS) module will be used. Modeling supply chains, inter-logistics, and other transportation purposes where time and distance are essential considerations may be done effectively with this new module.

3.3.2 Simulation Components

The current section will describe the FlexSim components that are most relevant to the creation of the simulation model.

A map and a point are the two main elements of the GIS module. A map visually represents geographic data using latitude and longitude coordinates. It is zoomable into any specific location on the map. An item used to define places in geographic coordinates is called a point. A route is formed by joining two points; it can be a road, a flying path, or a water path (if it crosses water) (figure 3.1).

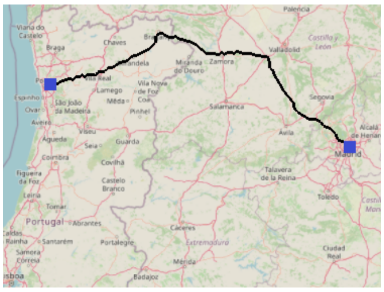

Figure 3.1: *Example of a map, two random points, and a driving route*

Entity

An entity corresponds to a part of the system that is transferred throughout the model and has specific characteristics. In the context of this dissertation, entities will correspond to the goods that the vehicles on the map carry.

Task Executer

The task executers will be the components traveling from point to point on the map carrying the goods (entities). The ones used will be trucks, as shown in figure 3.2. However, depending on the type of vehicle desired for the transport, the visuals will be changed accordingly. They will travel drawn routes characterized by distance and starting and ending points. In the context of this dissertation, all the routes will be driving roads.

Figure 3.2: *Example of a truck on FlexSim*

Load and Unload

The parts enter the system through the Source (figure 3.3), as this object determines when and how many parts are used. This object controls when the part enters the system. It has some properties that the user can alter. One of the most relevant ones is the definition of the arrival schedule. When the part reaches its final destination, it is eliminated in a Sink (figure 3.4).

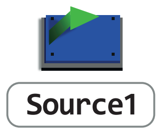

Figure 3.3: *Example of a Source on FlexSim*

Figure 3.4: *Example of a Sink on FlexSim*

Data

Some data are of the utmost value to the simulation, as they correspond to the details featured in the model and are directly linked to the results obtained. Sites of distribution facilities and delivery locations, the request list, and the characteristics of the vehicle are all examples. These values can be imported to FlexSim directly from Excel, where they are stored in global tables.

The length of the routes, or the distance between the points across the driving roads, is another type of data that needs to be stored. This is crucial because GIS module queries the routes from an online server, which means that the length values are not stable over time. To ensure consistency in the outcomes, these values must be stored and consulted when needed during the simulation.

Results

Another important aspect of this software is its ability to rapidly display the statistics and vital parameters related to the simulation model. A better analysis is ensured by the ability to filter the tracked objects. Additionally, dashboards may graphically present all the data in a vast selection of graphs and charts.

Processes

Processes control the logic of the model. Its organizational structure specifies the chronological order in which each action occurs, the event that triggers the process, and how it impacts the model.

The 3D model and Process Flow tools included in FlexSim may both be used to create simulation models. With underlying hidden logic, the first offers a drag-and-drop library full of detailed objects and resources replicating real-world circumstances. The latter overrides other logic and has a more abstract control over the logic of the model. However, both must be used together for the program to operate to its best capacity.

Each block in Process Flow that is used to describe and configure the behavior of the processes in the simulated system is referred to as an activity. They are flow items representing the activities or operations done on items in the system, such as processing a product, transferring it between locations, or storing it.

Figure 3.5 shows an example of a process used, the delivery of a parcel from one origin point to its destination. A scheduled event will trigger at some point the process. A vehicle will be created and linked to some point on the map, depending on its characteristics. The parcel characteristics will also be uploaded, allowing for better information tracking and the creation of statistics. A task sequence will be created, which can be visualized by a 3D animation of a vehicle traveling the route. When it reaches the destination point, it will stop for a while (delay), simulating the unloading of the vehicle, and then it is destroyed.

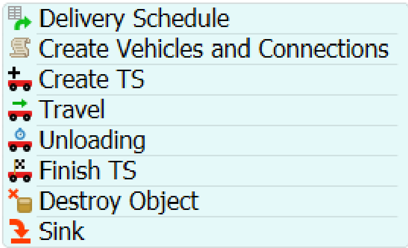

Figure 3.5: *Delivery process on FlexSim*

3.3.3 Structure of the Model

The primary model will be developed in FlexSim using activities from the Process Flow library. The logic behind the route construction, vehicle creation, and delivery performance will correspond to the processes used. The 3D model will be utilized to visualize the simulation of the model. In addition to these core components, FlexSim models can include additional elements such as statistics, reports, and charts to aid in analyzing and understanding the performance of the modeled system.

Customizing the properties and behaviors of the components to match the specific characteristics of the system will be required when building the FlexSim model. The resulting model will be run and visualized to understand system performance better and identify areas for improvement.

Chapter 4

Simulation Model

The current chapter will discuss the setup of the simulation model. Section 4.1 will describe how each order and the elements that characterize it were generated. The routes utilized to distribute the packages had to be designed, and different algorithms were used to do so. Section 4.2 goes into further detail on the objective of applying these heuristics and what each one entails. The model constructed on FlexSim will be described in the next section (section 4.3), with an emphasis on the underlying logic and the recording and processing of the outcomes.

Figure 4.1 depicts these steps.

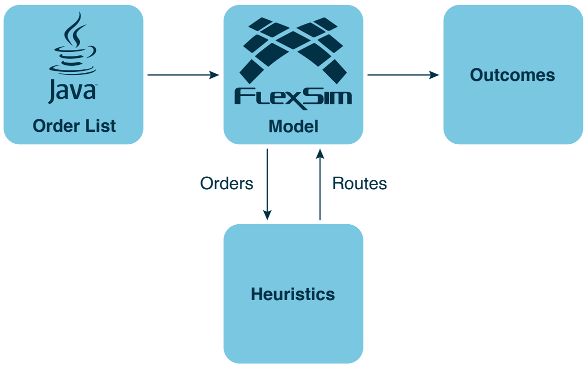

Figure 4.1: *Steps of the Setup of the Simulation Model*

4.1 Order Generation

As was previously mentioned, no dataset containing the orders from the clients was used. A Java application was created to generate pseudorandom orders characterized by a delivery destination and parcel weight and volume to produce a plausible list of orders. The list, which was kept in an instance of the ArrayList class, was then exported to a CSV file, and its contents were later copied into a global table on FlexSim.

The values for the typical parcel size in the literature varied greatly. In this dissertation, the weight and volume figures of the vehicles were calculated using a normal distribution. A diesel van could deliver between 140 and 180 packages on each trip [68]. However, because the number of important places is relatively limited, and in order to simplify the model, these values were trimmed in half. The average size of the package was calculated using the values presented in the previous chapter on the carrying capacity of a van, and the variance of 20 parcels was taken to represent one standard deviation.

A discrete uniform distribution determines the destination point to which the package should be delivered. However, this distribution does not take into account parcel locker stations. In fact, there is an alternative destination for each order in case the delivery can be performed to a locker. There is a probability of 32% of it being chosen; otherwise, the destination is the same for the two alternatives. This approach allows the user to choose later whether to employ parcel lockers in the simulation. Customers choose parcel lockers in the most convenient location, which is why the attributed parcel locker is not necessarily the closest to the original destination. This could be in a supermarket, near the workplace, among other possible places.

Five classes made up the structure of the Java program. Two classes were responsible for generating the parcel and choosing the delivery destination, respectively. A third was responsible for creating two instances of the previous classes and assigning an identification number to the order. Another class was responsible for creating the CSV file and exporting the data, while the last was the Main class, responsible for making the program executable.

4.2 Heuristics

Heuristics are problem-solving procedures used to arrive at a solution that is likely to be near to the best feasible answer. Three alternative heuristics were employed in this dissertation. Multiple solutions may be developed and studied by attempting to build trade-offs between the different objectives, hence increasing the robustness of the model. Indeed, one heuristic seeks to minimize the total distance traveled, whereas another seeks to minimize the number of routes required to complete all deliveries by maximizing vehicle load. The third seeks a middle ground between the other two.

The heuristics were implemented within the Process Flow in the FlexSim model, in a particular activity where custom code can be written. FlexScript, which is exceptionally close to C++, is the visual language used there. It is a high-level programming language that is simple to learn and is particularly developed for simulation modeling. Users may use FlexScript to construct and configure model objects, processes, and flows, as well as define the logic and behavior of the simulated system. It also includes a number of built-in methods and libraries for working with simulation data, including statistics, reporting, and visualization.

Heuristic 1

Heuristic 1 seeks to reduce the total distance traveled by vehicles performing the deliveries. To do this, each new order assigned to a route is the one whose delivery destination is closest to the last stop already in the route.

Heuristic 1: Minimize the distance traveled between stops

Input: Order list, Distance between every two points
Output: Routes
Set Point1 (Warehouse) as the starting point
Array $orders \leftarrow orderlist$
for $j \leftarrow 1$ **to** *number of orders* **do**
    $nextPoint \leftarrow 0$
    $shortestDistance \leftarrow M$
    for $i \leftarrow 1$ **to** $orders.length$ **do**
        if *distance from previous point to orders[i].destination* $<$ $shortestDistance$ **then**
            $nextPoint \leftarrow$ orders[i].destination
            $shortestDistance \leftarrow$ distance to orders[i].destination
    Update vehicle's weight, volume, and traveled distance totals
    if *vehicle's weight and volume totals* $>$ *vehicle's weight and volume capacities* ***or***
     distance traveled $>$ *vehicle's autonomy* **then**
        End the route at Point1
        Create another route starting at Point1
        Reset vehicle's weight, volume, and traveled distance totals
    else
        Remove $nextPoint$ from *orders*
        Update route with $nextPoint$
        Save $nextPoint$ as previous point
End the route at Point1

The nearest neighbor method served as the foundation for this heuristic. At first, the heuristic stores all orders in an array. Starting in the distribution center, the algorithm searches for the unfulfilled order with the closest destination to the previous stop. It examines whether the vehicle constraints have been broken before assigning the order to the route. In a negative case, the algorithm assigns the route the order and deletes it from the array. When the algorithm looks for the order whose destination is closest to this order in the next iteration, this order will not be in the array. If the constraints had been violated, then the algorithm would have created an additional route.

Heuristic 2

Heuristic 2 will distribute the parcels along the routes so that the load of each vehicle is maximized. By doing so, it aims to minimize the number of routes needed to satisfy all the orders.

The heuristic initially stores the orders in an array. Following that, for the amount of existing orders, it will traverse through the array and locate the order with the heaviest package, as they are sorted in decreasing weight order. They are then added one by one to the route while the restrictions are verified. If they are broken, the algorithm moves on to the next order to see if it

Heuristic 2: Maximize the load of the vehicle

```
Input: Order list, Distance between every two points
Output: Routes
Set Point1 (Warehouse) as the starting point
Array orders ← orderlist
Array sortedOrders
check ← 0
for i ← 1 to number of orders do
    weight ← 0
    nextPoint ← 0
    for j ← 1 to orders.length do
        if weight < orders[i].weight then
            nextPoint ← orders[i]
            weight ← orders[i].weight
    Add nextPoint to sortedOrders
    Remove nextPoint from orders
while check ≤ 1 do
    Array notUsed
    if check == 1 then
        End the route at Point1
        Create another route starting at Point1
        Reset vehicle's weight, volume, and traveled distance totals
        check ← 0
    for j ← 1 to sortedOrders.length do
        Update vehicle's weight, volume, and traveled distance totals
        if vehicle's weight, volume and traveled distance totals > vehicle's weight and
          volume capacities, and the vehicle's autonomy then
            Update route with sortedOrders[i]
            Save sortedOrders[i] as previous point
        else
            Add sortedOrder[i] to notUsed
            check ← 1
    End the route at Point1
    sortedOrders ← notUsed
    if check == 0 then
        check ← 2
```

still fits, and so on until all of the orders have been tested. If there are still packages that have not been assigned to a route, a new one is generated.

It is also worth noting that this heuristic separates per routes the orders according to their dimensions. It does not organize the orders within the routes. Thus, it becomes essential to apply another algorithm that organizes them, to decrease the distance traveled within the route.

Heuristic 3

Heuristic 3 seeks to strike a balance between the two previously described heuristics. It combines the search for the heaviest products in order to optimize vehicle load while seizing the chance and delivering all parcels ordered in the near vicinity.

Heuristic 3: Combine the previous heuristics

```
Input: Order list, Distance between every two points
Output: Routes
Set Point1 (Warehouse) as the starting point
Array orders ← orderlist
for j ← 1 to number of requests do
    weight ← 0
    nextPoint ← 0
    for j ← 1 to orders.length do
        if weight < orders[i].weight then
            nextPoint ← orders[i]
            weight ← orders[i].weight
    Update vehicle's weight, volume, and traveled distance totals
    if vehicle's weight, volume and traveled distance totals > vehicle's weight and
     volume capacities, and the vehicle's autonomy then
        End the route at Point1
        Create another route starting at Point1
        Reset vehicle's weight, volume, and traveled distance totals
    else
        Update route with nextPoint
        Remove nextPoint from orders
        counter ← orders.length
        while counter ≥ 1 do
            if nextPoint.destination == orders[count].destination then
                Update vehicle's weight, volume, and traveled distance totals
                if vehicle's weight, volume and traveled distance totals > vehicle's weight
                 and volume capacities, and the vehicle's autonomy then
                    Update vehicle's weight, volume, and traveled distance totals
                else
                    Update route with orders[counter]
                    Remove orders[counter] from orders
                    j ← j + 1
            counter ← counter − 1
```

The heuristic initially stores all orders in an array. The algorithm then searches for the heaviest package and adds the order to the route. Packages with the same delivery destination are added to the route as well. This process is repeated until the vehicle constraints are broken. If there are still orders unsigned to any route at this point, a new route is created and the process restarts.

To reduce the overall distance traveled, the route is ultimately structured using an algorithm adapted from heuristic 1. As a result, the orders added due to their size, and therefore the others, are sorted inside the route.

The results of the simulation rely heavily on the criteria used to create routes. In fact, the number of trips is determined by how the packages are distributed among the vehicles, and the total distance traveled is determined by the path of the route and the absence of unnecessary trips. An optimal distribution is difficult to achieve because it usually requires a large number of iterations, resulting in a high computational expense. Furthermore, in large or complex problems, it may be impossible to find them. As a result, it is sufficient to find a "good enough" solution rather than optimal. However, it is still critical to strive for a high-quality solution while minimizing costs or other measures of optimality as much as possible. In the case of this dissertation, the routes are created using only one iteration of an algorithm. Therefore, different heuristics were employed to ensure good and diversified results.

4.3 FlexSim Model

The simulation model was developed with the help of FlexSim, a powerful discrete event simulation software. More specifically, the version used was 22.2.3 [67].

The GIS module tools in FlexSim were first used to map the sites displayed in table 3.1 and then create routes between them. Different types of locations were used. As is seen in figure 4.2, the warehouse is green, parcel locker stations are red, and other kinds of destinations (homes, workplaces, etc.) are blue.

Driving roads were the type of route used because they were intended to be traveled in by road vehicles. The distance, duration, and cost are what distinguished them. As previously stated, the routes are queried via a routing server; therefore, a table containing the length that characterizes each route was constructed. Because there was no direct way to control the speed of the vehicle, the duration was adjusted based on the extent of the route and the intended average speed of the vehicle traveling it. Finally, the cost is a factor that could be used when calculating a trip. It can be used to find the shortest or the fastest journey, depending on whether it is equal to the value of the distance or the duration.

The type and the maximum number of vehicles used, the criteria used to create delivery routes, and whether parcel lockers are employed were all defined as model parameters. This made the model more adaptable because the corresponding values could be easily altered. Another benefit is that parameters are strict in that they can only accept specific values. In fact, each option within the parameter was assigned a numerical value. By linking them to drop-down lists created in a dashboard, the user could select the preferred settings. Furthermore, they are also global, meaning they are defined in one place, but they can be used anywhere in the model.

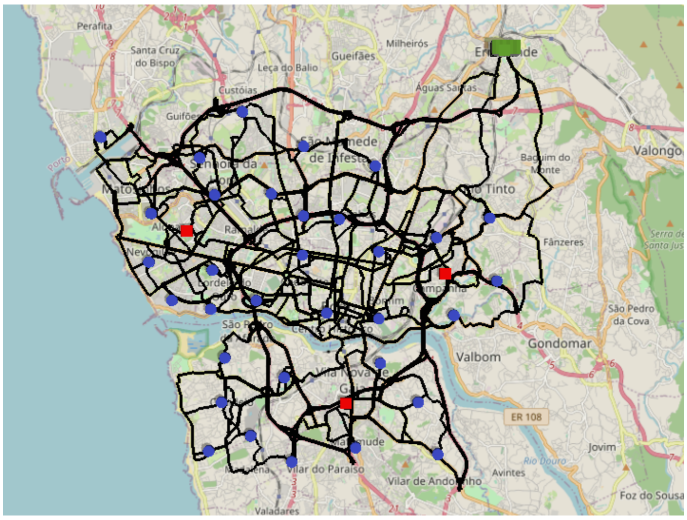

Figure 4.2: *Map with all relevant locations*

4.3.1 Process Flow

As previously stated, Process Flow is in charge of controlling the underlying logic of the model. Pre-built activities, in the form of a flowchart, can model the logic in an organized and scalable manner.

Before the primary set of activities may be executed, some instances of custom code activities must be run (figure 4.3). These will be responsible for acquiring the orders stored in a Global Table, splitting them into routes according to the specified heuristic, ordering the routes by descending distances traveled, and inserting the starting trips of each route in the source "Delivery Schedule". The starting date, which is the beginning of the workday (eight o'clock), the route name and number, the number of tokens produced, the starting and finishing places of the first deslocation, the number of the stop, and how many visits are remaining in the route are all contained in the source. Aside from that, a flag indicates whether the starting and ending points of the journey are the same. This flag will be helpful later in the "Unloading" activity. Tokens can be equated to symbolic HTTP cookies in the sense that their unique goal is to store some data. As the simulation runs, the tokens will proceed through the activities.

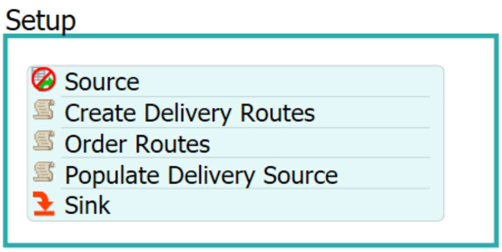

Figure 4.3: *Setup of the model on FlexSim*

Figure 4.4 depicts the primary set of activities. The simulation will begin with the "Delivery

Schedule" activity at seven in the morning in simulation time. A token will be generated for each entry there, which corresponds to a route. There will be an immediate delay to ensure that the vehicles begin moving at precisely eight o'clock. The duration of the delay will be determined by the type of vehicle, as when combined with the next delay, it will equal one hour. The activity "Acquire" will determine how many vehicles are available, and it will hold the creation of the surplus vehicles until more are available. "Start Route" will signalize the start of each route, which will be used later when creating statistics. The activity "Loading" will correspond to the time spent at the depot between the end of one route and the start of another.

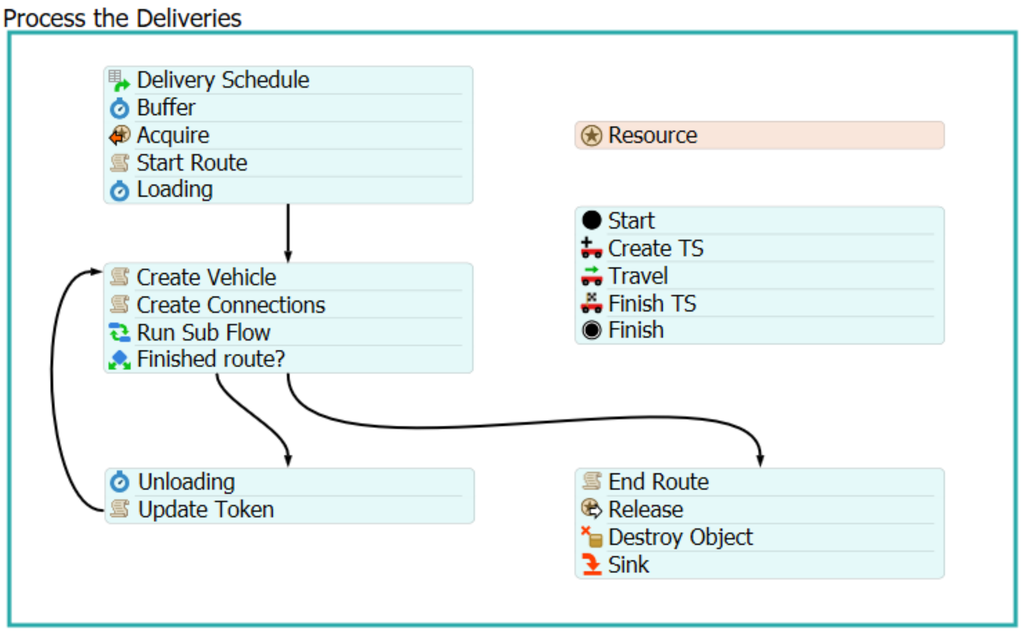

Figure 4.4: *Process Flow used on FlexSim*

A loop starts when the token gets to the "Create Vehicle" activity. There, a vehicle will be generated based on the information contained in the model parameters. The vehicle will be linked to the starting point of the route in the following activity. "Run Sub Flow" is linked to the set of activities next to it, which are responsible for performing the travel from the starting point to the destination point stored in the token. The "Unloading" activity will use the existing flag in the token. In the case that there are more than one deliveries to be performed in the same location, this flag will be responsible for adjusting the delay corresponding to the unloading time. It will be a quarter of the standard unloading time. Then a decision must be made. If the vehicle has reached the end of the route, it is destroyed; otherwise, the activity "Update Token" updates the data stored in the token to the next trip in the route. However, before the vehicle is destroyed, the completion of the route is signalized, and the asset is released. This means that if there is a route waiting for an available vehicle, it can then start.

In the model, another set of activities was employed (figure 4.5). Its purpose is to incorporate into the model the effects of traffic in the city. The busiest hours in Porto are from eight o'clock to half-past ten in the morning and from five to eight in the evening, and the congestion level is of 23% [69]. This means that the speed at which vehicles travel is lowered by that rate at the start of rush hour and returns to normal at the end of rush hour.

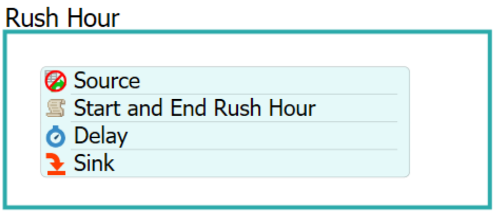

Figure 4.5: *Rush Hour on FlexSim*

4.3.2 Outputs

Some of the outcomes of the simulation must be registered for subsequent study. Numerous graphs and charts are available in FlexSim to display different sorts of data, such as statistics, performance indicators, and resource use, in a simple and understandable manner.

The usage of graphs will allow for the rapid and straightforward detection of patterns and trends in data, as well as the examination of performance disparities in data. They may also be used to show data in real-time, allowing users to monitor the performance of the system while the simulation is ongoing.

The Statistics Collector is a tool that collects information from objects and events defined during a simulation run. During the simulation, a statistics collector will listen to these objects and record the information in a table. They are valuable because they can readily adapt to satisfy data-gathering requirements by allowing them to tailor themselves to collect data from practically any event or statistic accessible during a simulation run. Furthermore, they provide direct access to the raw data of the simulation model, which can later be used to perform calculations, display in a chart, or export to be used elsewhere.

The type of graph displayed changes depending on the information displayed. The total distance and duration of the deliveries will be displayed in a table. The cost and CO_2 emissions, both total and average per route, will be displayed either in bar charts or tables. The evolution of order satisfaction will be displayed in a line chart. As an alternative, the finish time of the deliveries can be shown in tables.

The equations used to calculate the cost of each route and the CO_2 emission levels are equations 4.1 and 4.2, respectively.

$$Cost = FC + dist \times CK + dt \times CD \tag{4.1}$$

$$Cost = dist \times E \tag{4.2}$$

In equation 4.1, The fixed cost for each route is denoted by FC, dist denotes the distance traveled during the route, in kilometers, CK denotes the incurred cost per kilometer traveled, dt denotes the duration it took to complete the route, in minutes, and CD denotes the incurred cost per minute spent on the route. In the case of equation 4.2, dist denotes the distance traveled during the route, in kilometers, and E corresponds to the CO_2 emissions per kilometer traveled.

The values captured by the model simulation are the distance traveled inside each route and the associated duration, as well as the time when the vehicles departed and returned to the warehouse.

Chapter 5

Results Analysis

The simulation results of the model presented in the previous chapter will be stated and analyzed in this chapter.

There will be several simulation scenarios to reflect differences in last-mile delivery (LMD) logistics caused by different customer demand levels. Furthermore, other factors will vary for each demand level to increase the robustness of the model created. In fact, the type of vehicle used, the size of the fleet, and how orders are distributed among the routes will all produce different results. These will then be compared to the outcomes obtained when parcel lockers were used to determine how these lockers truly improve LMD efficiency and sustainability.

For each scenario, to ascertain whether the LMD is efficient and sustainable, the KPIs under analysis were the total cost, the CO_2 emissions, and the total lead time.

It is also worth noting that the simulation software used was FlexSim (Educational Version 2022 Update 2), and all simulations were carried out on an ASUS VivoBook X509 computer equipped with an Intel Core i7-8565U 1.8 GHz processor and 8 GB RAM.

5.1 Testing Scenarios

As previously stated, various levels of customer demand will be tested. Since the orders used in the model are fictitious, it is essential to define the number of orders used in each scenario before creating them. Considering there will be three levels of demand, henceforth referred to as level 1, level 2, and level 3 demands, it was determined that they would correspond to an average of two, five, and ten orders per location, respectively. There are 33 locations in total, excluding the warehouse, from where all vehicles depart, and the parcel locker stations, which serve as alternatives to traditional delivery. As a result, level 1 demand will have 66 orders, level 2 demand will have 165 orders, and level 3 demand will have 330 orders.

Before describing the results obtained, table 5.1 maps the heuristic used to construct the routes, whether parcel lockers are used, and the name given to each scenario. This will help to make the subsequent results easier to understand. Each scenario will be tested for the different types of vehicles. The number of vehicles used will also vary, depending on the number needed to ensure the delivery of all the orders.

Table 5.1: *Map between the scenario name, heuristic used for the route creation, and whether parcel lockers are used*

Scenario Name	Heuristic	Parcel Lockers
Scenario 1	1	Not Used
Scenario 2	2	Not Used
Scenario 3	3	Not Used
Scenario 4	1	Used
Scenario 5	2	Used
Scenario 6	3	Used

5.2 Level 1 Demand

In this section, the model was characterized by the lower demand amongst the different levels tested. Only a total of 66 packages were ordered. To analyze this context, different scenarios were simulated. In the scenarios where parcel lockers can be selected as a delivery destination, 19 customers will opt for them.

Cargo Bikes

The initial set of scenarios simulated employed cargo bikes to make the deliveries. The number of vehicles needed to ensure the delivery of all the orders changed between scenarios.

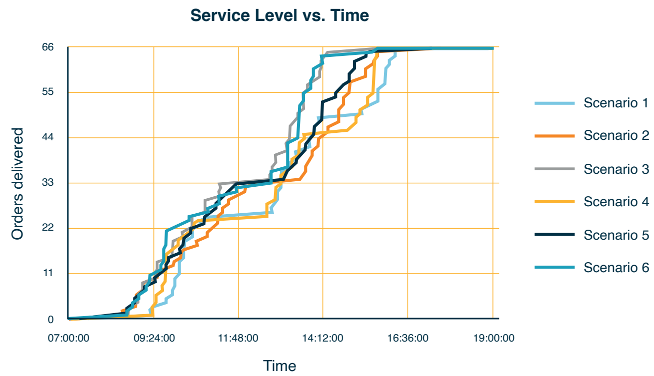

Figure 5.1: *Service level achieved by cargo bikes in different scenarios, for the level 1 demand*

The service level for the first six simulated scenarios is depicted in 5.1. In this context, service level is defined as the number of orders successfully delivered to customers. Since all of the tested scenarios met this requirement, the rate at which they did so is compared.

Scenario 4 was the fastest in terms of order delivery, followed by Scenario 6. Parcel lockers were employed in each of these instances. Even though scenario 1 appears to be the slowest, it is really scenario 2. There was one undelivered order that required a truck to return to the warehouse and retrieve it before it could be delivered, which took some time. It is vital to remember that the scenarios being examined have a varied number of routes and need a different number of vehicles to enable the fulfillment of all requests.

Table 5.2: *Measured parameters for each scenario using cargo bikes, for the level 1 demand*

Scenario	Number		Total Distance (km)	Duration
	Routes	Vehicles		
1	6	2	260.30	16:53:08
2	7	3	413.57	26:59:52
3	7	3	355.49	22:59:43
4	6	2	239.48	15:55:16
5	7	3	394.61	25:52:10
6	7	3	340.91	22:13:14

Table 5.2 contrasts the total mileage covered and the time required to finish the routes in the scenarios, as well as the number of routes and vehicles required. These variables are necessary to compute the total cost of the route and the CO_2 emissions using the expressions presented in the previous chapter. These factors reflect the effectiveness of the heuristic used to create the routes.

It is worth noting that all the deliveries were performed within the given workday. However, the duration of the route is superior in the sense that it corresponds to the sum of the duration of all routes. As seen in the table, the routes in which the longest distance is traveled also end up being the routes that take longer to be completed.

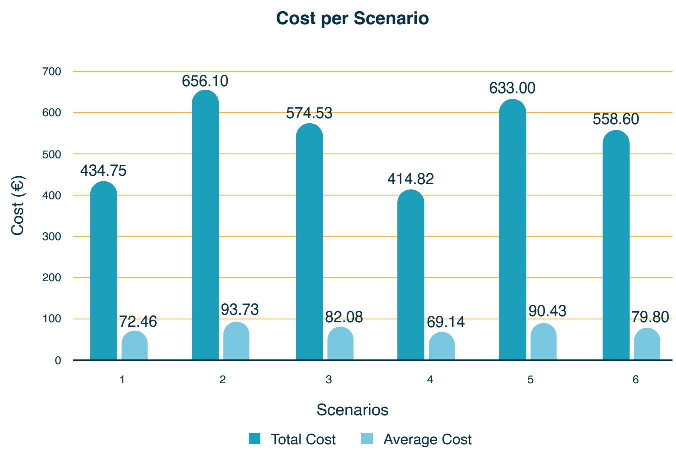

Figure 5.2: *Total cost and the average cost per route of the deliveries using carbo bikes in different scenarios, for the level 1 demand*

According to the figures 5.2 and 5.3, scenarios 1 and 4 involve the least costs and produce the lower amount of CO_2 expelled to the atmosphere. Scenarios 2 and 5 are the worst in both aspects. There is a reduction when parcel lockers are used, but it is not statistically significant, as it is 3.5% for expenses and 5.3% for emissions.

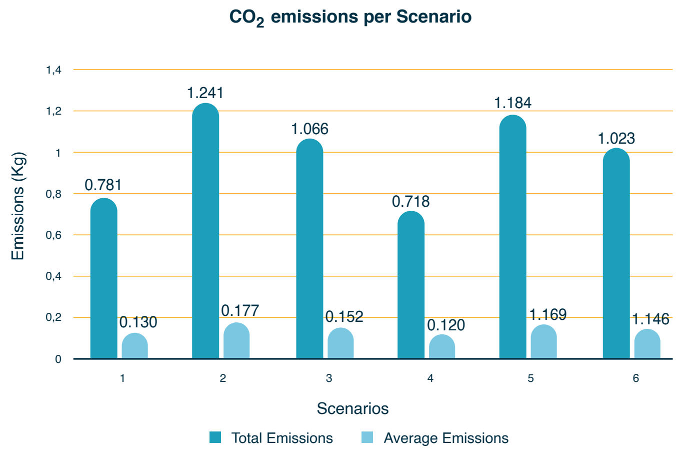

Figure 5.3: *Total emissions and the average emissions per route of the deliveries using carbo bikes in different scenarios, for the level 1 demand*

Vans and Trucks

Diesel and electric vans perform identically in terms of distance traveled and the lead time of the deliveries. In addition, since all the orders can be allocated to just one route, the results of the simulations for the different scenarios are identical. Consequently, the following analysis will be performed for diesel and electric vans, and trucks. The distance covered by each vehicle will be the same in each scenario, but the time it takes to complete the routes will vary due to differences in average speed across vehicles.

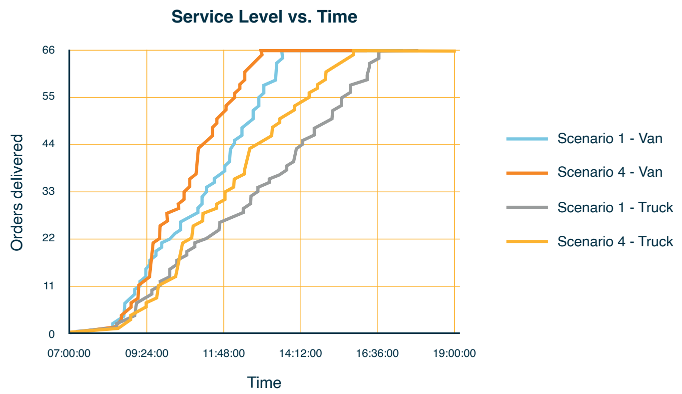

Figure 5.4: *Service level achieved by vans and trucks in different scenarios, for the level 1 demand*

As shown in figure 5.4, vans complete the deliveries faster than trucks. This is due to the fact that the routes are equal for each scenario, regardless of the vehicle utilized, which implies that the greater the average speed, the sooner the route is completed. The utilization of parcel lockers also helps to reduce the time of deliveries.

It is important to note that the time at which the final package is delivered, as depicted in figure 5.4, does not match the time determined by the duration of the route indicated in table 5.3. This

Table 5.3: *Measured parameters for scenarios 1 and 4 using vans or trucks, for the level 1 demand*

Vehicle	Scenario	Total Distance (km)	Duration
Van	1	116.21	05:51:01
	4	93.90	05:14:57
Truck	1	116.21	08:59:35
	4	93.90	08:10:24

is due to the fact that the vehicle still needs to return to the warehouse after delivering the cargo. The route is only deemed finished once the truck has returned to the warehouse.

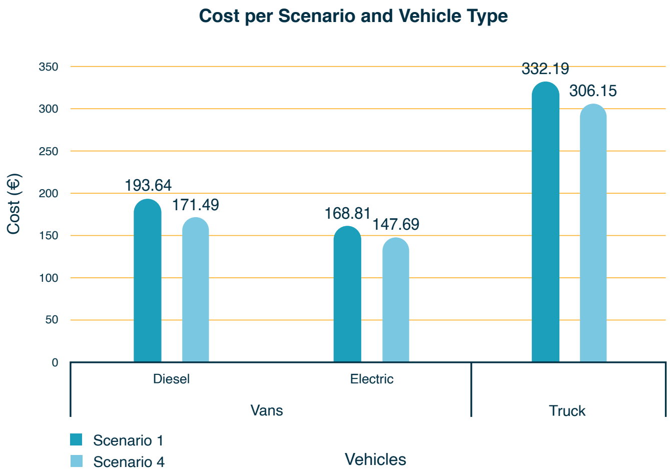

Figure 5.5: *Total cost and the average cost per route of the deliveries using vans or trucks in different scenarios, for the level 1 demand*

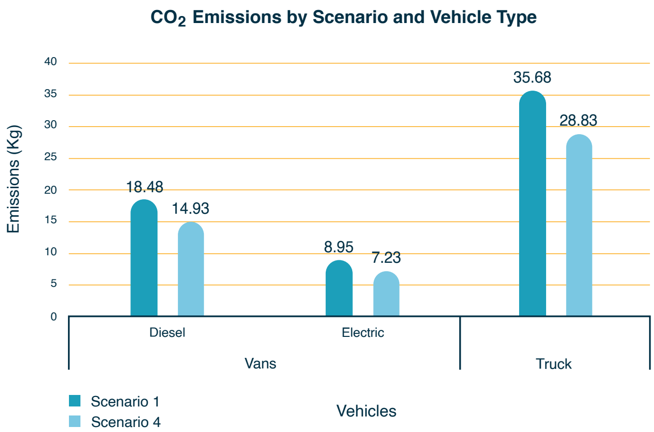

Figure 5.6: *Total emissions and the average emissions per route of the deliveries using vans or trucks in different scenarios, for the level 1 demand*

Figures 5.5 and 5.6 show that the electric van has the lowest related expenses. The difference is quite noticeable when compared to diesel vans, but it is significantly more when compared to trucks. In fact, compared to the electric van, utilizing the truck costs more than twice as much in both scenarios. When compared to the electric van, the discrepancy in CO_2 emissions is considerably more pronounced, with diesel vans emitting 107% more and trucks emitting 298% more. Using electric vehicles in conjunction with parcel lockers is then the most cost-effective and ecologically responsible alternative.

Demand Level Overview

Scenario 4 produces the most remarkable results for both instances of scenarios. It is both the most cost effective and the most sustainable option. Using parcel lockers results in more significant cost savings when trucks are employed, followed by vans and, finally, cargo bikes, although it has a favorable effect in all cases.

Vans are the type of vehicle that assures the fastest distribution of all the packages, whereas trucks are the slowest. They also have the least associated costs, particularly electric vans, while cargo bikes have the most. In fact, the cost of employing cargo bikes was 3.52 times higher than the cost of using electric vehicles. This is because they required a more extensive fleet to accomplish the fulfillment of all the orders. Nonetheless, they are by far the most environmentally friendly, emitting 0.12 times the amount of CO_2 to the atmosphere that the electric vans do. When comparing trucks with vans, vans outperform trucks in every aspect tested, since trucks are twice as expensive as electric vans and emit four times as much pollution.

5.3 Level 2 Demand

Consumer demand grew somewhat in this sector. In the scenarios mentioned here, a total of 165 orders were used. In the cases parcel lockers were used as delivery destinations, there were a total of 51 customers opting for them.

Cargo Bikes

In the first set of situations, the type of vehicle employed was a cargo bike. The number of routes and vehicles necessary to fulfill all deliveries changed depending on the scenario.

Figure 5.7 shows that the orders are delivered the fastest in scenario 5. However, it takes eight vehicles to accomplish this task. Scenario 6, on the other hand, takes the longest, but it only requires six vehicles. One thing worth noting is the periods of time that no delivery is performed, which can be seen in the graph as the segments where the line remains horizontal. Despite the fact that numerous vehicles are being utilized at the same time, they all wind up traveling to the warehouse at the same time, resulting in these protracted intervals of no deliveries performed.

The number of routes and vehicles that describe each scenario, as well as the overall distance and time spent driving, are displayed in table 5.4. The distance traveled in scenarios 2 and 5 is roughly double that of scenarios 1 and 4, respectively. This is due to the fact that they require twice as many vehicles to complete the deliveries in a workday.

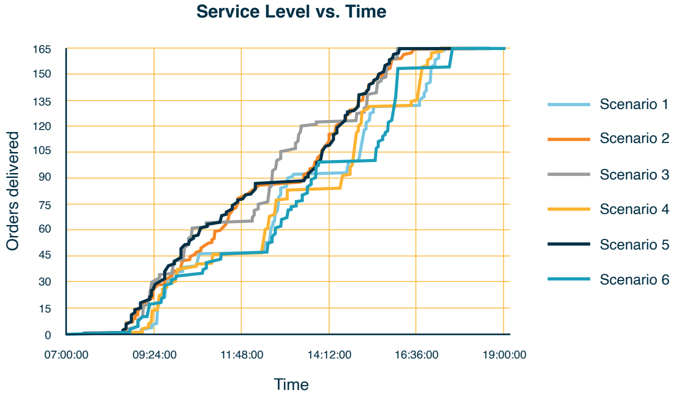

Figure 5.7: *Service level achieved by cargo bikes in different scenarios, for the level 2 demand*

Table 5.4: *Measured parameters, total cost and CO_2 emissions for each scenario using cargo bikes, for the level 2 demand*

Scenario	Number		Total	Duration	Cost (€)	CO_2
	Routes	Vehicles	Distance (km)			Emissions (kg)
1	15	4	552.56	36:33:05	970.82	1.66
2	16	8	1109.57	71:14:47	1695.06	3.33
3	16	6	697.69	45:49:28	1175.23	2.09
4	15	4	536.61	35:05:25	941.25	1.61
5	16	8	1059.38	67:56:50	1627.73	3.18
6	16	6	691.56	44:23:00	1146.45	2.07

When it comes to costs and CO_2 emissions, scenario 4 is the best in both circumstances, followed closely by 1. Using parcel lockers does not generate noticeably improved outcomes. Scenario 6 comes next, followed by Scenario 3. Scenarios 5 and 2 have far worse outcomes.

Vans

The kind of vehicle employed in the following set of simulated situations was vans. Since the distance constraint was not breached for any route, the simulation outcomes are identical for both types of van. The accompanying costs and CO_2 emissions, however, were not.

Scenario 1 was the scenario in which all orders were fulfilled the fastest, followed by scenario 5, then scenario 3. Scenario 2 was faster than scenario 5, while scenario 6 was the slowest.

Table 5.5: *Measured parameters for each scenario using vans, for the level 2 demand*

Scenario	Number		Total	Duration
	Routes	Vehicles	Distance (km)	
1	3	2	211.00	10:27:51
2	3	2	369.26	17:13:57
3	3	2	243.49	11:24:43
4	3	1	196.46	10:14:46
5	3	2	332.00	16:00:20
6	3	2	237.85	11:22:00

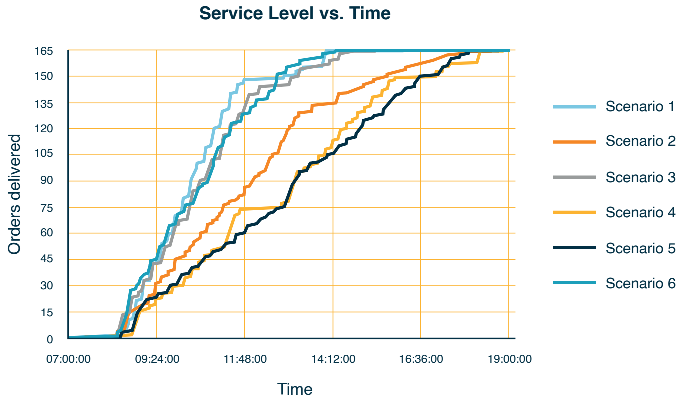

Figure 5.8: *Service level achieved by vans in different scenarios, for the level 2 demand*

To ensure that all orders were delivered, all scenarios required the same number of routes. However, in scenario 4, just one vehicle was required. As a result, it is the last scenario to complete the deliveries, as illustrated in 5.8. It is also the scenario in which the shortest distance is covered and in the shortest amount of time.

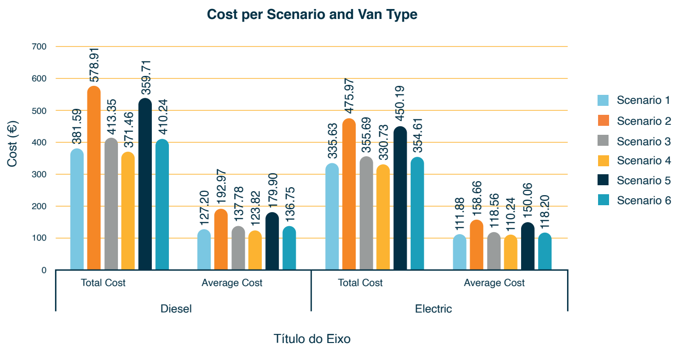

Figure 5.9: *Total cost of the deliveries using vans in different scenarios, for the level 2 demand*

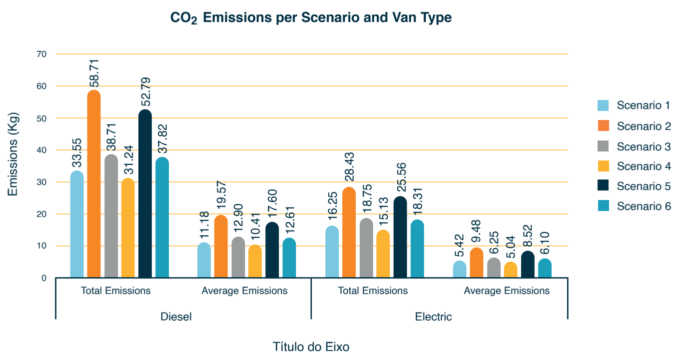

Figure 5.10: *Total emissions of the deliveries using vans in different scenarios, for the level 2 demand*

Once again, the diesel van has greater related expenses than the electric van. Despite the fact that this tendency is confirmed in all situations, it is significantly more substantial in scenarios 2 and 5 than in the others. Overall, the least costly scenario is scenario 4 when parcel lockers are used, and scenario 1 when they are not.

When it comes to CO_2 emissions, the difference between the van types is more noticeable, since the electric van is significantly more ecologically beneficial. Scenario 4 produced the fewest emissions, whereas Scenario 2 produced the most.

Trucks

Trucks are used as the vehicle type in the last set of situations. All scenarios required two unique routes to be completed by two distinct trucks because a single truck could not complete all deliveries during a workday.

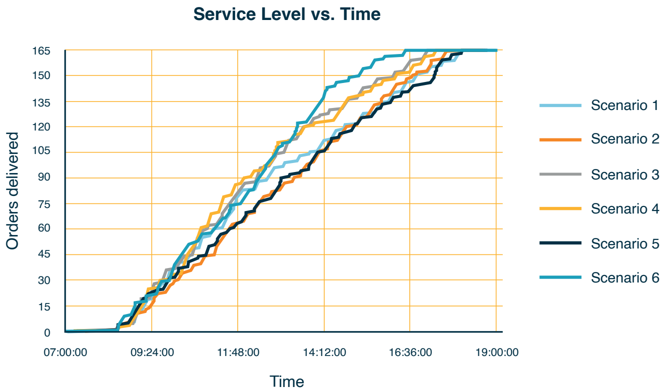

Figure 5.11: *Service level achieved by trucks in different scenarios, for the level 2 demand*

Figure 5.11 shows that scenario 6 was the fastest to deliver all orders at this level of demand while employing trucks. Then followed scenario 3, scenario 4, scenario 2, scenario 1, and ultimately scenario 5.

Table 5.6: *Measured parameters, total costs and CO_2 emissions for each scenario using trucks, for the level 2 demand*

Scenario	Number		Total Distance (km)	Duration	Cost (€)	CO_2 Emissions (kg)
	Routes	Vehicles				
1	2	2	179.86	15:20:32	642.89	55.23
2	2	2	269.17	20:31:16	811.50	82.64
3	2	2	192.99	15:25:56	654.37	59.25
4	2	2	179.81	14:56:52	635.02	55.20
5	2	2	260.85	20:39:03	807.92	80.08
6	2	2	185.21	15:22:44	647.56	56.86

Table 5.6 shows that the scenarios that traveled the least distance were scenarios 4 and 1, by an almost negligible margin. As a result, CO_2 emissions are nearly the same in both instances. Since the journey time is longer in scenario 1, the overall cost is higher in this scenario as well. Again in this example, the use of parcel lockers resulted in a less expensive process. These two scenarios were followed by scenarios 6, 3, 5, and 2, in terms of efficiency and sustainability. Using parcel

lockers helped to reduce costs and emissions in all of these cases, although the difference was not considerable.

Demand Level Overview

For this level of demand, scenario 4 performed the best for all types of vehicles as well. It is accountable for the shortest distances traveled, the smallest fleet size required, the lowest related expenses, and the lowest CO_2 emissions to the atmosphere. Scenario 2 presents the worst results, as it is the scenario that requires the highest number of routes and vehicles to perform all the deliveries.

When comparing the performance of various vehicle types, electric vans have the lowest related expenses. Cargo bikes, which are the most expensive, have related expenses that are more than three times those of electric vans. Vans also perform the deliveries the fastest. Cargo bikes, on the other hand, are the most environmentally friendly alternative, producing about a tenth of the emissions of electric vans.

5.4 Level 3 Demand

Level 3 demand corresponds to the highest level of customer demand simulated in the model. It is characterized by 330 requests. In the instances where this choice is available, 110 customers picked parcel lockers as the delivery place.

Cargo Bikes

The initial set of scenarios involved cargo bikes being employed to deliver the packages. Depending on the scenario, the number of routes ranged from twenty-nine to thirty-two, and the size of the fleet varied as well.

Table 5.7: *Measured parameters for each scenario, total cost and CO_2 emissions using cargo bikes, for the level 3 demand*

Scenario	Number		Total	Duration	Last Order	Cost (€)	CO_2
	Routes	Vehicles	Distance (km)		Delivered		Emissions (kg)
1	29	7	960.10	62:47:35	18:11:49	1716.74	2.88
2	32	15	2108.34	136:25:12	18:28:18	3265.45	6.33
3	31	8	1169.47	69:24:33	17:35:19	2029.92	3.51
4	29	7	947.27	62:05:56	17:54:47	1702.45	2.84
5	31	15	1978.34	128:30:55	17:50:23	3088.74	5.94
6	31	8	1069.45	76:40:25	16:49:23	1882.08	3.21

In terms of service level, scenario 6 delivered all orders the quickest, followed by scenario 3. The two slowest instances were 2 and 1, despite the fact that scenario 2 employed more than twice as many automobiles to accomplish the deliveries as scenario 1. Scenario 5 was faster than scenario 4, implying that the decline in service time was larger when parcel lockers were deployed in scenario 2 than when they were implemented in scenario 1.

Scenario 4 is the best in terms of overall cost and CO_2 emissions, followed closely by scenario 1. Scenarios 6, 3, 5, and 2 follow them. The worse the scenarios were, to begin with, the greater the reduction achieved by introducing parcel lockers.

Vans

The model was simulated using vans in the following scenarios. In each scenario, five routes were required to assure the delivery of all items.

Table 5.8: *Measured parameters for each scenario using vans, for the level 3 demand*

Scenario	Number		Total	Duration	Last Order
	Routes	Vehicles	Distance (km)		Delivered
1	5	2	273.74	15:15:30	16:49:29
2	5	5	609.25	29:47:58	14:06:12
3	5	2	342.17	17:12:59	17:52:29
4	5	2	249.92	14:20:21	16:13:25
5	5	4	594.44	29:24:13	18:02:43
6	5	2	328.26	15:48:10	17:21:42

Scenario 2 was the quickest to deliver all orders while covering the most significant distance and taking the longest time to do so. It was possible due to the deployment of a fleet of five vans, the largest among these scenarios. The second scenario with the most vans, scenario 5, is the last to deliver all the packages. The other scenarios only required two vehicles; the fastest was scenario 4, followed by scenario 1, scenario 6, and scenario 3.

Table 5.9: *Caption 3, for the level 3 demand*

Scenario	Diesel Van		Electric Van	
	Cost (€)	CO_2 Emissions (kg)	Cost	CO_2 Emissions (kg)
1	561.61	43.52	513.07	21.08
2	983.73	96.87	814.40	46.91
3	627.76	54.41	554.57	26.35
4	533.88	39.74	493.91	19.24
5	969.97	94.52	805.97	45.77
6	594.20	52.19	526.03	25.28

The scenarios performed consistently for both types of vans, with scenario 4 being the most cost-effective and ecologically friendly. It is also the scenario in which the shortest distance is required to satisfy all the orders. The following scenarios are scenario 1, scenario 6, scenario 3, scenario 5, and scenario 2. Using parcel lockers reduces both the cost and the amount of CO_2 emitted into the atmosphere.

Trucks

The final set of scenarios tested performed the deliveries using trucks. Due to its average speed, each route had to be executed by a separate vehicle, resulting in the same number of routes and vehicles.

Table 5.10: *Measured parameters for each scenario, total cost and CO_2 emissions using trucks, for the level 3 demand*

Scenario	Number		Total Distance (km)	Duration	Last Order Delivered	Cost (€)	CO_2 Emissions (kg)
	Routes	Vehicles					
1	3	3	202.48	21:49:33	16:49:29	890.99	62.15
2	4	4	518.46	41:13:33	14:06:12	1611.93	159.17
3	3	3	239.20	22:31:32	17:51:42	932.01	73.43
4	3	3	199.08	21:18:23	16:13:25	878.18	61.37
5	4	4	482.74	39:46:27	18:02:43	1556.75	148.20
6	3	3	236.52	22:53:21	17:52:29	937.23	72.61

The resulting findings are consistent with the obtained results from the other scenarios. Scenario 4 has the lowest related costs and emits the least CO_2. The utilization of parcel lockers helps to decrease the distance traveled as well as the time required to transit it. One thing to note is that scenario 2 outperforms scenario 5 in terms of overall package delivery velocity. They both need the usage of four vehicles. However, in scenario 2, the distribution of products throughout the routes is better balanced, resulting in a faster last delivery than in its parcel locker-using counterpart.

Demand Level Overview

Scenario 4 delivers the best outcomes yet again. The combination of applying heuristic 1 to build the routes and parcel lockers as delivery destinations result in the lowest costs and CO_2 emissions.

Electric vans offer the best cost-effectiveness outcomes, followed by diesel vans, trucks, and cargo cycles. The costs connected with cargo bikes are 3.69 times those associated with electric vans. Trucks managed to perform all the deliveries the fastest. Cargo bikes were once again the most environmentally friendly option.

Chapter 6

Conclusions and Future Work

In accordance with the objectives initially proposed, this chapter presents the main conclusions drawn from this dissertation. Its contributions will also be evaluated. In addition, some recommendations for future work will be made as to how to continue to develop this project.

6.1 Conclusions

The purpose of this dissertation was to develop a model of a last-mile delivery scenario that could be used as a decision-support tool for its planning. The simulation outputs of the model would then be analyzed to determine its efficiency and sustainability.

The model developed contained numerous factors that could be adjusted to understand the implications of the final results. In fact, the model was distinguished by various vehicle types, delivery route construction methods, and the use or non-use of parcel lockers. Each combination yielded distinct outcomes, which, when studied, enabled the user to plan the logistics of last-mile delivery better. Three distinct degrees of demand were employed in FlexSim to see how the behavior of the model altered for varying amounts of requests.

When the performance of the various heuristics was compared, heuristic 1 produced the best results. Not only did it provide fewer routes for each scenario examined, but it also assured the shortest distance traveled and the shortest time spent doing so. Heuristic 2 fell short of expectations, producing the poorest performance across all scenarios. When the routes were planned, sorting the shipments by weight had significant downsides since the distance traveled to finish each one was too considerable. Given that heuristic 1 was the best for all cases and heuristic 2 was the worst, it stands to reason that heuristic 3 was in the center, as it tries to combine the other two.

Parcel lockers are critical in lowering last-mile delivery costs and boosting sustainability. This method improved simulation results in nearly all of the cases studied. The critical focus should be growing the number of customers who choose this alternative over regular home delivery.

Different types of vehicles got different results in various aspects. Overall, diesel vans performed worse than electric vans in all scenarios, and trucks performed even worst. Trucks are not a viable option for last-mile delivery. The main drawback that electric vans present over diesel vans is that the acquisition price is far higher for the former than for the latter. In addition, battery degradation, which was not considered in the present model, also contributes to making the lifespan of an electric vehicle shorter than the diesel counterpart.

When comparing expenses, electric vans were the most affordable. The associated costs increased by 16% when diesel vans were used, by 86% when trucks were used, and by 253% when trucks were used. Cargo bikes, on the other hand, were the most ecologically friendly. Electric van emissions were 7.44 times higher, diesel van emissions were 16.44 times higher, and truck emissions were 25.96 times higher.

Since certain vehicle types perform better in one dimension while others perform better in another, there is no obvious decision about the optimum vehicle type. As a result, while deciding on the sort of vehicle to utilize, a decision-maker must consider the trade-off made between cost-effectiveness and sustainability. One possibility is to combine deliveries by using vans and cargo bikes. Performing the initial leg of the delivery in a van and then distributing the products among cargo bikes at a metropolitan hub may produce interesting outcomes that might be investigated in a future project.

Finally, it is reasonable to say that the model developed achieved its purpose, as it can readily be utilized to model various last-mile logistics scenarios. The locations in the model are easily changeable, implying that the planning might be done in any other city or area. The model is also scalable, since new components may be added without impacting the existing ones, which can help improve robustness and reality resemblance.

6.2 Future Work

Last-mile logistics is and will continue to be one of the most pressing concerns confronting metropolitan areas. As the global population grows, more people move to cities, and technology improvements encourage consumers to replace conventional on-site purchasing with e-commerce. Consequently, the number of products flowing will only expand over time.

New solutions are required to make LMD a more sustainable and efficient activity. Some of those already stated can begin to be incorporated in models similar to the one provided in this dissertation, allowing the impact on LMD to be examined. The combination of delivery vehicles and aerial drones is a viable candidate for FlexSim implementation.

Regarding the model at hand, there are some promising possibilities for making the produced model more durable and closer to reality. The speed of each car was set to remain constant at all times except when there was traffic. Defining the speed with an equation rather than using the average speed would make traffic flow more dynamic. Furthermore, the model would benefit if the weight of the cargo carried by the vehicle was also considered. The unloading process could be improved further by modifying its duration to follow a probability distribution. However, this would necessitate repeating the simulation of scenarios because they would no longer produce consistent results.

This dissertation focused on the immediate effects of using parcel lockers, both in terms of cost and environmental impacts. However, one of the primary benefits of using parcel lockers is the significant reduction in the likelihood of missed deliveries. Incorporating the possibility of missed deliveries into the model would provide a more accurate picture of the actual benefits of using parcel lockers.

One final word about using the optimizer tool in FlexSim. This tool uses evolutionary algorithms to intelligently and swiftly explore a given design space, allowing users to do multi-objective searches. It would be quite helpful to utilize this tool to optimize the routes and discover better solutions for this model in particular. The heuristics used left a lot of opportunities for improvement, which is easily possible with more advanced algorithms and metaheuristics.

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