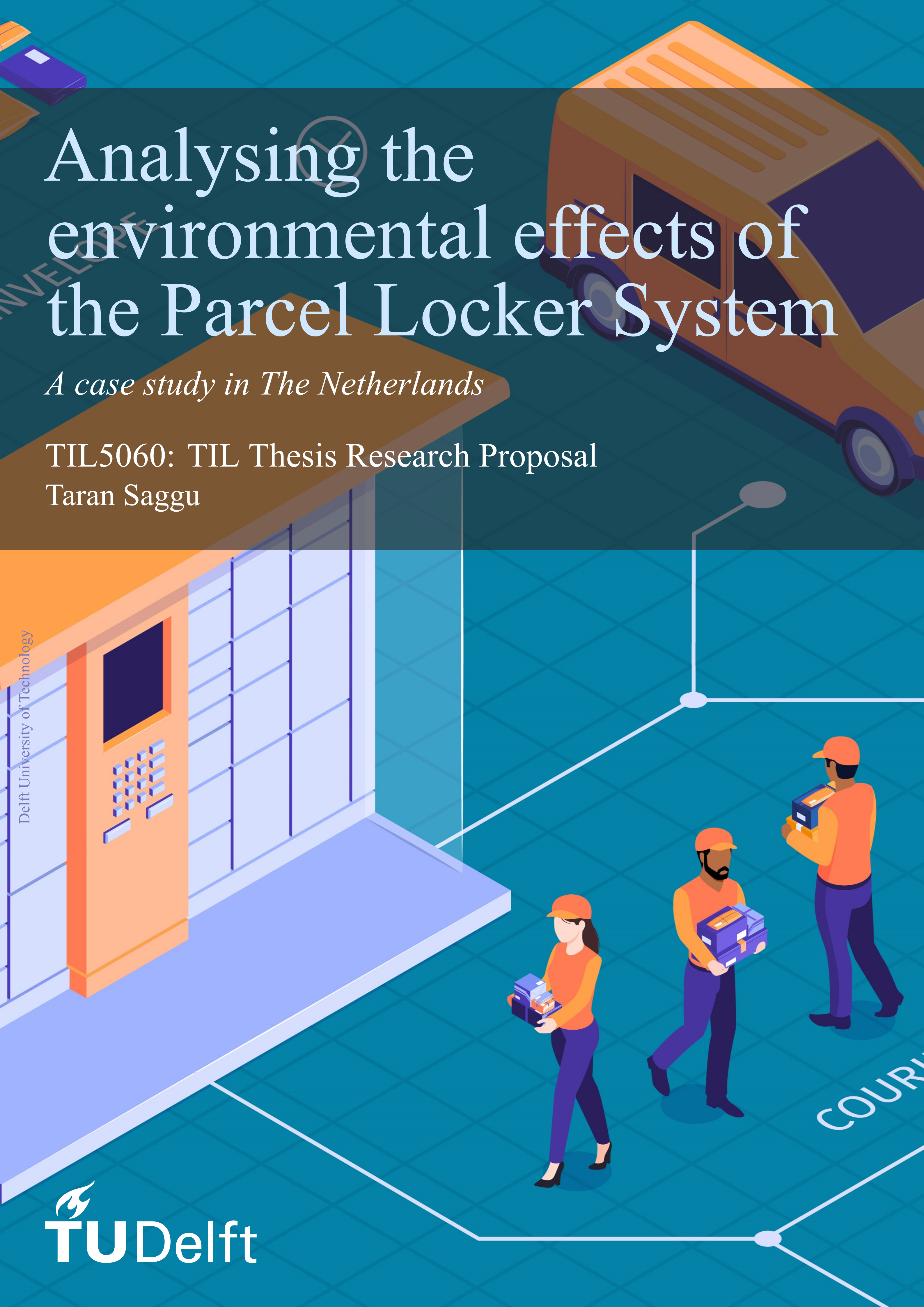

Analysing the environmental effects of the Parcel Locker System

A case study in The Netherlands

TIL5060: TIL Thesis Research Proposal

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TU Delft

Analysing the environmental effects of the Parcel Locker System

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TU Delft

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Abstract

The escalating trends in e-commerce have led to a surge in parcel delivery demands, necessitating innovative solutions for efficient and environment friendly last-mile deliveries. Parcel Lockers (PLs) have emerged as a potential answer to address the environmental impact of traditional delivery methods. The core of PLs lies in a benefit trade-off between the customer and the Logistic Service Providers (LSPs), where PLs lead to reduced vehicle kilometers (VKT) by LSPs but result in inconvenience to customers by enforcing them to travel to PL locations. However, a research gap exists concerning the assessment of the environmental implications of PL systems holistically which comprise the customers, the LSPs and the PL distributors. This master thesis aims to bridge this gap by conducting a comprehensive life cycle assessment (LCA) of a PL system via the Environment Footprint (EF) methodology. Extensive literature research is undertaken to understand the various aspects and factors that affect the usage of the PLs, leading to the development of a conceptual model encompassing its key components. The EF method is applied to analyze the climate change impacts specifically in areas of De Pijp and Ten Boer respectively. The method considers relevant characteristics, such as customer travel behavior and mode choice. The total environmental impact in the rural setup, where customers utilized cars to access the PL, is found to be the highest leading to $1028\ g\ CO_2$ eq emissions per parcel produced. The urban setting has the least overall environmental impact, due to customers walking to the PLs which amounts to $42.46\ g\ CO_2$ eq emissions per parcel. The PL system is also compared to conventional home deliveries (HDs) in this thesis which indicates that the PL system performs better environmentally, unless the mode choice by customers is cars. When considering only the transport emissions by LSPs in PLs and HDs, the PLs outperform HDs in both the scenarios. It is found that the PL systems reduce the emissions by upto 75% in urban setup and about 50% in rural setups which amount to about $36.3\ g\ CO_2$ eq emissions per parcel. Furthermore, a sensitivity analysis is conducted to evaluate the potential impacts of future policy implications and developments regarding the environmental performance of the PL system. The results furnish valuable insights into the different scenario factors and system design factors, facilitating informed decision-making abilities for policymakers to promote eco-friendly last-mile delivery practices.

Preface

Before you lies the master thesis on the topic *"Analysing the environmental effects of the Parcel Locker System"*. It has been written to fulfill the graduation requirements of the Transport, Infrastructure and Logistics (TIL) program at the Delft University of Technology in the Netherlands. I was engaged in researching and writing this thesis from March until September 2023.

During the beginning of the second year of my masters program, I had to write a research proposal as a mandatory course of my curriculum at TU Delft to help me in preparation for my actual thesis. I started researching about last mile delivery innovations and, then a novel innovation namely, Parcel Lockers came across me. I decided to go ahead with this topic as I found it interesting and relevant for my specialization track within the TIL program. When the course ended, I decided to further delve into research related to this topic and hence finally came up with this topic. Additionally, I have learned that struggling is part of the process. Therefore, this thesis has taught me valuable lessons both professionally and personally.

I would particularly like to thank my daily supervisors, Dr. J.A. (Jan Anne) Annema & Dr.ir. A.J. (Adam) Pel, for their excellent guidance and support during the process. Their expertise and experience has helped me shaped my thesis to the level that is present before you. Additionally I would also like to thank my chair supervisor, Dr. G.P. (Bert) van Wee for managing the whole process of my thesis for these past months. This has given me the freedom to conduct the research in my own way and maximized the learning opportunities, for which I am grateful.

Finally, I want to thank my family and friends for their constant support. I would also like to thank you, my reader: I hope you find the topic and this thesis interesting as much as I do.

Taran Saggu
Delft, September 2023

Summary

There has been a significant growth in the business to customer(B2C) market in recent years in countries all across the world as a result of digitization of services. With the rise of e-commerce, the amount of home deliveries (HDs) has also increased, especially during Covid-19 which resulted in about 334.9 million parcel deliveries in the Netherlands. This accounts for an increase of 27% compared to 2019. This growing demand of parcel necessitates efficient last mile delivery, which is currently the most inefficient process of the entire logistic supply chain and can account for 41–50% of shipment costs. Thus the innovations that improve delivery efficiency, reduce fuel consumption, and optimize resource allocation can help lower costs for delivery providers and improve their overall profitability. Increased delivery demands also accounts for congestion, pollution, and other negative effects on the environment, safety, and health. In addition to these effects, problems such as lack of economies of scale, slow identification of handover points, long walking distances, and the not-at-home problem still persist in the logistic supply chain.

Public Lockers or Parcel Lockers (PLs) are such an innovation to these issues where customers can pick up their orders at any time of their convenience, thus making them highly flexible. When a customer places an order online, they can choose to have their package delivered to a nearby PL location instead of their home or office. Once the package is ready for delivery, the logistics service provider (LSP) places it inside the designated locker at the chosen locker location.
The objective of this paper is to assess and quantify the environmental impacts of PL systems. This aids in providing a grounded assertion on identifying the parts of a PL system that contribute most to its environmental impact. A brief comparison of the transport emissions of LSPs in PL system to the conventional home delivery (HD) as a last mile delivery process follows next in this thesis. This ultimately answers the question on whether PL systems have a positive impact on the environment in terms of GHG emissions. The main research question of this thesis is:

"What are the environmental impacts of implementation of parcel lockers system?"

A PL system comprises of customer, the LSPs and the PL distributors as the key actors. The PL distribuotrs are in charge of the life cycle phases of the PL ranging from its production and packaging to it transport followed by it operation & maintenance and all the way to its recycle. The LSPs delivery parcel to the PL locations by delivery trucks in form of VKT. Finally the customers, based on their location and distance can choose which mode to use to access the PLs in order to retrieve or return their parcels. To answer the main research question, firstly the ways in which a PL system can be setup are studied via a literature review. It is found that important factors that influence the use of PLs are PL locations and customer mode choice to access PL locations. It is found that the PL system setups can broadly be setup in an urban setting or a rural setting. For this thesis the urban area of De Pijp in Amsterdam and Ten Boer in the province of Groningen are chosen respectively. Based on findings in the literature the Global Warming Potential (GWP) is chosen for this case study. This is a comprehensive indicator that has very high relevance in scientific literature that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in $kg\ CO2$-eq or $g\ CO2$-eq per parcel.

The literature review serves as a comprehensive foundation upon which the conceptual model is built through which the second sub-question is answered. Consequently a conceptual model is developed by a system diagram which helps identify the potential factors that results in potential environmental impacts of the PL system. The quantification of the potential impacts of the different PL setups becomes feasible through the conceptual model's visual representation and systematic approach. In order to determine the environmental impact of each PL system setup and transport mode, an extensive review is conducted in combination with data from the Ecoinvent v3.8 database. The *climate change* is selected as the environmental impact category in this study.

To evaluate the different emissions related to a PL system, a life cycle assessment (LCA) using the Environment Footprint (EF) method is used which considers all life cycle emissions of a PL system. This method enables in hot-spot identification of a system or a product. The reference data from the Environment Product Declaration

(EPD) is extrapolated and made specific to case study which is then used in the Ecochain Mobius software. This is data comprises of different parameters related to the different life cycle stage of the PL. In this research, the LCA consists of a PL production, packaging, transport, use by customers and LSPs, maintenance and finally end-of-life of PLs. To allow for a fair comparison between different PL setups and the transport emissions by LSPs in PL system and HDs, the GWP emissions are expressed in $g\ CO2$-eq per parcel.

The PL systems are most efficient in urban areas owing to use of green mobility ways by customers and reduced VKT by LSPs. Electricity consumption by the PLs in urban area is the 'hot-spot' or the most negatively impacting phase of the PL system accounting for 48.3% of total emissions while for rural setup where customer bike to PL location have the LSP transport emissions as the highest. Customer travel causes most emissions when they travel to PL locations by means of a car due to increase in vehicle kilometers travelled (VKT) both by the LSPs and the customers. Comparison of *transport emissions* caused by LSPs in PL system setup and conventional HD scenario is done which shows that the PL systems are generally beneficial and produce up to 49% less CO_2 emissions in rural setup and 75% less CO_2 emissions per parcel in over a life cycle time of 15 years considered in this study. However, it is evident from the case study that overall PL system performs worse only in the case where all the customers travel by car in order to access PLs. This is where benefits of PLs are undone if all the customer trip are made by car.

A sensitivity analysis on two categories of factors namely: scenario and system design factors is conducted to gain insights into the effects of most impactful factors and more sustainable practices in the future. It is seen that emissions grow exponentially when delivery failure rate in HDs are increased. Hence it is concluded that the parcel delivery failure rate should be kept as low as possible (below 5%) to avoid additional and unnecessary VKT by LSPs. Trip chaining can result in reduced emissions by up to 79.34% due to reduced overall extra distance to travel to PL locations by the customers. Finally scenarios involving more PL locations in the future is implemented where it is concluded that majority of reduced emissions are seen in the case of PL system in rural setup where customers use cars for travel to PL locations. A 40% increase in PL locations can result in a reduction of 385 gCO_2 eq per parcel as environmental gain in reduced VKT by customers and LSPs outweigh the increase in emissions of the PL life cycle.

This is followed by an anlysis of system design factors where less energy is consumed by PLs due to possible policy regulations or technological advancements in the future can results in about 18.04%-30% reduced emissions based. Whereas setup of additional sorting centers, especially near rural areas in the future results in less amount of VKT by LSP delivery trucks. This can have a positive impact on the environment by reducing emissions upto 17.7%-35% in rural areas where customer use bike to travel to PLs.

The core of this thesis lies in the distribution of benefits between customers and LSPs. While customers need to travel to reach PL locations for package retrieval, this inconvenience is offset by the substantial gains achieved in the efficiency of logistics operations. The pivotal benefit lies in the significant reduction of vehicle kilometer traveled (VKT) by delivery trucks. As LSPs consolidate multiple deliveries into a single trip to replenish PLs, fewer vehicles cover more deliveries, resulting in an overall decrease in the VKT. This contrasts with conventional HDs, where customers receive packages at their doorstep without needing to travel, but LSPs face the challenge of higher VKT due to dispersed destinations. This distribution of advantages underscores the role of PLs in optimizing logistics operations while acknowledging the trade-off customers make in traveling to access their parcels.

Overall, it can be summarized that PLs can offer a convenient and efficient solution for package delivery, given that the transport used by customer is green (either by walking or biking) and they combine trips as much as possible. This will benefit both recipients and delivery service providers by decreasing number of failed deliveries and emissions from delivery vehicles. Despite the limitations of this thesis, it contributes towards the holistic understanding of PL systems both academically and practically. This is done by bridging the research gap and potentially influencing policy makers for informed decision making that promote sustainable behaviour amongst the different aspects of the PL system. A variety of factors or aspects can be improved and scope of the study can be expanded to different dimensions other than environment in the future.

Abbreviations

A list of abbreviations are shown in Table 1 which is used thought this thesis report instead of the full form. This helps the reader to get a clear understanding and make the text easy to read by avoiding repetition.

Table 1: *A list of abbreviations used in this thesis report*

Abbreviation	Full form
B2C	Business to Customer
PL	Parcel Locker
LSP	Logistic Service Provider
HD	Home Delivery
LCA	Life Cycle Assessment
TIL	Transport, Infrastructure and Logistics
EPD	Environment Product Declaration
EF	Environment Footprint
GHG	Green House Gas
GWP	Global Warming Potential
CO_2	Carbon dioxide
$kg\ CO_2$ eq	Kilogram carbon dioxide equivalent
VKT	Vehicle-Kilometers Travelled

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1 Introduction

There has been a significant growth in the business to customer (B2C) market in recent years in countries all across the world as a result of digitization of services. In 2015, roughly 7.5% of all retail sales were conducted online, while in 2024 this number is expected to increase to 21.8%. With the rise of e-commerce, the amount of HDs has also increased [32], especially during the Covid-19 pandemic, which resulted in about 334.9 million parcel deliveries in the Netherlands. This accounts for an increase of 27% compared to 2019. The last mile delivery is the most inefficient process of the entire logistic supply chain [9] and can account for 41–50% of shipment costs [33]. Thus the innovations that improve delivery efficiency, reduce fuel consumption, and optimize resource allocation can help lower costs for delivery providers and improve their overall profitability.

Traditional delivery methods may struggle to cope with the higher demand regarding the direct delivery to consumers. This leads to several challenges such as delivery delays, missed deliveries, and increased transportation congestion. This also accounts for congestion, pollution, and other negative effects on the environment, safety, and health[4]. The majority of delivery vehicles are still powered by internal combustion engines that contribute to these adverse effects [33]. In addition to these effects, problems such as lack of economies of scale, slow identification of handover points, long walking distances, and the not-at-home problem still persist in the logistic supply chain [2] [13].

Public Lockers or Parcel Lockers (PLs) as shown in Figure 1.1 are an innovation to these issues where customers can pick up their orders at any time of their convenience, thus making them highly flexible. When a customer places an order online, they can choose to have their package delivered to a nearby PL location instead of their home or office. Once the package is ready for delivery, the logistics service provider (LSP) places it inside the designated locker at the chosen locker location. The customer receives a notification with a unique pickup code or QR code. To retrieve their package, the customer visits the PL location, enters the pickup code or scans the QR code to authenticate themselves, and the locker system opens the corresponding locker. The customer then collects their package from the locker, and the locker door securely closes for the next use. PLs offer convenience, security, and 24/7 accessibility, making them a popular choice for both customers and LSPs in the last-mile delivery process.

The PLs are usually located in places that are constantly visited by people such as supermarkets, transport hubs (stations) and apartment blocks [33]. These are unmanned and can be both emptied by the customer and filled by the LSP.

Figure 1.1: *A PostNL PL in the municipality of Waterland, on the Graaf Willemlaan in Monnickendam [56]*

1.1. The Parcel Locker system

Typically, the PL service starts when a customer orders a product via an online retailer. This then leads the LSP to dispatch the courier to deliver this parcel to the PL locations possibly close to the respective customers. The customers then have the flexibility to collect their parcels by deciding a convenient time and the mode of their choice to travel to these PLs. Customers that use PLs, often choose to pick up their parcels on foot, bike or car. A typical PL system is depicted in Figure 1.2 through a parcel joruney perspective. If the customer wants to return or exchange a parcel, they can similarly travel back to PL locations where the courier can collect their parcels and process their request.

This type of PL system can be used by couriers and users for delivering and collecting packages. These PLs can be installed in for example neighbourhoods, supermarkets, metro stations, malls or near workplaces, which essentially act as an interface where delivering and collecting of the parcels takes place.

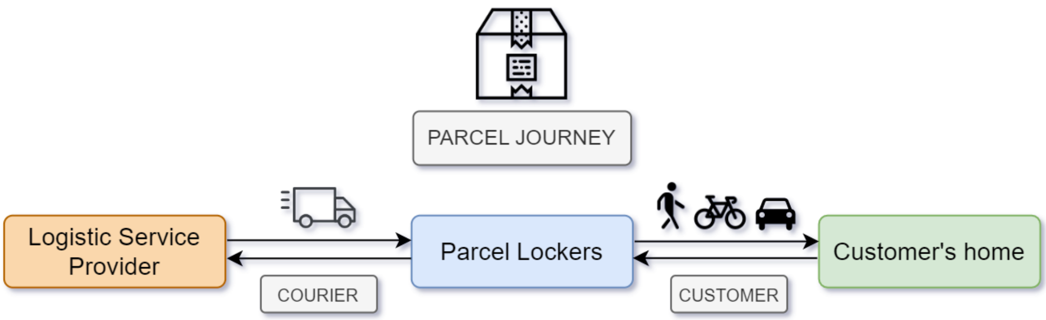


Figure 1.2: *A PL system depicting parcel journey*

PLs are being used in numerous countries (see chapter 3) owe their success to high parcel delivery rates and reduction in failed deliveries by the couriers and ultimately by the LSPs. Recently companies like InPost have announced their intention to increase their PL network with new key partnerships [45] in the UK, France, Spain and Portugal. PostNL in the Netherlands also plans to expand it PL network to 1500 lockers by end of 2024, so that everyone can have an easy and a close access to PLs. Recent years have shown that PLs have been gaining popularity as a last mile delivery innovation. Moreover, the estimation is that PLs will become a $1.6 billion industry by 2028, hence it is necessary to investigate the environmental impact of this system for its sustainable development.

The aim of this thesis is to analyze & assess the environmental impacts associated with implementation of PL systems in different setup scenarios. This aids in identifying the parts of a PL system that contribute most to its environmental impact. This is be followed by a brief comparison of the transport emissions of LSPs in PL system to the conventional home delivery (HD) as a last mile delivery process. Finally, a reflection on policy making for sustainable measures considering the environmental aspects to improve such a system is be done.

1.2. Research Objective and Questions

As stated above, the aim of this thesis to analyze & assess the environmental impacts associated with implementation of public lockers at preferred locations and reflect on their effectiveness on improving last mile delivery operation. This is achieved by answering the following main research question:

> *"What are the environmental impacts of implementation of parcel lockers system?"*

In order to answer the main research question, the following sub-questions need to be answered first:

- *SQ1: What are the different ways in which the PL system can be setup?*
- *SQ2: What are the potential factors that determine the environmental impacts of PL system?*
- *SQ3: How can the potential impacts of the different ways that the PL system is setup be quantified?*

Firstly, the different ways in which the PL system can be setup are studied. This includes an examination of factors related to the adoption and usage of PL systems in different countries. Secondly, determination of the potential factors that influence the environmental impact of such systems is done by developing a conceptual model that incorporates the 3 aspects of the PL system namely: LSPs, Customers and PL distributors. All the relevant environmental impacts are visually represented in this model. Lastly, the potential factors that determine the environmental impact of PL system are quantified using a Life Cycle Assessment (LCA) methodology. This also includes the interpretation and evaluation of the results of this methodology. By doing this, the impacts of the implementation of PL systems in an urban and a rural setting are be compared and reflected upon. Addressing these questions not only offers immediate advantages with PLs but also yields valuable perspectives on the prospective environmental benefits of PL systems. This, in turn, empowers well-informed decision-making concerning the environmental implications of this last-mile delivery innovation.

1.3. Scope

Environmental Impact Analysis

Within this thesis scope of analyzing the environmental impact of PL systems in the Netherlands, several key aspects can be considered. An environment footprint (EF) analysis by means of a LCA involves quantifying the emissions associated with PL system in an urban and a rural setting. The scope of this thesis is further expanded to comparison of emissions of the PL system with the conventional HDs. The aim is to assess the reduction in emissions achieved by utilizing PLs and quantify the corresponding environmental benefits. Furthermore this thesis reflects on a sensitivity analysis based on the different scenario and system design factors by analyzing the emissions of different setups. Through this, the assessment of the environmental efficiency of different PL system setups and identification of opportunities for further improvements in environmental performance of the PL system is done. Note that whenever emissions are mentioned to in this thesis, the scope is limited to Global Warming Potential (GWP) emissions which are expressed in $Kg\ CO_2$-eq or $g\ CO_2$-eq per parcel.

Policy Implications

Besides environment impact analysis, this thesis briefly reflects on some policies in section 7.2 based on the results presented in chapter 6. This is done by exploring factors that influence use of PLs. Another important aspect is the comparison of PLs with alternative delivery methods, such as conventional HDs. This analysis evaluates the environmental impact of these methods and identifies their strengths and weaknesses from an environmental perspective, providing a basis for informed decision-making and identifying the most sustainable delivery options. Finally, this study explores potential policy interventions and recommendations by stakeholders that can improve the environmental performance of PL systems and promote their usage.

1.4. Relevance

This study makes a substantial contribution by presenting a scientifically valid statement regarding the environmental performance of a PL System, both in urban and rural contexts. The study focuses on enhancing last-mile delivery efficiency, a critical contributor to the overall environmental impact of the logistics sector. By analyzing the environmental impacts of PL systems, insights about mode choice by customers and how the system performs against HDs can be gained. Consequently these insights can be used as an advantage to improve last-mile delivery systems and minimize associated environmental consequences. The outcomes of this study have implications for policymakers, delivery service providers, and retailers, enabling the development of sustainable policies, enhance energy efficiency, and promote eco-friendly practices.

Furthermore, the study considers consumer factors such as PL locations and customer mode choice that provide a strong base for development of scenario for this thesis. Analysis of different scenarios can help in hot-spot identification of the most negatively impacts aspects of the PL system. Conducting a sensitivity analysis based on scenario and system design factors can guide initiatives such as efficient energy consumption, low failure delivery rates and placement of sorting centers close to rural areas aimed at improving the environmental performance of PL systems. In conclusion, the analysis of the environmental impact of PLs in the Netherlands addresses crucial environmental challenges, provides insights into sustainable logistics practices, and contributes to the transition towards a greener and more responsible delivery system.

1.5. Thesis structure

The remainder of this report is organized as follows: In chapter 2, the research methodology applied in this thesis report is described. This has two key components namely: Data Acquisition and Data Processing. This is followed by chapter 3 where background information on PLs and review of some studies on PLs and their relation to the externalities specifically related to environment are presented. This section is used to answer the first sub-question on how can the PL system be setup. The second sub-question is answered in chapter 4, where a conceptual model is developed which illustrates the potential factors pertaining to the PL system that have an environmental impact. These factors along with their interrelationships and effects are explained in this section. The third and final sub-question is answered in chapter 5, which entails a case study which is designed based on the literature review and the conceptual model. After the sub-questions are answered, the results of the case study are discussed in section 6.1 where the overall and setup specific *'Climate Change'* impact results are discussed. This section also includes sensitivity analysis to enhance the quality of this thesis. Finally, a conclusion of this thesis and a discussion which includes policy implications, limitations and future recommendations is reflected upon in chapter 7.

2
Methodology

This chapter provides detailed information about the methodology used to answer the main research question in this research. Figure 2.1 briefly mentions the different methods that are used to answer the sub-questions and consequently the main research question in this thesis. section 2.1 provides an overview of the literature study, including the search method for relevant papers and selection criteria. section 2.2 explains the process of developing the conceptual model and the input used in this process. Finally, section 2.3 details the construction of the quantitative environmental impact model and the collection of input data.

Subquestion	*Methodology*
SQ1: What are the different ways in which the PL system can be setup?	Literature Research
SQ2: What are the potential factors that determine the environmental impacts of PL system?	Literature Research & Conceptual Model
SQ3: How can the potential impacts of the different ways that the PL system is setup be quantified?	Life-Cycle Assessment

Figure 2.1: *Methodologies for the sub-questions*

2.1. Literature Research

For this thesis, a comprehensive literature research is conducted for better understanding of a PL system. The literature study is first used to explore about different aspects on the PL system and the current trends of PL use in different countries. This provides input in the ways in which a PL system can be setup. Secondly, the important factors that influence the use of PLs are studied to further explore and refine the conceptual model by showing relationship between different aspects of PL system. Additionally the literature research gives partial input in developing of a conceptual model discussed in detail in chapter 4 by providing insights into what kinds of emissions are studied when PLs are studied.

The literature research strategy is based on finding the articles including keywords related to the selected topic as shown in Table 2.1. Search engines used were Google Scholar and Scopus for finding articles and some websites that describe the challenges in Last-Mile Delivery currently. A total of 16 research papers and articles were found relevant to this thesis. Abstracts of each of the papers found initially were read briefly to get an overview followed by snowballing method on some relevant publications [58] resulting in 4 additional articles.

A brief overview of each article found is presented later in chapter 3 (Table 3.1-Table 3.3). Some additional criteria based on the year of acceptance of articles in different conferences: Only the articles belonging to or newer than the year 2016 were selected, which allows for the most recent access and insights in the field of PL along with their environmental impact. Focusing on recent papers allows for clear identification of emerging trends and potential gaps in the existing literature relating to PLs that may have emerged in the last few years. This ensures that the research is both current and comprehensive, enhancing the quality and relevance of this thesis.

Table 2.1: *Research strategy*

Concept groups	Last-mile delivery; Parcel Lockers; Pickup points; Environment effects
Keywords	Last-mile delivery: Innovation, optimization PLs: Location, acceptance, distance, systems, customer access Pickup points: Emissions Environment effects: Emissions, traffic, sustainable city logistics, externalities
Year	Recent articles referred (2016 or newer)

2.2. Conceptual Model

A conceptual model is developed in this research to provide a visual representation of the PL system regarding its environmental impact. This model is based on the societal impact model [55] by only considering the environment aspect. The development of such a societal impact model was previously taught in the curriculum of the masters programme of Transport, Infrastructure and Logistics (TIL) in the course *"Innovations in Transport and Logistics"*.

The conceptual model is developed by means of a system diagram which serves as a visual representation of the key components and interactions within the system, with a specific focus on environmental aspects. It includes all the three key aspects of the PL system as later described in chapter 4. The different decisions taken by the actors involved are represented in this model which ultimately have different kinds of emissions related to them. These decisions and their effects that were included in the conceptual model were obtained from the literature study and an EPD report [1] which provides insights into the different phases of life cycle of PLs. This system diagram provides a clear and concise representation of how the PL system interacts with the environment, helping stakeholders to understand and address its environmental implications effectively. By illustrating the relationships between these aspect and the environmental factors, the system diagram provides a clear understanding of how the PL system influences the environment.

2.3. Quantification of potential environmental impacts using LCA

To briefly give context and relating it to previous methodologies, the conceptual model forms the basis for the quantification of different potential environmental impacts of a PL system. Additionally the literature review aids in knowing which type of emissions have been taken into account in previous studies regarding the environmental impacts of PLs. The scenario setups of the PL system are discussed in subsection 2.3.1 along with the location motivation. While, the software used to conduct the LCA in this thesis is described in subsection 2.3.2. The application of LCA is further explained in chapter 5 where the GWP (Global Warming Potential) emissions of the different life cycle phases of the PL system are modelled and quantified. The means of gathering data about PLs and the transport emission factors are discussed in subsection 2.3.3. Lastly, subsection 2.3.4 describes which of the 16 impact categories is relevant and is chosen for this study. Finally a reflection and identification the parts of PL system that contribute most to its environmental impact (i.e. "hot spot identification") [17] in different PL system setups is done which makes the basis for conclusions and recommendations.

The utilization of the Environmental Footprint (EF) method in conjunction with the Ecoinvent v3.8 database within Life Cycle Assessment (LCA) is applied in this thesis. Life Cycle Assessment (LCA) is a systematic and comprehensive methodology used to evaluate the environmental impact of a product, process, or system throughout its entire life cycle. This approach considers all stages, including raw material extraction, production, distribution, use, and end-of-life disposal or recycling. LCA involves the quantification and analysis of various environmental aspects, such as energy consumption, greenhouse gas emissions, water use, and waste generation. LCA plays a crucial role in supporting environmentally conscious choices and fostering the development of greener and more eco-friendly practices [18]. A generalised LCA methodology is explained in Appendix C.

2.3.1. Comparative Case Study

A comparative case study is done in this thesis by considering the implementation of PL system in an urban setting and a rural setting which is discussed in detail in section 3.6.

To first compute and then consequently compare the environmental impact of the PL systems within its different setups (urban and rural), a full *Life-Cycle Assessment (LCA)* for the PL system is chosen. This provides a holistic and systematic approach to evaluate the environmental impacts of the system throughout its entire life cycle. Its benefits include informed decision-making, improved environmental performance, sustainable design, and support for policy development and stakeholder engagement. A full Life Cycle Assessment (LCA) is critically important as it considers all stages of the PL system's life cycle, which helps identify the environmental hotspots and consequently the potential areas for improvement throughout the system. This ultimately reflects into informed policy making and recommendations for a more sustainable last-mile delivery system.

The focus of this thesis takes into account the LSPs, the PLs and the customers for the LCA study due to the reasons mentioned in section 1.1. This is where mobility data for LSPs and customers along with different life cycle phases data for the PLs is considered. For this specific reason a system boundary is defined as shown in Figure 2.2 to make it clear which processes are included in this study.

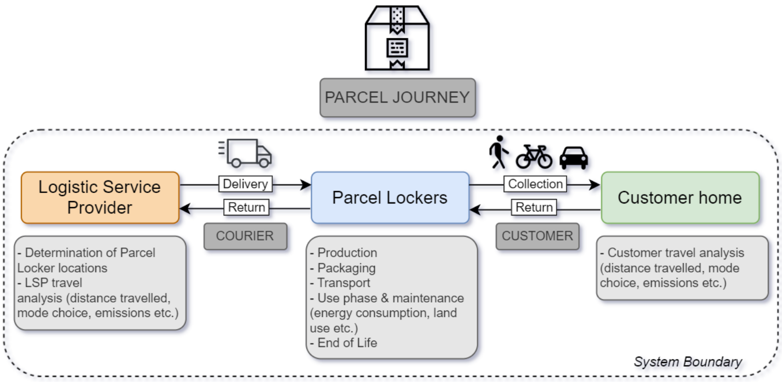


Figure 2.2: *System boundary of a PL system*

<u>Motivation for PL location choices</u>

This section describes the motivation for choosing an urban and a rural location for this case study.

De Pijp

For this thesis the urban location chosen for the PL system setup is 'De Pijp', an urban neighbourhood in Amsterdam. This choice is made due to the easy availability of demographics and city characteristics. Since there are a larger number of PostNL PLs for parcel collection available in the area of the De Pijp as shown in figure Figure 2.3, the inhabitants of Amsterdam can choose the nearest collection point [39]. Moreover previous research findings regarding last mile delivery efficiency has been been done which concluded that the usage of PLs is beneficial concerning the location of De Pijp [54].

Figure 2.3: *Parcel Machine network in De Pijp [39]*

Ten Boer

The rural location for the PL system setup is chosen to be 'Ten Boer', a village and a former municipality in the northeastern Netherlands, in the province of Groningen. PostNL currently has over 400 PLs across the Netherlands in a whole host of municipalities, including Almere, Tilburg and Breda. PostNL in addition to this is also in communication with different municipalities across the Netherlands to achieve 1,500 PostNL PLs in 2024 [42]. Similar to the urban location setup, previous research has been done on willingness to use PLs in Ten Boer which throws light on travel behaviour of the residents of the location. This proves to be beneficial for this study [5]. PostNL parcel collection points distribution in Ten Boer and the surrounding area is shown in Figure 2.4 which shows that the PL network distribution is very limited when compared to an urban setup [40].

Figure 2.4: *Parcel Machine network in Ten Boer [40]*

2.3.2. Software

In order to make this thesis suited to the scope of study chosen, the LCA on software Mobius by Ecochain is conducted via the environment footprint method using references from the Ecoinvent v3.8 database released in 2021. A number of well established LCA softwares other than Ecochain Mobius are available currently such as SimaPro, GaBi, oneClickLCA, and openLCA. The main motivation behind choosing Ecochain Mobius over other LCA softwares is its ease of use due to intuitive interface and extensive in-tool guidance for new users. Additionally Mobius's cloud based application improves the accessibility and ensures centralized data security for its users [20].

SimaPro v9.1.0.11 (2019) was used to create the EPD of the PL for the reference data and used to analyse the environmental impacts of 4FH Universal lockers (3 columns) from SteelCase throughout its life cycle. To be precise the locker in that case was available for use for 8 hours a day, 5 days a week for 15 years. The configuration of PL used in this study is the 4-tower configuration which is later explained in section 5.2.

Since the upstream and core process do not affect the duration for which these lockers are operated, i.e., only the downstream activities will have a different emission impact as self-service PLs are available 24 hours 7 days a week. The system's scope considered in the EPD includes the whole life cycle of the product, from obtained raw materials to manufacturing, use and end of life. System in the EPD is divided in 3 stages as explained in Appendix B:

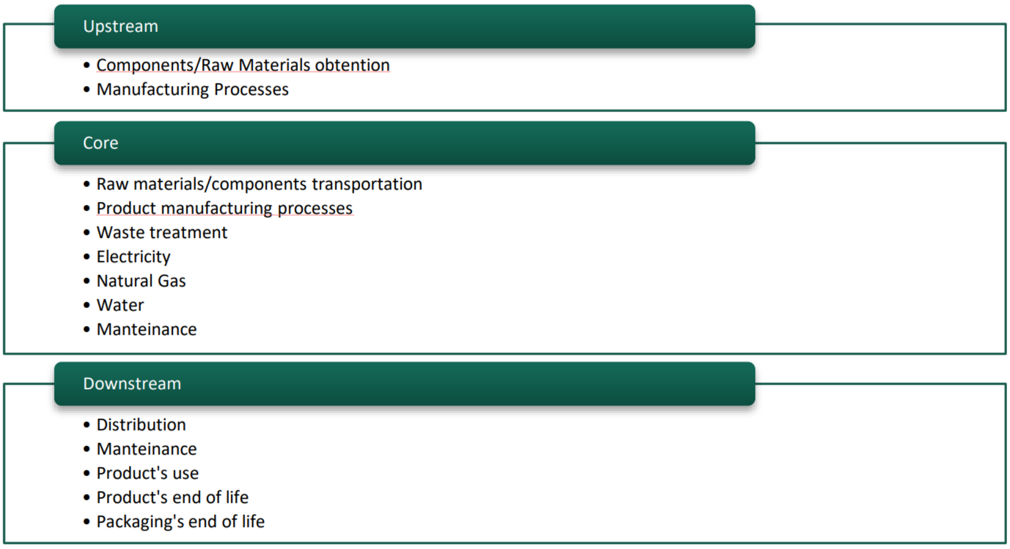


Figure 2.5: *System's scope for reference data [1]*

A provision of applying four LCA methods is incorporated in the Ecochain Mobius software namely: EN15804; openLCA; Environment Footprint (EF)and the SBK Bepaligsemethode. The EN15804 and the SBK Bepaligsemethode methods focus more on determining the environmental performance of buildings, construction projets and civil engineering works. OpenLCA is an open-source software tool with a flexible platform used to perform life cycle assessment (LCA) studies. It supports various LCIA methods, such as ReCiPe, CML, IMPACT World+, and others, enabling users to choose from a range of impact assessment methodologies based on their study's objectives and requirements. However, openLCA has a steep learning curve, espcially for new users at it requires thorough knowledge of the different LCIA methodologies in it.

Lastly, the Enviroment Footprint (EF) method is suitable for assessing the overall environmental performance of products and organizations across various industries that can cover a wide range of product categories beyond construction. It includes multiple impact categories, such as climate change, acidification, eutrophication, and others, to provide a comprehensive picture of a product's or organization's environmental footprint. The EF method aims to provide a harmonized and standardized approach to environmental assessment across the European Union. The EF method can also be related to policy relevance as this method aligns with EU policies on sustainability, green procurement, and environmental labeling, making it relevant for compliance and reporting purposes. Hence, for these reasons the EF method is chosen for this case study.

Modelling of different life cycle stages of PL system for this thesis

Contrary to the stages considered in the reference EPD report's system scope as shown in Figure 2.5, as the entire PL system is considered in this case study, Figure 2.6 shows how the different life cycle stages of the PL system are modelled and exactly which components of the PL system are included in which of the respective stages.

The production phase includes the materials and energy required for construction and assembly of PL. This is followed by packaging phase in which the different materials required are considered and modelled into Ecochain. Once the PL is assembled and packaged, it is transported by the distributor to the respective PL installation location. The most crucial phase of the PL system life cycle comes after this which is the use phase. This phase considers the access of PLs by customers and LSP trucks for collection and delivery of parcels. This phases additionally includes the materials and energy use for the maintenance and continuous use of PL during its entire life cycle. Once the current life cycle of PL is considered to be over, the phase end-of-life comes into affect which considers the energy use for treatment and processing of PL materials for its next life cycle. Detailed description of how the phases are modelled is given in chapter 5.

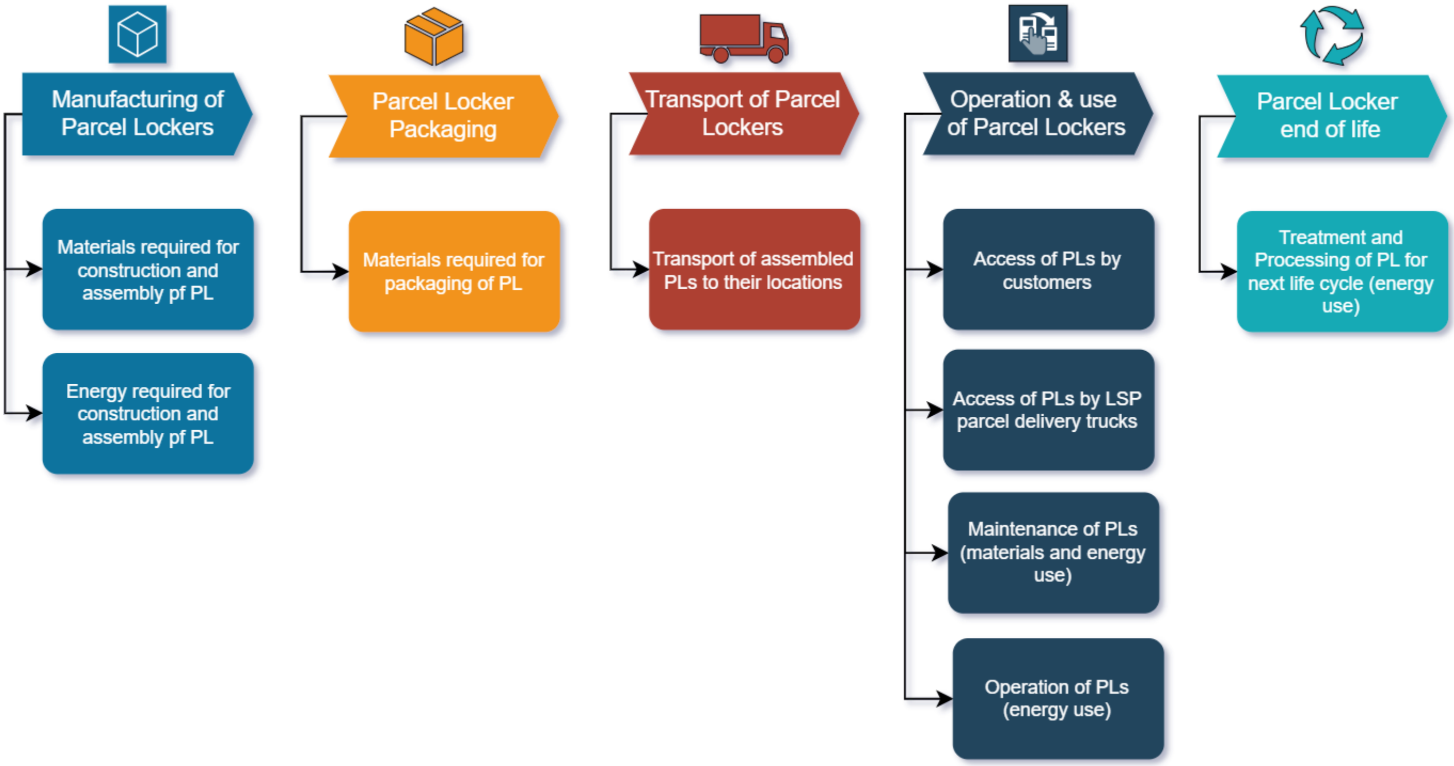


Figure 2.6: *The different life cycle stages of the PL system and their components in Ecochain Mobius software*

Although all the different life cycle stages as shown in Figure 2.6 are discussed and elaborated upon in this thesis, the aspects 'Access of PLs by customers' and 'Access of PLs by LSP parcel delivery trucks' of the *'Operation and Maintenance phase'* are elaborated in more detail. This helps in deriving insights into how the PL system is accessed by both the customers and the LSPs.

2.3.3. Data Acquistion

Parcel Lockers

Data required for this thesis i.e, for the different stages of the life cycle of the PLs is referenced from the Environment Product Declaration (EPD) report of a steel locker from a company called Steelcase based in Madrid, Spain [1]. This EPD is a transparent, objective report that communicates what a product is made of and how it impacts the environment across its entire life cycle [15]. The data on the PL use of materials and resources is based on data published in the year 2020 and is valid until 2025. While the emission factors for the full LCA of PLs referenced from the Ecoinvent v3.8 database in the Mobius software are based on the year 2021. The report is presented in *Appendix B* for future reference and ease of use of the different parameters.

The different types of PLs are researched though literature and articles and then discussed in section 3.2. Consequently the most relevant PL type for this case study is chosen to be the 4 tower modular PL configuration owing to the least amount of occupancy rate as mentioned in section 3.3. This makes it the most efficient configuration and which is also further described in chapter 5.

Transport Emissions

The transport emission data for majority is already included in the Mobius software where the emission factors are referenced from the Ecoinvent v3.8 database in different scenarios. While data on transport emission factors for accessing the PLs by car by the customers is assumed through literature research and used in this thesis [16]. An emission factor of $0.167\ KgCO_2$ per t-km for delivery trucks is referenced from Ecochain v3.8 database (*see Figure D.7*) and used from this case study while an emission factor of $0.192\ KgCO_2$ per km is used for cars via literature [16], is used by customers to access the PLs. These transport emission factors, similar to the data on PL, are based on the year 2021 are also later used in section 5.2 and be reflected upon in chapter 6.

2.3.4. Impact category

The emission involved in different aspects of the this PL system can contribute to varying environmental impacts which are discussed in chapter 4. Their characterization into impact categories can be used to quantify the ability of each of the assigned elementary flows to impact the indicator of the category. Some of the environmental impact categories are shown in Figure C.3. Additionally Figure C.4 gives a representation of the units in which the various impact categories are expressed.

Typically, the 'Climate Change' environmental impact category is used due to its high relevance amongst stakeholders [30] according to Mikosch, N (2022). In order to represent this impact, the Global Warming Potential (GWP) or the climate change impact category is selected for this thesis. The GWP is a comprehensive indicator that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in $kg\ CO2$-eq.

3
Literature Review

Through an extensive and meticulous literature review, it has become evident that a notable research gap exists regarding the environmental impact of PL systems, encompassing LSPs, customers, and PL distributors as integral components. While literature has extensively examined the operational efficiency, economic viability, and user convenience and preference aspects of PLs, there is a lack of comprehensive studies that have systematically investigated their environmental implications. The existing literature primarily focuses on conventional delivery methods and larger-scale logistics operations, leaving a significant knowledge void concerning the specific environmental consequences associated with the implementation and operation of PL systems. As sustainability becomes an increasingly crucial aspect of modern logistics, addressing this research gap is vital to advancing our understanding of the overall environmental performance of PL systems and promoting ecologically responsible decision-making among stakeholders. By undertaking this study, a contribution of valuable insights that can inform sustainable practices in urban logistics and enhance the environmental performance of last-mile delivery services can be made.

The purpose of this literature review is to analyse PLs as a novel innovation for more efficient last mile delivery and their potential impact on the environment. This is achieved by first reviewing grey literature to inspect and analyse the main challenges in the logistics supply chain. After having clear findings that last mile delivery is the most inefficient process in the entire logistic process [9], scientific literature is reviewed on the innovation of PLs and its relation to the externalities specifically related to environment.

This review starts by analysing the literature connecting PLs and their impacts on the environment is found. This involves finding literature on various attributes discussed in section 3.1 (*see Table 3.1 - Table 3.3*) that need to be taken into account for implementing PL system as a solution to last mile delivery. This is followed by discussing types of PLs in general and their applications in section 3.2. Then some key aspects of a PL system which are reflected in the case study later in chapter 5 are described in section 3.3. Current trends of PL use as an innovation in last mile deliveries in different countries are briefly reviewed in form on an infographic in section 3.4. This review on current trends play a key role for getting a broader view on how the PL services are setup. Key factors that influence the PL usage are briefly discussed in section 3.5. section 3.6 describes the PL system setups in an urban and a rural setting by discussing their distribution and accessibility factors. Finally this chapter ends by brief discussing on home deliveries in section 3.7 which highlights its benefits and drawbacks.

3.1. Key research articles

This section presents a total of 16 articles (*see Table 3.1 - Table 3.3*) that were found relevant to the case study for this thesis. The exploration of the articles encompasses an array of pivotal factors that underpin the adoption and utilization of PL systems. These articles offer insights into diverse aspects, including customers' intentions to use such systems, their chosen modes of access, and the inherent advantages of these systems over conventional HDs. A reflection on these articles broadens the understanding of the relationships between these factors and the environmental footprint of PL systems, thus shedding light on the sustainability potential they hold within the evolving domain of last mile delivery.

Table 3.1: *Overview of articles*

Author(s)	***Paper***	***Methods***	***KPIs used***	***Summary/Findings***	***Limitations & Future recommendations***
Lyu, G., & Teo, C. P. (2022)	Last Mile Innovation: The Case of the Locker Alliance (LA) Network [27]	-Locker choice model -Facility location model for LA	-Walking distance, locker location	-Customers can pickup from lockers near residential areas resulting in model not always placing the lockers in the vicinity of locations with peak parcel volumes -Inclusion of 250 meters is appropriate for the LA network in Singapore	-Examination of the impact of the open locker system on the entire e-commerce value chain - Interesting to see how traffic flows can be streamlined using this solution and the associated environmental impact
Tsai, Y. T., & Tiwasing, P. (2021)	Customers' intention to adopt smart lockers in last-mile delivery service: A multi-theory perspective[53]	-Quantitative survey -Integration of resource matching theory, innovation diffusion theory, and theory of planned behavior	-Convenience, reliability, privacy security, compatibility, relative advantage, complexity, perceived behavioral control, and attitude	-Perceived behavioral control influences the convenience, reliability, and privacy security on Thai consumers' intention to use smart locker -Customer attitude influences the compatibility, relative advantage, and complexity -Strongest effects is shown by attitude	-Intention of customers in Thailand can be explored for novel last-mile delivery innovations (robotic delivery, drone delivery etc), and if they can grow in -Need for a change in the sample size and selection method
Seghezzi, A., Siragusa, C., & Mangiaracina, R. (2022)	Parcel lockers vs. home delivery: a model to compare last-mile delivery cost in urban and rural areas[50]	-Analytical model -Sensitivity analysis	-PL density, PL fill rate and PL annual costs	-PLs have lower cost of delivery than HD, key benefits mainly derive from the higher delivery density and the drastic reduction of failed deliveries. -PLs are more critical in rural regions because of lower expenses, as well as higher HD costs	-Deterministic values considered for model input, which calls for additional analysis incorporating probabilistic distribution -Analysis of revenues can be done to evaluate the economic profitability of the solution
Gatta, V., Marcucci, E., Nigro, M., Patella, S. M., & Serafini, S. (2018)	Public Transport-Based Crowdshipping for Sustainable City Logistics: Assessing Economic and Environmental Impacts [12]	-Stated preference survey and discrete choice modeling -Cost benefits evaluation	-CO2 particulates, distance	-A redcution of about 239 kg of particulate matter annually by implementing a crowdshipping service in Rome -Economic sustainability reahed when the people are incentivized because a system is helping to reduce problems for society	-Use of micro-simulation for detailed environmental evaluation -Requirement for analysis of technical requirements and coordination amongst shippers, logistic operators, and crowd-shipping platform providers
Peppel, M., & Spinler, S. (2022)	The impact of optimal parcel locker locations on costs and the environment[33]	-Multinomial logit model for willingness to use SPLs (stationary PL) -Mixed-integer linear programming model	-Availability at home, travel distance, CO2	-About 11% cost savings can be achieved due to placing SPL optimally -Urban areas see a positive impact on total CO2 emission savings by up to 2.5%, while less populated areas see an increase in emissions by about 4.6% due to longer travel distances for collecting parcels	-Number and size and lockers can be adapted and additionally the regional setups, city designs, customer habits and population densities can be considered -Multi-objective models can be tested -A situation where the SPL are built publicly and delivery companies use it by paying a fee can be considered

Table 3.2: *Overview of articles*

Author(s)	*Paper*	*Methods*	*KPIs used*	*Summary/Findings*	*Limitations & Future recommendations*
Schwerdfeger, S., & Boysen, N. (2022)	Who moves the locker? A benchmark study of alternative mobile parcel locker concepts[49]	-Flexible heuristic multi-stage optimization	-Cost, distance	-Mobile lockers enable shorter travel time and long overlap times without significant cost invested into a network of stationary lockers. -Mobile lockers can potentially be superior to fixed lockers	-Case specific optimization techniques can be considered in the future -Incentives in the future for customer for sharing multiple alternative pickup positions, accept short overlap times and longer walking distances toward their lockers.
Prandtstetter, M., Seragiotto, C., Braith, J., Eitler, S., Ennser, B., Hauger, G., Hohenecker, N., Schodl, R., & Steinbauer, M. (2021)	On the Impact of Open Parcel Lockers on Traffic[46]	-Assessment of usage patterns for data collection about parcel quantities -Simulations for assessment of distance travelled	-Distance, CO_2 emissions	-PLs have a positive impact under specific conditions which can be easily achieved given they are promoted -No clear statement that "a PL will reduce the emitted CO_2" can be made due to the individual surroundings and conditions -Important that either the rate of successful first deliveries or the utilization rate of PLs is increased	-Beneficial if parcel retrieval occurs through trip chaining which can be done by smart placement of PLs -Future development of a model where a grocery shop operates the PL
Schnieder, M., Hinde, C., & West, A. (2021)	Sensitivity Analysis of Emission Models of Parcel Lockers vs. home delivery Based on HBEFA [48]	-Literature review -Parcel delivery simulation -Emission modelling: HBEFA	-Mode shares, emissions	-Group of people collecting their parcels from a PL by means of car should be minimized otherwise HDs result in lower emissions	-Use of accurate data in future specific to the city rather than use of average values for a detailed emission model development
Lemke, J., Iwan, S., & Korczak, J. (2016)	Usability of the parcel lockers from the customer perspective the research in Polish Cities [25]	-Online qualitative surveying	-Number of respondents, grade, qualitative parameters, cost, location of PLs, responsiveness	-Customer propose the PL placement in areas surrounding public transport stops and stations. -About 600 parcels delivered in a day by courier servicing InPost PLs with travel distance of about 70 km in comparison to 60 parcels and 150 km respectively in HDs -PLs have CO_2 emissions of about 1516 tons per year in comparison to 32500 tons in traditional courier service	-This innovation could be utilized in markets other than the B2C e-commerce market. Shop deliveries could be a potential challenge for this type of deliveries
van Duin, J. R., Wiegmans, B. W., van Arem, B., & van Amstel, Y. (2020)	From HD to parcel lockers: a case study in Amsterdam [54]	-Cost effectiveness analysis, multi-criteria analysis and simulation	-Transportation costs, Accessibility Customer, Service, Efficiency, Feasibility, Safety, Sustainability and Reliability	-Instead of having a total of 1475 stops for the whole delivery of 1770 parcels, this alternative delivery model has only 47 stops for the PL route -The delivery costs could annually save up to €121,356 (De Pijp area)	-More precise determination of the size and locations of PLs by the use of simulation modelling is required

Table 3.3: *Overview of articles*

Author(s)	***Paper***	***Methods***	***KPIs used***	***Summary/Findings***	***Limitations & Future recommendations***
Pham, H. T., & Lee, H. (2019)	Analyzing the Costs and Benefits of Installing Unmanned Parcel Lockers: Focusing on Residential Complexes in Korea [34]	-Expected benefit estimation -Social discount rate analysis -Sensitivity analysis	-Reliability, sustainability, profitability -ENPV, ERR, B/C ratio	-PLs especially in residential areas have a high benefit-cost ratio of 4.89 -The most crucial factor in terms of PL benefits was time savings -Support from the government is required for setup of PLs in semi public locations that would optimize land costs	-Data availability is limited on the cost and benefit variables. -For future, it is essential to conduct a more reliable research about the social discount rate and the value of time for Korean cases
Mitrea, I. A., Zenezini, G., De Marco, A., Ottaviani, F. M., Delmastro, T., & Botta, C. (2020, July)	Estimating e-consumers' attitude towards Parcel Locker usage [31]	-Research study -Data analysis	-Willingness to adopt PL, location preferences, sociodemographic characteristics, specific feature of PLs	-This service has a high potential for adoption (988 potential adopters out of the 1053) -Majority of the users prefer having PLs located close to home(80.1%) as compared to other locations -An average deviation of 5-10 minutes is acceptable to consumers for collecting their parcels	-The distribution of age that is considered in the sample is not representative of the population -Stated behaviour and actual behaviour relationship needs to be investigated
Molin, E., Kosicki, M., & van Duin, R. (2022)	Consumer preferences for parcel delivery methods: the potential of parcel locker use in the Netherlands [32]	-Stated choice experiment	-Costs, delivery moment, and distance	-It is predicted that the HDs will reduce from 71% to only 7% with increasing the HD costs by a small amount and additionally expanding PLs (close to the vicinity of households)	-This research is based on a convenience sample. More research is needed to find better ways to make delivery companies and online stores work together. -An average price of €65 is assumed which leads to speculation whether consumers are then equally sensitive to the variation in delivery costs
De Maere, B. (2018)	Economic and ecological impact of automated parcel lockers vs home delivery [8]	-Quantitative analysis -Survey and framework development	-Journey preference, VKT, transport mode, delivery costs, emission levels	-Courier is mainly responsible for the emissions caused by delivering the parcel (131.76 g per parcel) in the HD model -In the PL scenario, the courier only emits a small amount of CO_2 (2.56 g per parcel) due to PL parcel consolidation along with HD parcels	-Future research on the base model can be done which is simplified in this experiment
Faugere, L., & Montreuil, B. (2017, July)	Hyperconnected Pickup & Delivery Locker Networks [11]	-Conceptual network designs	-Costs, demand, P/D efficiency, capacity	-There are several challenges to implementation of hyperconnected network such as engineering design, efficiency, operating policy and integration	-For multi-operator use, extension of research on business models is required for hyperconnected pickup and delivery networks
Giuffrida, M., Mangiaracina, R., Perego, A., & Tumino, A. (2016)	home delivery vs Parcel Lockers: an economic and environmental assessment [14]	-Activity-based estimation model	-Operational costs, Emissions	-Environmentally, PLs have a legit convenience if their reach distance does not exceed 0.94 km in a urban context and 6 km in an extra-urban one -Economically, PLs have a legit convenience if their reach distance does not exceed 3.5 km in a urban context and 9 km in an extra-urban one	-Exclusion of additional kinds of cost which can vary (e.g. opportunity cost for the time the customer spends to pick-up the parcel) -Identification of the best possible location for positioning the PLs is a crucial point

These articles offer insights into diverse aspects, including customers' intentions to use such systems, their chosen modes of accessing PL locations, and the inherent advantages of these systems over conventional home deliveries. Notably, the higher delivery density and the consequential reduction in failed deliveries have been heralded as the primary benefit of these systems. It is also reflected in articles (Schnieder et al., 2021)[48] and (Giuffrida et al., 2016)[14] from the tables above, the conditions under which the PL use will prove to be beneficial over conventional deliveries. From additional studies conducted previously, it is evident that weight and size are less important attributes as data on delivery of parcels as that the vast majority of ordered parcels would fit into PLs where 85% of parcels had length smaller than 50 cm, 90% had a width smaller than 40 cm, and 80% had a height smaller than 20 cm. Based on this an assumption is also made in section 5.1 for the total parcel weight delivered to PLs which ultimately impacts the transport emissions.

However, the environmental implications of PL system involving all the aspects; customers, LSPs and PL distributors, have not been thoroughly researched yet and it is thus interesting to analyze CO2 emissions for such a PL system. Based on the literature reviewed in this chapter, the the KPIs from Table 3.1 - Table 3.3 of interests for this thesis are the VKT by LSPs, CO_2 emissions caused by the different aspects of the PL system, distance and transport mode choice by customers and LSPs. Furthermore a comparison between the transport emissions of LSP parcel delivery trucks in PL system and conventional HDs gives interesting insights into the benefits of PL system.

3.2. Types of Parcel Lockers

The concept of PL service can be broadly classified into 2 categories namely: Stationary and Mobile Lockers [49] according to (Schwerdfeger et al., 2021)[49] (*see Table 3.2*). As the name suggest, the former category of stationary lockers are installed at fixed locations such as supermarkets, neighbourhoods, train stations and workplaces etc. Thus these types of lockers have a requirement of visitation both by customers to process their parcels and couriers to supply shipments. While the mobile lockers can vary their position over a given time period which allows for better reach of customers throughout the day. The PLs themselves can be further classified into 5 types which mainly account for their specific application [51]:

- Modular Lockers: These lockers as the name suggests, have modular designs which allows for easy exchange, removal or addition of modules quickly at any time.
- Cooling Lockers: These comprise the group of lockers that are refrigerated to keeps food items fresh between the temperatures of 2°C and 7°C. This is done by means of insulation, fan cooling and a refrigerant gas.
- Postal Lockers: These group of lockers mainly used for various postal deliveries which can include mails, local and international ordinary parcels.
- Self-Service PLs: These group of PLs, which also are the focus of this thesis, are aimed to simplify the last mile delivery by online retailers. They are robust lockers installed in various locations which comprise small, medium and large lockers for different parcel sizes. These enable customers to pickup their parcel at their convenience and in a secure way by the use of a one-time password (OTP). A type of this locker terminal can handle 50-100 parcels a day.
- Laundry Lockers: As the name suggests, these lockers are used for doing a customer's laundry when they are registered with a laundry service provider. These lockers have some additional features such as ventilation slots and larger corner gussets for additional rigidity.

3.3. Parcel Locker System

As briefly mentioned in chapter 1, Parcel Lockers or PLs are automated lockable storage boxes that facilitate the delivery and collection of parcels by its couriers, delivering company and users. This is where couriers deliver parcels to the PL locations and customers travel to these locations via different modes from their residences. This system in general is comprised of 5 aspects :

- *Distribution of PLs:* This is an important aspect as the number of PLs in a certain location should be able to fulfill the demand of consumers while ensuring a low occupancy rate. This parameter is highly dependent on the spatial distribution of population in a respective area. For instance urban residential areas in the Netherlands such as 'De Pijp' have an even distribution of PLs such that the customers are able to walk or bike on average of about 5 minutes to reach a PL. Whereas in rural area of Ten Boer, PL distribution is central making their location a bit further compared to urban areas.

- *Configuration of PLs:* PL systems recently implement modular designs of PLs where their capacities and layouts can be tailored according to the requirements of the consumer. According to a study conducted in Seattle [47], a 4 tower PL was selected and installed in the Beltown neighbourhood with approx. 12000 people in a 0.3 square-mile area. The modular PL was fitted with 3 compartment sizes namele, small; medium and large. The configuration in this specific study was with 8 large, 28 medium, and 19 small cells. Cells were about 1.5 ft wide and 2 ft deep, and the heights of the small, medium, and large cells were respectively about 5, 10, and 25 inches. This 4 tower configuration is cheaper then 5 tower one and was the most ideal one for as it results in a low occupancy rate which causes less number or packages to be left outside the PL system. For ease of computation this locker configuration is also selected for this case study in section 5.2.
- *Location of PLs:* According to literature research, plenty of surveys have been conducted indicating that the majority of customers (around 80.1%) would prefer PLs close to home according to (Lemke et al., 2016)[25] and (Mitrea et al., 2020)[31] as seen from Table 3.2 and Table 3.3. This decision generally lies in the hands of the LSPs as seen later in chapter 4 and is further elaborated in section 3.5.
- *Customers and their mobility behaviour:* In order to eliminate failed delivers, the LSPs can deliver orders to a set PL location. Likewise, consumers enjoy the convenience of 24-hour accessibility. With parcel lockers located closer to their home than post offices, they can pick up and return items at their convenience with minimal queuing and indirectly lowering service costs at the same time [24]. For this thesis, it is assumed that customers pick their parcels through a dedicated trip and within 24 hours of parcel delivery by LSPs.

  This also means taking into account the maximum distance that customers are willing to travel in order to collect their parcels from the PL stations in their neighbourhood or vicinity. According to (Mitrea et al., 2020)[31], majority of e-consumers are available to deviate from usual daily trips (e.g. home-workplace or home-university), between 5 to 10 minutes to collect their parcel [31]. Additional literature research, PLs can influence and change the activity chains, number of trips, as well as modal split and the travelled distances for pick-up/drop-off parcels. Based on this study conducted by (Hofer et al., 2020)[21], results shown in Figure 3.1 depict the average acceptable travel time by consumers to PL locations by different modes.

Accepted Indicators	Walk	Bicycle	Public Transport	Car
Travel time [min]	10.3	7.5	9.1	7.2
Travel distance [km]	0.7	1.9	1.2	3.6

Figure 3.1: *Accepted average travel time and distance to reach a PL [21]*

- *Logistic service providers:* From the perspective of Logistic Service Providers (LSPs), a PL system offers a flexible and efficient alternative for parcel delivery and pickup. The usage of the PL system varies based on customer preferences and service offerings. Typically, customers have the freedom to retrieve their parcels whenever convenient, leading to the potential for multiple uses per day. This adaptability allows customers to align their parcel collection with their schedules, optimizing convenience. Time windows for parcel retrieval can vary, accommodating diverse customer preferences.

  The usage pattern influences the required number of lockers within a system. For efficient operations, LSPs must balance the number of lockers with the expected parcel volume. An optimal ratio is sought between the number of lockers, the anticipated frequency of usage, and the number of parcels being serviced. Factors such as the density of customers, delivery schedules, and locker accessibility play a role in determining the appropriate locker quantity. An assumption on all these factors are discussed in section 5.1.

These 5 aspects can be amalgamated into 3 key aspects which form the PL system: the customer; the LSPs and the PL distributors, and will be used throughout the rest of the thesis. The LSPs make decisions on PL locations and then consequently deliver parcels to the lockers based on demand and number of lockers. The customer access PLs in order to collect or return their parcels. Their choice of mode choice depends on the location of PLs. PL distributors are in charge of the life cycle emissions for the PLs and make decisions on the configuration of PLs.

The primary benefits of PLs arise from high parcel delivery rates and reduction in failed deliveries. Additionally, reduction in failed deliveries can have an overall reduction in emissions and congestion in certain network areas which can have a considerable positive effect on the environment. It can be concluded that the utilisation rates of PLs is closely related to their location. Other key features of PLs are its 24/7 parcel access, secure deliveries, electronic logged deliveries and collection and provision of returning parcels [26].

However from a customer's perspective, they can also be very inconvenient in certain situations when parcel size is too big to fit in the compartments of a PL station. Additionally, there is the principal disadvantage for the customer to travel to the PL stations for picking up or dropping-off their parcel. This can be inconvenient to certain age groups of people who are used to getting their parcels delivered at home as the last mile delivery.

PLs have also shown a significant potential in reduction of the emission when compared to traditional home deliveries. The emission per parcel by the courier is far less in the PL scenario than the home deliveries (2.56 g per parcel in PL compared to 131.76 g per parcel home deliveries). However this was when the delivery vans that were already delivering parcels to customer homes included parcels that needed to dropped off at nearest PLs leading to very short extra travel distance. This is in contrast to making dedicated trips by LSP trucks to PL locations to drop off the parcels which is also considered to be the case in this study.

3.4. Current trends of PL use in different locations

The facility to collect parcels from PLs are mainly offered by courier express parcel services (CEP services) with a corresponding market share in the respective segment. According to the International Post Corporation (IPC) cross-border survey conducted in 2022 across 39 countries researching over 33000 people, 33% of people order at least once per week and 83% once a month [7].

While parcel delivery to people's residences has the highest satisfaction rates among customers, about 65% of them extremely satisfied with the delivery location being the PLs. This was possibly mainly due to the PLs being present in the close vicinity and offering a flexible collection time of their parcels [6]. According to a report of 2020 whose data was collected during October 2019, PLs were most common in Estnoia and Finland where about 62% and 50% respectively, of the e-commerce shipments were received at a PL station [37]. Table 3.4 shows the different PL systems implemented across different countries throughout the world [6] [36]. This table helps in knowing what are the current trends in the different countries regarding PL system deployment:

- *Introduction of PLs:* It can be generally deduced that PLs are a fairly novel innovation in most countries discussed below as it is only in the recent past years that PLs have been introduced. Thus in most countries, the beginning is done by means of a test or a pilot phase where only a small number of lockers are placed to see if they perform well to the expectations of the stakeholders.
- *PL manufacturer:* Through literature it is found that most countries have the trend where the PLs themselves are outsourced from manufacturers either from different countries or locally. Since a case study is conducted for this thesis in the Netherlands, it can be seen from literature that the PLs are produced by a local manufacturer, which in turn results in savings on import duties and overall PL costs.
- *PL network expansion:* Finally it is seen that most countries plan to deploy PLs in the range of few thousands over the coming 2-5 years. This is proposed to order to ensure that the demand of all the customers in different areas of the countries is served.
- *Special provisions:* Some countries require special provisions in order to be able to access PLs, for instance in Germany, prior registration is required by customer and requiring them to use a smart card. Other countries like Denmark have Bluetooth technology in their PLs which used to communicate with the customers. While PLs in Switzerland can be used for other purposes like shopping placement or storing keys.

Table 3.4: *Overview of current PL scenarios in different countries*

Country	PL system description
AUSTRALIA	- Australia Post launched a PL system in 2014 together with MyPost Deliveries - Currently around 200 PL stations provided in partnership with InPost
BELGIUM	- Cubee, the PL service in Belgium was introduced in 2017 The Belgian postal group and Dutch partner De Buren have converted the former bpost-branded PL network into an open, independent system - Currently there exists a network of 250 PL terminals in Belgium and the Netherlands combined
CHINA	- Hivebox ran almost 150,000 lockers in China making it the single largest provider, also globally. Currently there is a network of 330,000 PLs in China and Hivebox cooperates with other organisations via the system and provides value added services such as storage, automated vending machine in the lockers, lottery etc - Hivebox plans to acquire 94,000 lockers controlled by state owned postal service company China Post. Another player is Cainiao Network which provides residential self-pickup lockers under the brand Cainiao Post. Plans to have 100,000 self-pickup locker terminals
CROATIA	- Croatia Post has decided to invest in PL and more than 150 lockers and has already been installed with an aim of 301 lockers in total with each locker having 96 compartment of XS, S, M and L sizes - Hardware manufacturing will take place in China while the software will be provided by Estonian Post
SWITZERLAND	- My Post 24 network comprises of over 2,700 collection points in Switzerland which uses the KePol PL system - 183 terminals with 221 compartments are currently serving about 9000 households in nearby vicinity where customers can additionally place shopping in the locker temporarily, or store keys at the My Post 24 terminals
DENMARK	- PostNord Denmark and Swipbox in collaboration have created a co-owned company; Nordic Infrastructure, which owns the PL network there, each locker consists of 13 compartments. By May 2020, over 800 lockers were operational and by the end around 1500 total - Contrary to most other PLs solutions, batteries are used in these Danish lockers and Bluetooth is used to interact with the customers
FRANCE	- La Poste in France began in 2014. By end of 2015 around 200 pickup stations in busy areas of the 5 largest cities - These self-service terminals are supplied by KEBA, an Austrian firm and can handle 40-100 parcels/day
PORTUGAL	CTT Portugal Post first launched 5 PLs in Lisbon for 1 year trial. Later a new network of lockers named Locky was launched in the Iberian market with an investment of 8 million euros - Locky intends to install 1000 lockers until the end of the year, which will turn this network into the largest and most extensive network nationwide
FINLAND	- By 2018 end, the company Posti in Finland installed its 1000th PL at Helsinki Central Railway Station ad 1600 PL in total as of May 2020. By 2022, a staggering amount 4000 PLs were installed - Posti in addition to expand the network, is also working on improved tech services which enables manual work to be digitalised. At sorting stage, system can tell whether locker space is available and can direct parcels to another pickup point. Posti is also working to expand the usage type of its PLs, such as recycling, consumer to consumer sales and delivering rental devices
NETHERLANDS	- PostNL in Netherlands, initially tested in 2014, has changed its approach to PL solution over the years Instead to buying or renting existing machines - PostNL in partnership with a local manufacturer decided upon a custom-made PL with 25 compartments each and have about 400 of them in different municipalities across the country. The expansion of PLs is to reach 1500 by end of 2024.
SPAIN	- Correos in Spain launched the 'CityPaq' in late 2014 with plans to install 60 terminals supplied by KEBA. There exists a network 5000 PL terminals with varying sizes and 10 compartments per locker each - It is highly scalable as modules can be added or removed based on demand. By May 2020, Correos finalised terms with 2 delivery providers to have same PL access levels and conditions as the post
GERMANY	- Deutsche Post DHL in Germany since its launch in 2001, has installed over 4500 PL provided by KEBA and about 7000 by 2021. - The PL stations are supplied by KEBA in addition to own lockers manufactured by Polygon to the current network of 'DHL Packstations' - Prior registration required by the customer, requiring them to use their smart card and pick-up code sent to them via a notification
UK & POLAND	- InPost serves both in UK and Poland with about 1200 PLs in UK. It plans to expand the network to 6000 PLs over the next few years. Locations include supermarkets, Esso petrol stations and Transport for London sites, as well as outside retailers such as Toys R Us - Network in the UK is accessible to courier partners such as UK Mail, DX, DHL Express, Hermes and APC Overnight - In Poland there are about 6000 PLs where InPost being an independent postal service provider offers secure parcel services via its Paczkomaty facilities. Most of them have 76 locker boxes in 3 sizes. Consumers can select a Paczkomaty delivery from selected e-retailers with parcels ready for collection within 48 hours

3.5. Factors influencing the usage of Parcel Lockers

The adoption and utilization of PLs are governed by a multitude of complex factors that influence their usage patterns. Some of these factors include regional setups, city designs, recipient habits, attitude, convenience, privacy, security and population densities also play an important role that influence the degree of usage and adoption of PLs in certain areas [53]. In this discourse, we delve into two pivotal factors that significantly impact the usage of PLs: the strategic location of these lockers and the mode choice exercised by customers.

- **Location of PLs**
  As briefly mentioned in Table 3.3, the utilisation rates of PLs is closely related to their location. About 80% of customers prefer the PLs location close to home[31], hence PLs in residential areas could be an area of interest to be more specific. This encapsulates the core effect of customers willingness to use them and travel short distances to access their parcels. Additionally when considering the location of PLs by LSPs, there are two main approaches that can be adopted: more locations with fewer lockers or fewer locations with more lockers. Opting for more locations with fewer lockers entails spreading out the lockers across a larger geographic area. This approach aims to provide customers with easy access to a PL within close proximity to their homes or workplaces. It encourages a higher frequency of use, as customers find it convenient to drop off or retrieve parcels on a regular basis. This approach may require smaller lockers in terms of size and capacity but enables greater flexibility in parcel management. More locations with fewer lockers may suit densely populated urban areas where convenience and quick access are essential. This factor affects the VKT as more PL locations with fewer lockers lead to shorter travel distances for customers but more by logistic service providers.

  Alternatively, having fewer locations with larger, bulkier lockers focuses on consolidating the locker presence in key strategic areas. Customers might have to travel a bit farther to access these lockers, potentially resulting in less frequent usage but a higher parcel volume per visit. This approach aims to reduce the number of locker installations while accommodating higher demand at centralized points. Fewer locations with more lockers might be favored in rural areas with lower population density, where optimizing resource allocation becomes critical. This factor affects the VKT as fewer PL locations with large lockers lead to shorter travel distances for LSPs but further distances for customers.

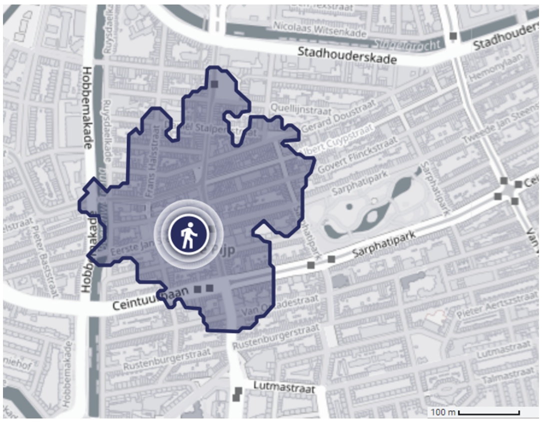
- **Mode choice of customers**
  Additionally, findings from other authors have shown that the benefits of a parcel machine will be undone if these trips are done by car[8]. This means that PLs should be reached with eco-friendly modes, either by bike or foot, by its users to have a positive environmental impact. However if the PL location is far from the customer, especially in rural areas where the PL density is low, then travelling via car can become a necessity. An assumption based on mode choice of the customers based on their location from PLs is made in section 5.1.

3.6. PL system setup: Urban vs Rural

Urban

As highlighted in section 3.3 which highlights the key aspects of a PL system, in an urban area PLs would be potentially placed at various locations throughout the city to serve the high population density and meet the demand for convenient access. They would be strategically distributed in areas such as residential complexes, office buildings, shopping centers, and transportation hubs. These could be integrated with existing infrastructure, such as apartment buildings, retail stores, or transportation hubs.Additionally since urban areas generally have higher parcel volumes, a larger number of modular lockers and compartments would be necessary. Due to superior internet connectivity in urban areas, customers have the provision to utilize features like real-time monitoring, remote access control, and notification systems for parcel pick-up and drop-off.

In an urban setting of a dense network of PLs, most preferred mode of transports for accessing the PLs are by walking and biking [5]. If PL are stationed at a 5-minute walk range from a home address, then inhabitants are more willing to collect a parcel on foot [54]. Majority of the respondents in a survey conducted in the Netherlands are willing to travel 5-10 minutes, resulting in buffer zone of approximately 400 to 800 metres for walking [5]. This also translates into a zone of about 2000 meters for biking. For this study, an urban region in the Netherlands chosen is 'De Pijp', which is an Amsterdam neighborhood and a former borough of Amsterdam, now part of the Zuid district. This area has a population of about 35,525 inhabitants and has an even distribution of the PL network. The catchment area of a PL location is shown in Figure 3.2 via the most preferred modes for accessing these PL locations.



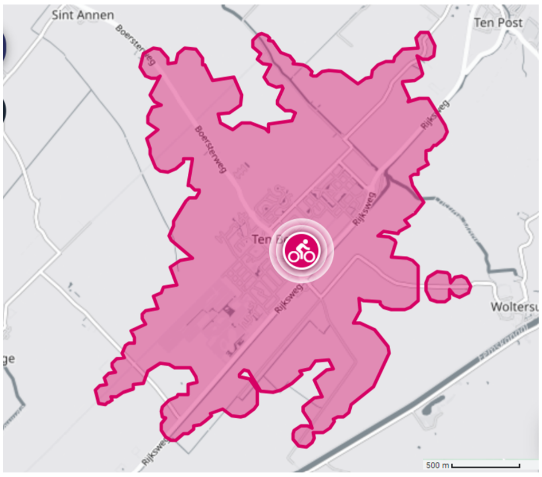
(a) Catchment area through 5 mins walking from a PL location in De Pijp

(b) Catchment area through 10 mins biking from a PL location in De Pijp

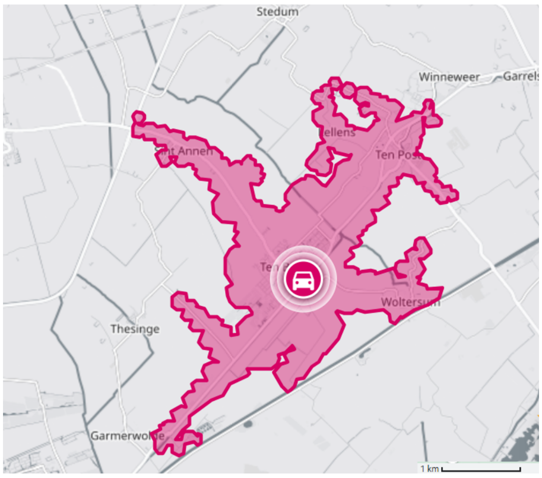
Figure 3.2: *Catchment area of PL location in De Pijp, Amsterdam through different modes*

Rural

In contrast to a setup in an urban area, the PL system in a rural area would typically have a centralized location to serve multiple nearby communities. It would be located in a village or town center, making it accessible to residents within a larger geographic area. This system should preferably be integrated with local facilities like post offices, community centers, or retail stores, leveraging existing infrastructure and providing additional services to the community. In rural areas, where access to electrical infrastructure may be limited, the locker system might incorporate alternative power sources such as solar panels or battery systems to ensure a reliable power supply. These areas may additionally face challenges with internet connectivity, requiring efforts to ensure reliable connectivity for the PL system. Maintenance and support services would be provided for both urban and rural PL systems. However, in rural areas, special considerations might be needed due to longer travel distances for service personnel. Regular maintenance visits and prompt response times are essential to ensure the smooth operation of the lockers in rural areas.



(a) Catchment area through 10 mins biking from a PL location in Ten Boer



(b) Catchment area through 10 mins driving from a PL location in Ten Boer

Figure 3.3: *Catchment area of PL location in Ten Boer through different modes*

Similarly, in a rural setting of a network of PLs, most preferred mode of transports for accessing the PLs are by biking and by car [5]. The travel distances in rural area are about 10 mins on average which translate to about 2.8 kms by biking and 5 kms for driving a car to PL locations. For this study, a rural region in the Netherlands is chosen 'Ten Boer', a village and a former municipality in the northeastern Netherlands, in the province of Groningen with approximately 4,600 inhabitants. This area does not have a dense network of parcel pickup points hence it is a considerably different setup from an urban one. The catchment area of a PL location is shown in Figure 3.3 via the most preferred modes for accessing these PL locations.

3.7. Conventional HD

Traditional HD involves direct shipment of packages to the customer's residential or business address. Extensive literature underscores a multitude of benefits associated wih this method. It offers a high level of convenience and a personalized experience, as packages are brought directly to the customer's preferred location. Studies indicate that this convenience plays a pivotal role in customer satisfaction and retention. Furthermore, conventional HD is known to contribute to enhanced accessibility for a diverse range of consumers, including those with limited mobility or residing in remote areas. Moreover, some sources suggest that centralizing deliveries to residential addresses could potentially lead to fewer vehicles on the road, aligning with sustainability goals.

However, the literature also underscores certain environmental drawbacks. The increased use of delivery vehicles, particularly in densely populated urban areas, has been associated with elevated emissions and air quality concerns.

3.8. Relevance of literature review

By thoroughly examining existing research and scholarly works in this chapter, the review identifies and highlights the critical components and key aspects of the PL system; customers, the LSPs and PL distributors. Additionally key factors that determines the usage of PLs help streamline and clearly define assumptions in section 5.1. The PL system setups in urban and rural areas chosen also help in quantifying the potential environmental impacts of the PL system. This knowledge accumulation from the literature review answers the first research sub-question and serves as a comprehensive foundation upon which the conceptual model is built chapter 4. Through this model, the decisions and potential environmental impacts of LSPs, customers and PL distributors is captured, enabling a holistic understanding of their roles, responsibilities, and contributions to the system's environmental impact.

The conceptual model then becomes a dynamic tool that not only visually presents the interconnected web of key aspects but also provides a structured framework to assess and quantify the environmental implications of the parcel locker system. Therefore, the relevance of the literature review extends to shaping the foundation and structure of the conceptual model, ultimately facilitating a comprehensive analysis of the environmental impact of the parcel locker system.

4 Conceptual Model

This chapter describes a conceptual model that provides a visual representation of the PL system and conventional HD regarding the environmental impact. The different factors that contribute towards the environmental impact are also represented in Figure 4.1. This aids in identifying factors that are important and relevant to consider when addressing the environmental impact of PL system.

For the clarity of the reader, all the factors and aspects of the conceptual model are discussed in detail first and then followed by stating what exactly is included in the scope of this thesis and carries over to the case study in chapter 5.

4.1. Conceptual Model

The conceptual model as shown in Figure 4.1 provides a general framework to identify and understand potential environmental impacts associated with the life cycle of PLs. This model is based on a novel last-mile delivery innovation, the PL system which comprises 3 aspects: the Logistic Service Provider (LSP), the Customers and the Distributors. These components of the PL system are displayed in blue colour. One of the aspects of the PL system is also involved in HDs; the LSP which is also highlighted in blue colour. The different decisions variables that are manipulated by the key actors of the PL system are depicted by white boxes. These include the decisions on different life cycle stages of the PL by the distributor, determination of PL locations by the LSPs , the mobility behaviour of the customers and the logistics operations by the LSPs for instance. The yellow coloured boxes are used to depict the effects of the decision variables. The other factors that are related to the LSP and customers are depicted in grey boxes. The different types of emissions from all the three components of the PL system are depicted by orange colour boxes which are discussed in detail below. These emissions from the different aspects of the PL system ultimately have impacts on the environment which is depicted by the red box.

Model construction

As mentioned in section 2.2, the conceptual model is developed by means of a system diagram. This approach provides a visual representation of the interconnected components and relationships within the system, facilitating a holistic understanding of its functioning and environmental implications. By depicting LSP, customers, and PL distributors as key aspects, the diagram captures the entire life-cycle of the PL system, from production to end-of-life. Also as mentioned in section 3.5, that PLs should be reached with eco-friendly modes, either by bike or foot, by its users to have a positive environmental impact, it has been taken as the basis for including the customer location in the conceptual model (*see Figure 4.1*). Additionally the different phases are considered from the reference EPD report [1] and included in the conceptual model. The decisions of the different actors involved in the PL system are thought logically and assumed.

Scope of PL system and its purpose

It is previously mentioned in chapter 1 that as e-commerce trend is accelerating, the demand for the number of parcel being delivered continues to grow. Consequently the demand for efficient and convenient delivery options has also increased. In the recent years PLs have emerged as a viable solution to address the challenges associated with the last-mile delivery of online purchases. This benefits both the customers and the LSPs as it results in convenient delivery, 24/7 accessibility, reduced delivery attempts, consolidated deliveries, sustainable delivery option and cost savings. These benefits in turn creates the need for customers and LSPs to travel to PL locations for parcel delivery and collection. The PL systems described in this section comprise of 3 aspects: Customers, LSPs and PL distributors.

Conventional HD

The conventional HDs involve the LSP delivering parcels to the individual customers by travelling to their place of residence or a chosen address of their preference. HDs are solely done by the LSP which deploy their parcel delivery trucks and thus result in transport resistances.
Although the distance travelled by LSP trucks in real world scenarios would vary on a daily basis, it is assumed to be a constant number of VKT by the vehicle which includes the distance between the sorting center and the respective area plus the distance covered by LSP trucks when travelling to individual customer residences which is further elaborated in section 5.1. The VKT by LSP trucks result in environmental impacts by HD system in this case as shown in Figure 4.1.

PL locations

The PL locations themselves can have considerable effects on the environment. Strategic placement of PLs in convenient and accessible locations can contribute to more efficient delivery routes and reduced overall transportation distances thus increasing transport efficiency. Determination of PL locations that ultimately have an affect on accessibility of this system in done by LSPs, thus influencing mobility behaviour of customers to some extent.
Although as mentioned in section 3.5, that urban and rural areas have different PL distribution, for ease of computation it is assumed that the combined PL demand and capacity, irrespective of their distribution, is a fixed number in urban and rural settings which is also reflected later in section 5.1.

Transport Resistance

Factors which affect the PL system and ultimately the environment are travel time, cost and effort. These are the resisting factors which obstruct the need to travel to these PL locations [57]. Low resisting factors results in high amount of transport and vice-versa. This in turn also can potentially reflect in the mobility behaviour of the customer.
These factors are a results of the LSPs that determine the deployment of PL locations. For the HDs there are potentially high and varying number of kilometers travelled by the parcel delivery vehicle expressed as VKT. For PL systems on the other hand, the VKT are potentially low and fixed as the LSP trucks travel only to the PL locations.

Customer location and their mobility behaviour

The customer location or residence can be broadly classified into two categories: urban or rural. These locations have a considerable affect on their mobility behaviour which ultimately impacts their mode choice to access the PL systems. As mentioned in section 3.6, customers residing in rural areas prefer to access PL locations via bike or car. Whereas in an urban setting the more preferred mode choice are walking and biking. Other customer behavior characteristics such as dedicated trip by driving to and from PLs or combining parcels pickup with other trips can contribute to additional vehicle emissions and traffic congestion.
While customer behaviour depends on several factors, it is assumed that customer mode choice will solely depend on the distance to PL location in this thesis. The choices of modes by customers are also limited to three in this thesis namely; on foot, bike and car respectively. Furthermore customer purpose of package collection is solely assumed to be a dedicated trip initially for the case study.

Logistics operations

The LSPs make important decisions that relate to the logistical operations. These decisions are influenced by the transport resistances discussed previously. The logistic operation decisions result in choice of mode transport, routing, scheduling and parcel handling for both PL systems and HDs. Usually all of these decisions are important when considering the entire logistical chain.
However for this thesis, the point of interest in only the environmental impact for which only VKT by the LSP trucks is considered. The key difference in the effect of the decision is LSPs target destination being customer residence in HD scenario and PL locations in a PL systems. The VKT is also highly dependent on the respective sorting center that serves the demand of the PL locations and customers.

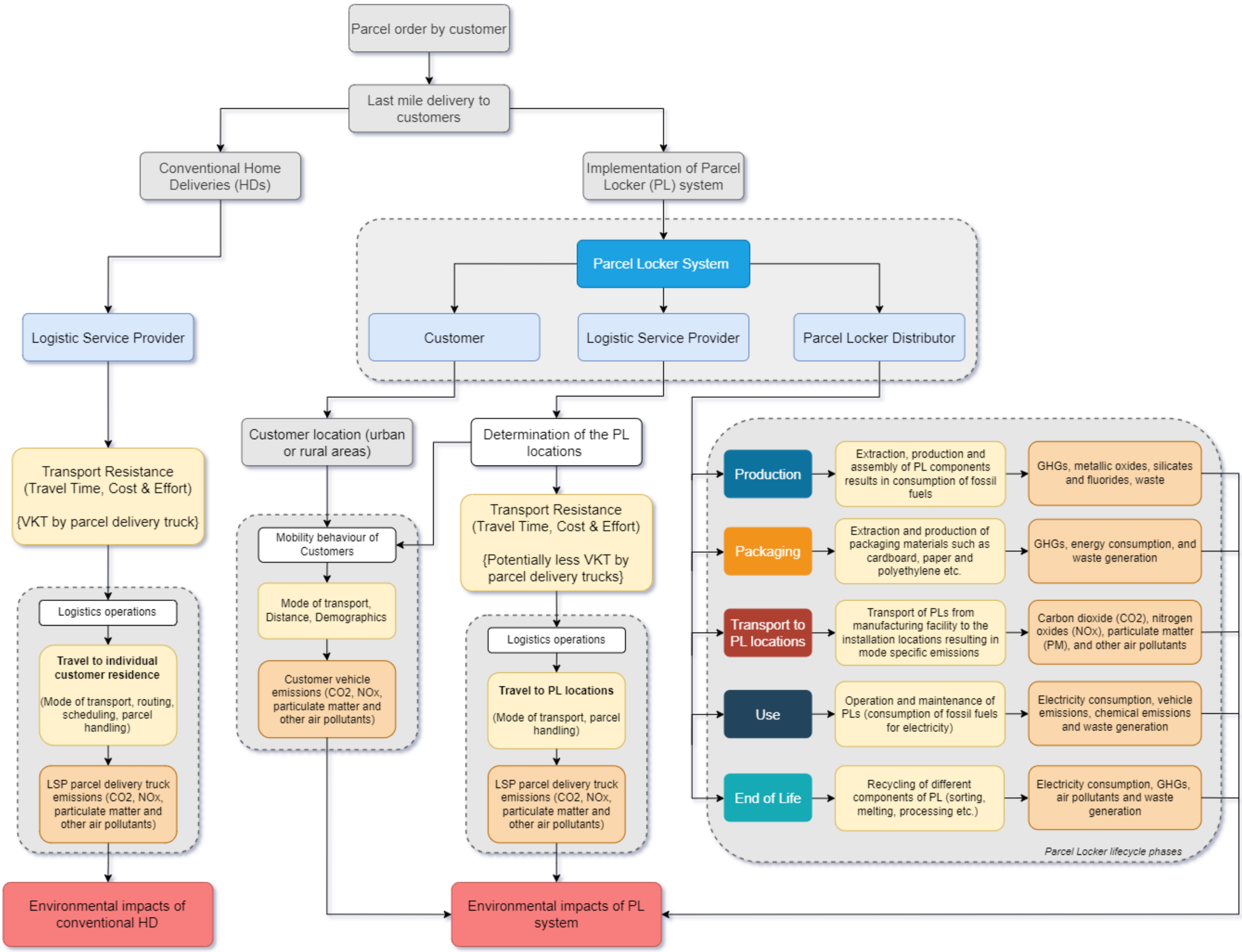


Figure 4.1: *Conceptual Model for potential environmental impacts of PL system and conventional HD*

Vehicle emissions

The vehicle emissions which have an impact on environment are influenced by mode choice by the LSPs to deliver or collect the parcels and the customer that use specific modes to access PL locations. Some of the most common emissions caused by vehicle are carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), and other air pollutants. Accessing PL locations via walking has no environmental impacts.
Although there are many emissions caused by vehicle travel, but due to reasons mentioned in subsection 2.3.4, the GWP or the climate change impact category is selected for this thesis which is expressed in $kg\ CO2$-eq or $g\ CO2$-eq.

PL life cycle phases

The decision on the different life cycle phases of the PLs that are made by the distributor ultimately reflect on the various emissions that affect the environment. Some of the relevant factors and impacts to this study are:

- Production: This phase consumes fossil fuels and begins with the extraction of raw material needed for PL construction. This is followed by processing and assembly of components. As a result GHGs, metallic oxides, silicates, fluorides and wastes are produced. The different materials and their quantities are referenced from the EPD report [1] and the emission factors are referenced from the Ecoinvent v3.8 database in Mobius.

- Packaging: For safe and undamaged transport of PLs to its installation sites, proper packaging needs to be done. This phase involves extraction and production of packaging materials such as cardboard, paper and polyethylene etc. As a result the emissions produced are GHGs.
- Transport: This phases involves the activity of transporting the assembled and packaged PLs to their installation sites which results in mode specific emissions which are mainly carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), and other air pollutants. The transport emissions factors considered for this case study is 192 gCO_2 per km [16] for cars used by customers to access the PL locations. All the Other emission factors are referenced from the Ecoinvent v3.8 database in Mobius.
- Use: This phases includes the PL use by the customers and the LSPs delivering their parcels. Operation and maintenance of PLs are a crucial part of this phase which requires significant energy consumption. It is necessary in order to power their operation, including features such as lighting, display screens, and electronic locks. This electricity could be generated from fossil fuels such as coal or natural gas resulting in GWP emissions. Other emissions include vehicle emissions, chemical emissions and waste generation that are related to the maintenance of the PLs.
  In a PL system, continuous electrical supply is essential for the proper functioning of various components. These components comprise primary elements like the electric motor and control board, as well as secondary elements like lights, sensors, and cameras. The electric motor serves to power the locking mechanism, with power consumption reaching up to 20 watts per hour during operation. The control board, responsible for managing system functions, consumes approximately 10 watts per hour while in use. Ensuring safety and security, lights and sensors operate at an energy consumption rate of 5-10 watts per hour each. Moreover, the integration of cameras within the system results in an additional 40-50 watts per hour of power consumption when activated [22].
- End-of-Life: This phase comprises the recycling of different components of PLs by sorting, melting, processing etc. which can be further utilised for its next life cycle. In order to carry out these processes electricity is consumed, which as stated above could be from use of fossil fuels. Other emissions that negatively impact the environment are GHGs, air pollutants and waste generation which mainly occur due to material treatment and certain non-recyclable by products.

Although the different life cycle phases have various types of emissions, only the GHG emissions expressed in kg $CO2$-eq or g $CO2$-eq are relevant to this thesis and are considered for the case study in chapter 5. Assumptions based on life cycle phases are further carried over in section 5.1.

4.2. Relevance of conceptualization

Conceptualizing the potential factors that determine the environmental impact of the PL system through a system diagram aids in answering the second research sub-question.

This conceptual model serves as a valuable tool to answer fundamental questions related to the environmental impact of the PL system. It systematically identifies and highlights the potential factors that influence the system's environmental outcomes. Through this model, one can explore how each aspect, such as customer behaviors in terms of their mode choice and location, PL life cycle phases, and VKT by LSPs, contributes to the overall environmental impact. This insight enables the assessment of the environmental implications of the PL system. The quantifying the potential impacts of these different setups becomes feasible through the conceptual model's visual representation and systematic approach in chapter 5. Furthermore, the conceptual model's structure is particularly advantageous for conducting case studies. It lends itself to investigating different ways the PL system can be set up and operated in the future. For instance, it allows for exploring scenarios involving varying scenario and system design factors such as delivery failure rates in HDs and sorting center locations later in subsection 6.3.2 and subsection 6.3.3.

In summary, the conceptual model serves as a foundational framework that not only clarifies the factors influencing the potential environmental impacts of the PL system but also facilitates a structured approach to quantify the impacts under different scenarios. This methodological approach enhances the depth of analysis and supports the overarching goal of understanding and optimizing the environmental sustainability of the parcel locker system.

5

Case Study

This section of thesis presents the setting up of the case study to assess the environmental effects of PLs using LCA. This section follows a structured format, beginning with a list of assumptions for this thesis in section 5.1. This is followed by section 5.2 that provides a detailed description explanation of the different aspects and values for each of the phase of the PL system life cycle and the PL system setups. Finally, a brief description of the setting up of the conventional HD is also presented in this section. The system setup is supported by relevant data and figures to enhance the clarity and visual representation. This chapter enables the reader to gain detailed understanding of how the phases are modelled into Ecochain Mobius. Based on this section, the findings of the case study are discussed in section chapter 6.

Before the case study is setup for thesis, the core assumption of this thesis is that initially the PLs are fully used which leads to the formulation of the base case scenario. For ease of computation, the best case scenario is also assumed for HDs, which means no delivery failure rates. This in a way works against the principle of PL systems. If PL systems outperform HDs despite the assumption of the best possible scenario for HDs, then inclusion of delivery failure rates is not needed initially for this case study. Otherwise, if the environmental impact of the PL system per parcel are worse than HDs, then delivery failure rates will be included to make them scenario more realistic. As the thesis progresses towards section 6.3, the focus shifts from the most positive case to the inclusion of different uncertainties and real world situations. For instance scenarios such as delivery failure rates in HDs, trip chaining and other system design factors for PL systems are reflected upon later.

5.1. Assumptions

Several assumptions are made for ease of modelling the different phases of the PL system in this case study listed below and as shown in Table 5.1:

- Lets start the assumptions from an LSP perspective, where they setup PL system in either urban or rural areas. It is assumed that the total number of PLs that are situated in both the settings (urban and rural) have around one truck load capacity such that the trucks can drive there once per day.
- It is assumed that the LSP trucks have a capacity of 55 parcels. It is also assumed that the demand of parcels is high in both the settings also about 55 parcels per day and the number of parcels delivered to the PLs and the customers by the LSPs are 55 each day for both PL systems and HDs.
- For this thesis and also the case study in section 5.2, although there is an expected difference in PL location and density, the total demand of parcels in PLs in urban and rural areas is assumed to be the same irrespective of their numbers for ease of computation. However this difference is reflected later in section 6.3 where the distribution of lockers is varied accordingly.
- It is assumed that the PLs in case of PL systems and parcel delivery trucks by LSPs in case of HDs serve demand of different customers each day. A single customer order frequency is assumed to be once a month as mentioned in section 3.4. But since the customer orders are not synchronized and it is difficult to pin point each customer order placement patterns, it is assumed that the daily overall order frequency by customers in total belonging to the urban and rural settings in this case study to be 55. Hence on a daily basis 55 customers in total travel to retrieve a total of 55 parcels per day, meaning about 1 parcel per customer per day.

- Since PLs give its users flexibility to collect parcel at their preferred times during a day, for ease of computation it is assumed that a maximum retrieval time of parcels from PLs is 24 hrs, i.e lockers can be used once per day or the lockers have to be emptied by the customer (parcel collection) so that trucks come to empty lockers the next day.
- Failed deliveries in case of conventional HDs are not included in this case study. This is due to lack of data and although, this works to the disadvantage of the PL systems, the failed deliveries are discussed later in the subsection 6.3.2 and be reflected upon in section 7.2 in the discussion. Hence for now it is assumed that 100% of the parcels are delivered on the first try by the couriers.
- Only the GHG emissions are considered for this case study that are expressed in terms of $Kg\ CO_2$-eq. These emissions are reflected per parcel in Figure 6.1 in $g\ CO_2$-eq for ease of interpretation and comparison to HDs.
- It is assumed that the customers make a dedicated trip for collection of their parcel from PLs in urban and rural area. This means that combining trips with other purposes such as work, leisure is out of the scope of this study. This is to make the base case scenario as simple as possible, however trip chaining for the purpose of parcel collection by customers, especially in rural setup is reflected upon in subsection 6.3.2 and in chapter 7.
- It is assumed that all the customers use the same mode of transport to access PL locations as specified in different scenarios. This means that in urban setting, if the PL locations are close by to the customers from their location, all of them would walk about an average of 0.8 km. Similarly if the PLs are located a bit further from their location, all of the customers would bike and average distance of 2 kms. Consequently for rural setting where the PL density is low, customers travel larger distances as compared to urban setting to access PL locations. This means that customers are more inclined to take the bike for distances around 2.8 km and more inclined to take the car for distances around 5 km.
- The time horizon for which the total climate change emissions are calculated is assumed to be 15 years. This means delivering 55 parcels to PLs everyday for 15 years for PL systems. Additionally this also translates to delivering 55 packages to customers everyday for 15 years for the conventional HDs.
- In the HDs, the delivery trucks travel to individual customer residence location for parcel delivery. This results in more VKT by parcel delivery trucks compared to PL systems. It is assumed that the VKT travelled by delivery trucks in both the urban and the rural setting to be 75 kms plus the respective distance they have to travel from their sorting centers [23].
- For urban setting, the sorting center in Westzaan is 25 kms away from De Pijp, hence the total VKT by LSP trucks is:
  25 km (distance from sorting center in Westzaan to De Pijp) + 75 km (assumed VKT by LSP trucks to serve 55 customer order) = 100 kms VKT which translates to 1.81 kms travelled per parcel in urban setting.
- For rural setting, the sorting center in Hoogeveen is 75 kms away from Ten Boer, hence the total VKT by LSP trucks is:
  75 km (distance from sorting center in Hoogeveen to Ten Boer) + 75 km (assumed VKT by LSP trucks to serve 55 customer order) = 150 kms VKT which results in 2.72 kms travelled per parcel in rural setting

Base case scenario

This case study starts by setting up of the base case scenario where both in PL system and HD, all the aspects and external factors are assumed to be the same as discussed above. To be more elaborate it is assumed that number of parcels delivered over the entire time horizon of 15 years are same in both the cases. It also means that the sorting centers that serve the demand of customers in urban and rural regions in both the cases are also assumed to be the same. Scenarios where some factors change in the PL system or there are uncertainties are discussed and reflected upon in chapter 6 (section 6.3).

Table 5.1: *Assumption for this case study*

Assumption(s)	***Urban scenario***	***Rural scenario***	***home delivery***	***Source/Reference of assumption***
Customer order frequency	Everyday	Everyday	Everyday	As mentioned in section 3.4, the frequency of order by a customer is assumed to be everyday PL systems and home deliveries as the orders are not synchronized.
Average parcel weight	2.9 Kgs	2.9 Kgs	2.9 Kgs	Since about 75% of the parcels weigh less than 2kg [32], the average parcel weight is assumed to be 2.9 kgs as shown in *Appendix D*
Multiplication factor for amount of material and energy required for PLs	Material: 3.3 Energy: 4.2	Material: 3.3 Energy: 4.2	Not applicable/ Not required	For the different amount of materials required for the considered PL in this thesis, a multiplication factor of 3.3 is chosen as shown in *Appendix D*
Impact category	GWP	GWP	GWP	The indicator GWP, expressed in CO_2 is chosen for this study as it allows for comparisons of the global warming impacts of different emissions involved.
Lifecycle duration for which impact is considered	15 years	15 years	15 years	This is same the lifetime considered in the EPD reference report [1]
Sorting center location for modelling access of PLs by LSPs	Westzaan	Hoogeveen	Urban: Westzaan Rural: Hoogeveen	The PostNL sorting centers chosen in Westzaan and Hoogeveen will serve the demand of the PL placed in urban and rural settings [44]
Number of packages delivered at once	55	55	55	Since the PL design considered in this case study can accommodate 55 packages of three varying sizes, the parcel delivery truck capacity is assumed to be 55 parcels
Electricity consumption by PL	80 watts per hour/ 0.8 KW per hour	80 watts per hour/ 0.8 KW per hour	Not applicable/ Not required	The electricity consumed by a PL on average is assumed to be 0.08 KWh [22] of which about 0.05-0.06 kilo watts per houris consumed by camera and security systems
Maintenance of PLs and electricity consumption	Every 3 months, 0.5 KWh	Every 3 months, 0.5 KWh	Not applicable/ Not required	Self assumption
Vehicle-Kilometers Traveled (VKT) by delivery truck	25 kms	75 kms	Urban: 100 kms Rural: 150 kms	Self assumption and literature research on location of PostNL sorting centers in the Netherlands [44]

5.2. Case study

For this study, an urban region in the Netherlands chosen is ’De Pijp’, which is a neighborhood and a former borough of Amsterdam. On the other hand a rural region in the Netherlands chosen is ’Ten Boer’, a village and a former municipality in the northeastern Netherlands as mentioned in section 3.6. The data from the EPD of the Steel Case Lockers can be extrapolated as PLs are self service lockers which are be in use for a longer duration throughout the day and all the weekdays throughout the year. In addition to this the configuration found in this study to be the most effective for residential areas is the 4-tower configuration according to the study conducted by Ranjbari, A., (2023) [47].

Hence, the materials required for production of the 4 tower PL as mentioned in section 3.3 are referenced from the EPD conducted for a steel locker. This steel locker had different dimensions (H1645mm D450mm W1200mm; 3 columns) from the one proposed in this study as shown in Figure 5.1, hence the amount of materials required (kg) in production and packaging have been extrapolated accordingly (see *Appendix D*, Figure D.2) and assumed in the software Mobius Ecoinvent v3.8 database as shown in Figure 5.3 and Figure 5.4.

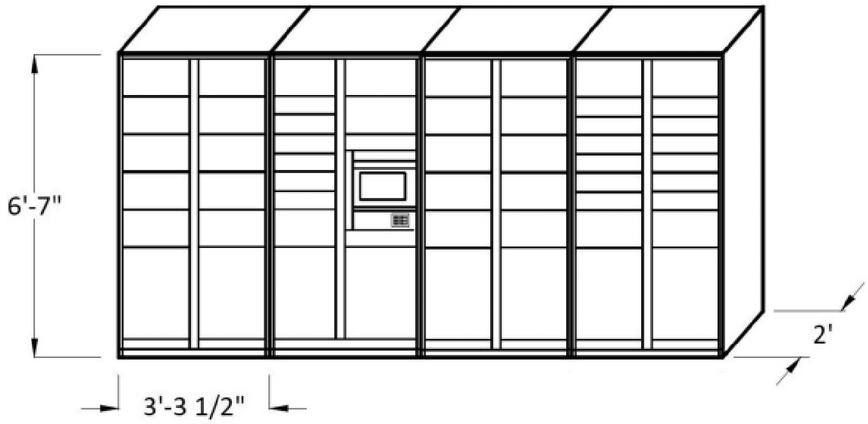
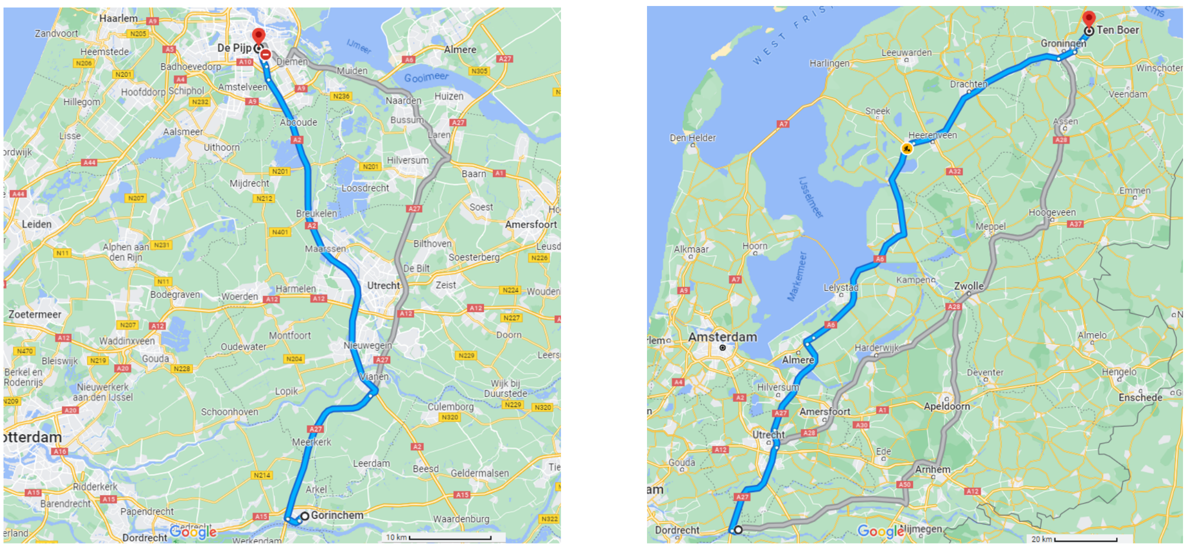


Figure 5.1: *4PL tower configuration [47]*

PL locations

Since 2021, the new automated PLs in Utrecht are the product of a collaboration with retailer Jumbo and distributor Dujardin-Remmers [41] as also seen from section 3.4. Dujardin Remmers is an innovative security solutions company based in Gorinchem, Netherlands located about 73.6 kms from the urban region of De Pijp area. For transport of PLs from Gorinchem to the rural area of Ten Boer, they need to be transported over a distance of about 235 kms via road as shown in Figure 5.2. This is used to compute the transport emissions of the PL from the manufacturing facility to the area of installation which are discussed below in the transport phase.



(a) Distance between Gorinchem and De Pijp, Amsterdam (73.6 kms)

(b) Distance between Gorinchem and Ten Boer (235 kms)

Figure 5.2: *Distance between distributor of PLs and their installation sites*

Sorting center locations

The delivery trucks need to only travel to PL locations from the nearest sorting centers in case of PL systems. The PostNL sorting center that serves the demand of customers in the urban PL system scenario is assumed to be in Westzaan [44] which is 25 kms from De Pijp in Amsterdam. Similarly, the location Hoogeveen is chosen for the PostNL sorting center that serves the demand of customers in rural PL system scenario, which is about 75 kms from Ten Boer [43].

Production phase

All the materials required for the construction of PLs are firstly modelled into the first phase. All the reference data for emissions are embedded itself in the software (Ecoinvent v3.8) which includes databases for all kinds of process and products. Hence the emissions related to the amount of materials used in the production of PLs such as Aluminium, Steel, Polypropylene, ABS (Acrylonitrile Butadiene Styrene), ZAMAK and Paint shown in Figure 5.3 are modelled into the Mobius software. All the relevant impacts have been selected and modelled accordingly in the software from the Ecoinvent v3.8 database as shown in Figure 5.3. For more clarity, see Figure D.4 which shows the climate change impact category for instance the material *ABS* used in PL production. Other materials are also referenced similarly from the database.

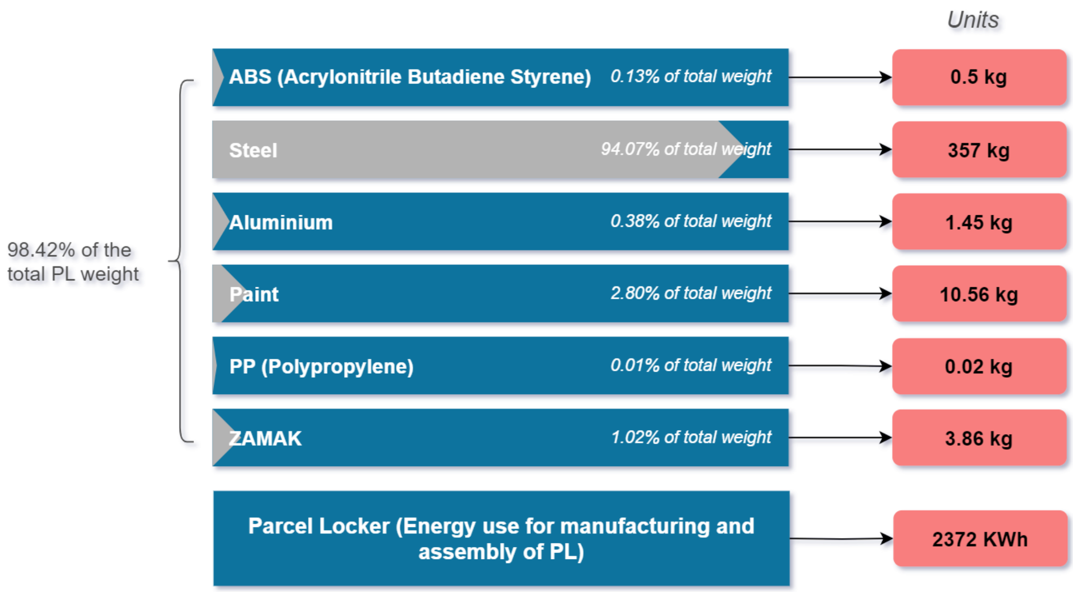


Figure 5.3: *Production phase describing input of amount of materials and energy required for PL production*

Packaging phase

The next phase modelled for the PL system is the packaging phases where the different quantities and materials are fed into the software. Figure 5.4 shows the materials in kg used for a packaged PL that will be installed in either an urban or a rural setting are Cardboard, Low-density Polyethylene (LDPE), Paper, Polyethylene and Polypropylene. The different materials used for packaging of PLs for their safe and undamaged transport are input in the software as shown in Figure 5.4.

For more clarity, see Figure D.5 which shows the climate change impact category for instance the material *Kraft paper* used in PL packaging. Other materials are also referenced similarly from the Ecoinvent v3.8 database.

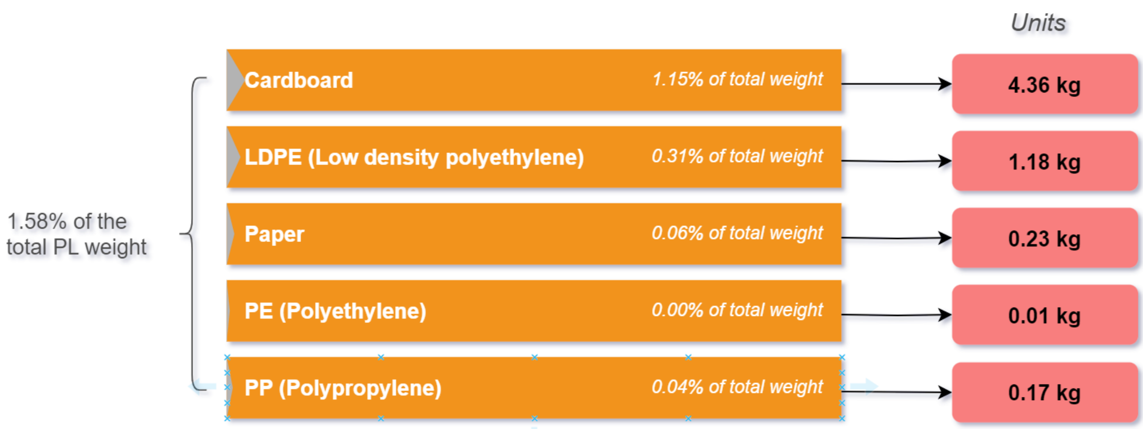


Figure 5.4: *Packaging phase describing input of amount of materials required for PL packaging*

Transport phase

As mentioned above, the transport of finished PLs will take place from Gorinchem to the areas of De Pijp and Ten Boer respectively via Lorry. This phase models the transport of the assembled and packaged PLs to their respective installation locations. The emissions related to this phase are initially expressed in t*km (mass*distance) of goods transport by road which are then translated into kg CO_2 eq emissions. In the content declaration section of the EPD report (*see Appendix B*, the total product weight is first computed by multiplying the reference locker weight by the multiplying factor of 3.3 resulting in the PL weight being 373 kg. The weight in tonnes (10^3 kg) is computed and then multiplied by the distance between the distributor and installation locations.
For urban and rural setups, the distance between the PL distributor is 73.6 kms from De Pijp and 235 kms from Ten Boer respectively. Hence this results in

$$\frac{(379.3kg \times 73.6km)}{1000} = 27.9tkm \quad \text{and} \quad \frac{(373kg \times 235km)}{1000} = 89.1tkm \text{ of goods transport respectively}$$

Figure 5.5 shows the transport emissions of the PLs that is modelled in the software by taking into account the emissions per tonnes per km (tkm) produced. Also refer to Figure D.6, which shows the climate change impact category for transport of 1 t-km of PL transport from distributor to installation location.

Figure 5.5: *Transport phase describing input of amount of tonnes-km travelled by lorry to transport the finished PLs to their installation location*

Use phase
This is the most crucial stage in order to get insights of how the use of the PL system varies in different settings. This stage includes the operation and maintenance and use of electricity by the PLs at respective locations. Additionally this phases also incorporates the emissions involved when the PLs are accessed by the LSPs and customer. For this phases, the amount of electricity used for operation & maintenance, the distance from the sorting centers to the PL locations and the average customer travel in order to access PLs are some of the parameters that are modelled in the software. For both the cases, it is assumed that maintenance of PLs requires about 2 kg of disinfectant (isopropanol) to clean the surface for a life cycle of 15 years.

Urban
For urban setting, the preferred mode choice for accessing the PL locations are either by walking or by using bike as discussed in section 3.6. Modelling of this phases can be seen in Figure 5.7 and Figure 5.6 where the average travel distance by walking is assumed to be 0.6 kms and about 2 kms by bike which translates to about 5 mins of travel times with both of these modes. The distance from the sorting centre in Westzaan to De Pijp is 25 kms and the along with the computed average weight of the parcels, it is translated in tonnes per km.
According to Figure 5.7, it can be seen that there is no climate change impact when the customer walks to the PL location which is to be expected as walking is a green mobility behaviour and for customer travelling to PL location by bike(electric) as seen in Figure 5.6:

- Access by customer input parameters
  $(2kms$ of bike travel $\times 55(numberofcustomerstravellingdaily) \times 365(days) \times 15(years)) = 602250kms$ of biking

  $(0.8kms$ of walking $\times 55(numberofcustomerstravellingdaily) \times 365(days) \times 15(years)) = 240900kms$ of walking

- Access by LSP input parameters
  ($25kms$ of LSP truck travel $\times$ 0.1595 tonnes $\times$ $365(days)$ $\times$ $15(years)$) = $21831.56tkm$ of LSP truck travel

- Maintenance input parameters
  ($2kg$ of disinfectant $\times$ $15(years)$) = $30kg$ of disinfectant required

  ($0.5KWh$ of energy required $\times$ $4(Maintenance/year)$ $\times$ $15(years)$) = $30KWh$ of energy required

  ($73.6kms$ of PL distributor truck travel for maintenance $\times$ 0.1 tonnes supplies for maintenance $\times$ $4(Maintenance/year)$ $\times$ $15(years)$) = $441tkm$ of PL distributor truck travel

- Energy use input parameters
  ($0.08KWh$ of energy required $\times$ $24(hours)$ $\times$ $365(days)$ $\times$ $15(years)$) = $10512KWh$ of energy required

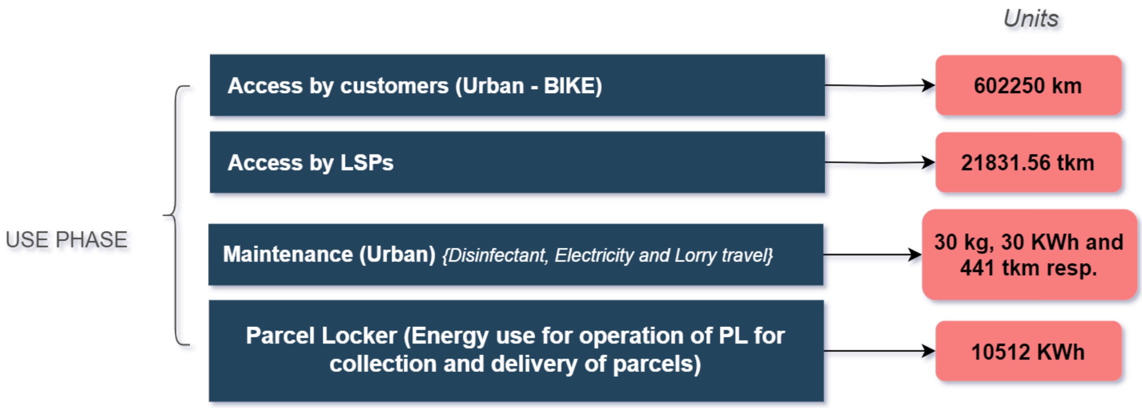


Figure 5.6: *Use phase (Bike - Urban) describing input of amount of the kms travelled by customers by bike, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

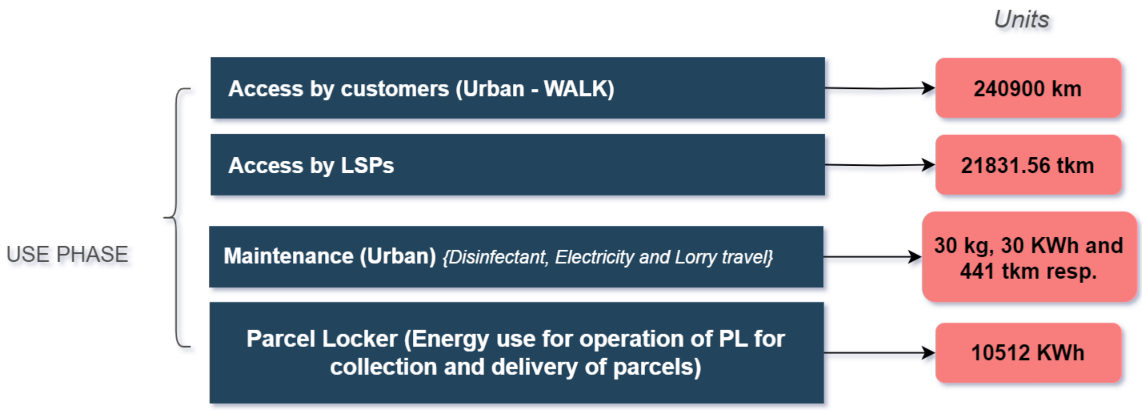


Figure 5.7: *Use phase (Walking - Urban) ddescribing input of amount of the kms travelled by customers by walking, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

Rural
For the PL system setup in a rural setting, the preferred mode choice for accessing the PL locations are either by bike or by using car similarly mentioned in section 3.6. Figure 5.8 and Figure 5.9 show the different attributes of the use phase of the PL system by bike and car in rural setting. The average distance for bike is assumed to be 2.8 kms for bike and 5 kms for car which translates to about 10 mins of travel by both of these modes. The average medium gasoline-powered car emission per km is assumed to be 192 g per km [16]. Similarly the distance

between the sorting center in Hoogeveen and Ten Boer is 75 kms via road.

- Access by customer input parameters
  ($2.8kms$ of bike travel $\times$ $55(numberofcustomerstravellingdaily) \times 365(days) \times 15(years)) = 843150kms$ of biking

  ($5kms$ of car travel $\times$ $55(numberofcustomerstravellingdaily) \times 365(days) \times 15(years)) = 15050625kms$ of driving

- Access by LSP input parameters
  ($75kms$ of LSP truck travel $\times$ 0.1595 tonnes $\times$ $365(days) \times 15(years)) = 65494.68tkm$ of LSP truck travel

- Maintenance input parameters
  ($2kg$ of disinfectant $\times$ $15(years)) = 30kg$ of disinfectant required

  ($0.5KWh$ of energy required $\times$ $4(Maintenance/year) \times 15(years)) = 30KWh$ of energy required

  ($235kms$ of PL distributor truck travel for maintenance $\times$ 0.1 tonnes supplies for maintenance $\times$ $4(Maintenance/year) \times 15(years)) = 1410tkm$ of PL distributor truck travel

- Energy use input parameters
  ($0.08KWh$ of energy required $\times$ $24(hours) \times 365(days) \times 15(years)) = 10512KWh$ of energy required

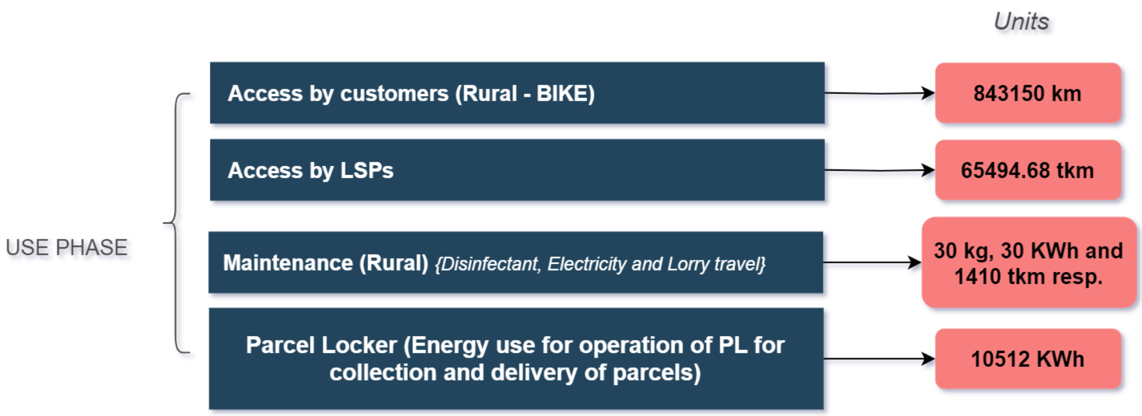


Figure 5.8: *Use phase (Bike - Rural) describing input of amount of the kms travelled by customers by bike, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

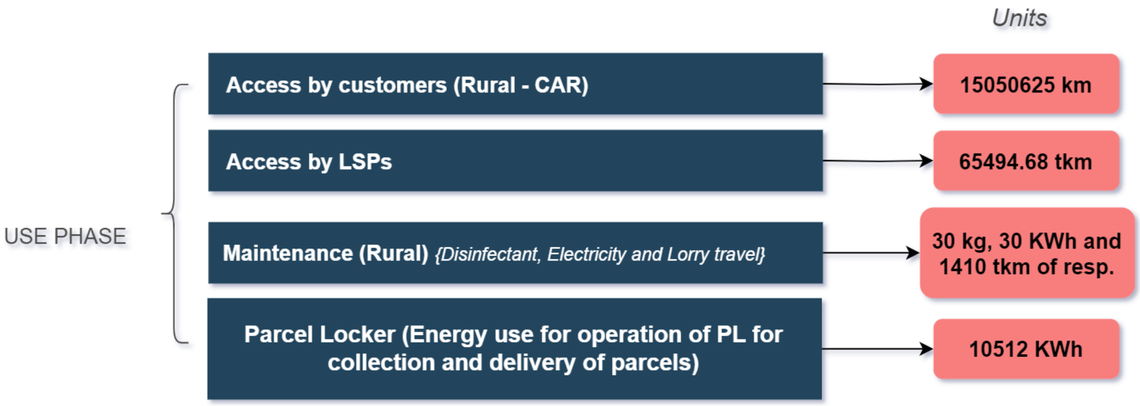


Figure 5.9: *Use phase (Car - Rural) describing input of amount of the kms travelled by customers by driving car, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

End of Life phase

Figure 5.10 shows the input parameters for the software. About 17% of the product that is the PL itself and 74% of the packaging is recycled which has been included in the 'End-of-Life' stage of the PL system. This results in about 4.4 kgs and 64 kgs of the packaging and PL being recycled respectively, and available for use in its next life cycle phase. In addition to this certain energy is also required for treatment and processing of the PLs for its next life cycle.

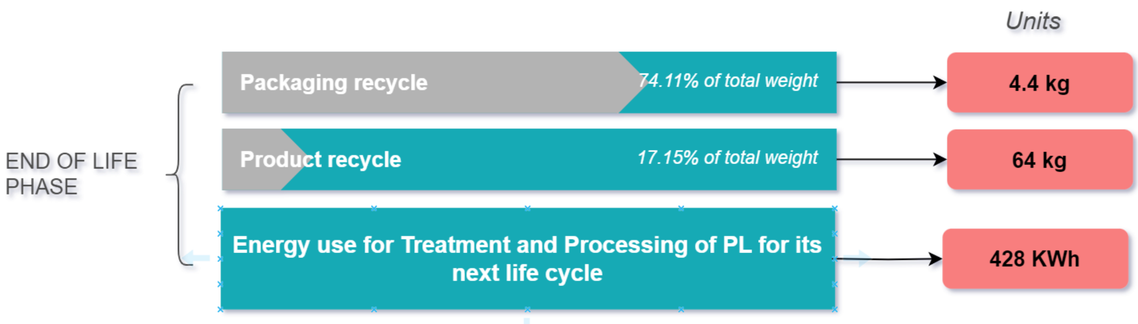


Figure 5.10: *End of Life phase describing input of amount of materials and energy required for PL recycle*

Conventional home delivery

Rural

For the conventional HD scenario in rural areas, similar parameters as the PL setup are modelled. According to previous research conducted in Poland, the courier servicing InPost PLs is able to deliver about 600 parcels in just one day, with travel distance of about 70 km in comparison to respectively 60 parcels and 150 km in traditional delivery system [23]. 60 parcels is somewhat similar to the maximum number of parcels that can be accommodated in the PL considered for this case study.

Hence a rough calculation of The emissions related to this phase similar to the PL case, are initially expressed in t*km (mass*distance) of goods transport by road which are then translated into kg CO_2 eq emissions. The weight of the parcels carried by a delivery truck in tonnes (10^3 kg) is computed and then multiplied by the distance between the distributor and installation locations.

For urban and rural setups, the delivery truck is assumed to be at similar load capacity as that of the trucks thats are used by the LSPs in the PL case. Hence the number of parcels in a delivery truck is considered to be 55 with average parcel weight of 2.9 kgs. The distance covered on average by a delivery truck is assumed to be 150 kms during one day of delivering parcels [23]. Hence delivering parcels twice a month this results in:

$$\frac{(2.9kg \times 55parcels)}{1000} \times 150km \text{ daily travel} \times 365days \times 15years\text{= 130989.375 tkm of goods transport}$$

Figure 5.11 shows the amount of tonnes-km that are travelled in the conventional HD trucks. These are modelled in the software by taking into account the emissions per tonnes per km (tkm) produced. The emission factor of delivery truck is $0.167KgCO2/t - km$ which has been taken into account with tkm of goods transport.

Urban
For HD in urban areas, all the parameters are same except the VKT bt the parcel delivery truck, which in this case is assumed to be about 100 kms during one occasion of delivering parcels. Hence from the assumption that in the HD case, the trucks also deliver twice a month, this results in:

$$\frac{(2.9kg \times 55parcels)}{1000} \times 100km \text{ daily travel} \times 365days \times 15years\text{= 87326.25 tkm of goods transport}$$

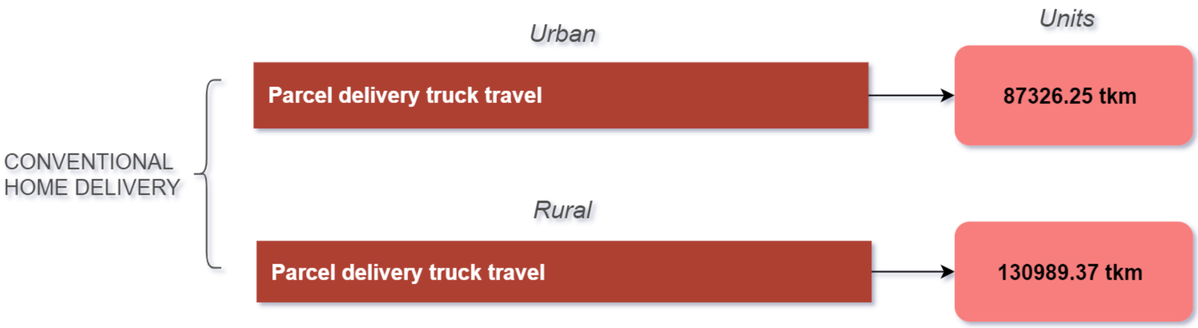


Figure 5.11: *Use phase (HD truck emissions in urban and rural setting) describing input of amount of tonnes-km travelled by LSP trucks deliver parcels to customers at their home*

The outputs of the input parameters in this section are discussed and reflected upon in chapter 6. The figures presented in this section allow for better clarity for the reader.

6
Results

This section of thesis presents the findings and outcomes of the analysis conducted to assess the environmental effects of PLs using Life Cycle Assessment (LCA) which provides a comprehensive framework for evaluating the environmental impacts associated with the entire life cycle of PLs, from raw material extraction and manufacturing to use, maintenance, and end-of-life disposal. The results presented in this section are based on the application of LCA methodology, considering the impact category of climate change which is expressed in kg CO_2 eq emissions.

The results presented in this section are intended to provide a clear understanding of the environmental effects of PLs. For the detailed results of the GWP climate change impacts (expressed in Kg CO_2 eq) of the different PL system setups and conventional HDs discussed in section 5.2, refer to Appendix E. The findings contribute to the existing knowledge by quantifying the environmental impacts and highlighting the key areas that warrant attention for sustainability improvement. Additionally, the results also serve as a basis for informed decision-making, supporting policymakers, logistics companies, and other stakeholders in devising strategies to mitigate the environmental impacts of PLs and promoting more sustainable practices.

The presentation of results follow a structured format, beginning with a aggregate GWP results of the PL system setups in section 6.1. This is followed by subsection 6.1.1 and subsection 6.1.2 that provide a detailed analysis of the different PL system setups. This enables detailed insights in the shares of emissions of the different elements of the PL systems. Following this, an analysis of the environmental implications in terms of carbon emissions and other relevant factors for PLs and HD are compared in section 6.2. This assessment helps in identifying which method is more environmentally friendly and aligns with sustainability goals. Finally, section 6.3 describes a sensitivity analysis that is done to see which aspects of the PL system's life cycle have the most potential for environmental improvement. The scenario results are presented in terms of their environmental impact. The results presented in this chapter are supported by relevant data, graphs, and charts to enhance the clarity and visual representation of the findings. Any uncertainties or limitations in the analysis are acknowledged and discussed to ensure a comprehensive and balanced interpretation of the results.

Overall, the results presented in this section shed light on the environmental effects of PLs, providing valuable insights into the sustainability aspects of their operation. These findings contribute to the ongoing efforts to enhance the environmental performance of parcel delivery systems and guide the implementation of effective measures for reducing their ecological footprint.

6.1. Climate Change Impact: GWP results

This section presents the GWP results of the considered PL system setup scenarios as discussed in section 3.6. Specifically, section provides a comparison of GWP values across different transport mods, while section breaks down the GWP for each transport mode to the LCA components and discusses their respective contributions. All the emissions shown in Figure 6.1 are expressed in g CO_2 eq per parcel.

- **Transport emissions caused by Customers**
  These emissions expressed in gCO_2 eq represent the transport emissions caused by customers when they

travel to access the PL location for retrieval or return of their parcel. For the mode choice biking or walking, the emissions are negligible and thus can be considered as having no environmental impact. While considering the customer travel emissions to PL location in rural area of Ten Boer via car, this is translated into in $g\ CO_2$ [16] per parcel:

$$\frac{(192gCO_2/km \times 15050625kmsofdriving)}{(55 * 365 * 15)parcels} = 960g\ CO_2 \text{ eq per parcel}$$

- **Transport emissions caused by LSPs**
These emissions expressed in gCO_2 eq represent the transport emissions caused by LSP parcel delivery trucks. These are caused when these trucks travel to the PL locations from the sorting center serving the demand of respective customer locations (urban or rural) and customer's residence in case of HD. The transport emissions by LSP delivery trucks to PLs in urban area per parcel are:

$$\frac{(167gCO_2/t - km \times 0.1595tonnes \times 25kmsofdriving \times 365days \times 15years)}{(55 * 365 * 15)parcels} = 12.1g\ CO_2 \text{ eq}$$

Similarly, the transport emissions by LSP delivery trucks to PLs in urban area per parcel are:

$$\frac{(167gCO_2/t - km \times 0.1595tonnes \times 75kmsofdriving \times 365days \times 15years)}{(55 * 365 * 15)parcels} = 36.3g\ CO_2 \text{ eq}$$

- **Emissions caused by PL distributor**
These emissions expressed in gCO_2 eq represent the environmental impact caused by the PL distributor that is responsible for the different life cycle phases of the PL itself and thus the emissions caused during the phases that include:
(1) Production, (2) Packaging, (3) Transport, (4) Operation & Maintenance: and (5) Recycle of PLs.
The emissions caused by these life cycle are fixed in urban and rural settings, for urban area per parcel being:

$$\frac{9141.5 \times 10^3 gCO_2(emissionsforlifecyclephases)}{(55 * 365 * 15)parcels} = 30.35g\ CO_2 \text{ eq per parcel}$$

Similarly for rural setting, the emissions per parcel are:

$$\frac{9667.32 \times 10^3 gCO_2(emissionsforlifecyclephases)}{(55 * 365 * 15)parcels} = 32.10g\ CO_2 \text{ eq per parcel}$$

SCENARIO ↓ / EMISSIONS →	Customer mode choice	Transport emissions caused by Customers per parcel (g CO_2 eq)	Transport emissions caused by LSPs per parcel (g CO_2 eq)	Emissions caused by PL distributor per parcel (Life cycle phase of PL) (g CO_2 eq)	Total emissions per parcel (g CO_2 eq)
PL system Urban Setup	Walk	0	12.1	30.35	42.46
	Bike	0	12.1	30.35	42.46
PL system Rural Setup	Bike	0	36.32	32.10	68.42
	Car	960	36.32	32.10	1028.42
Home Delivery (Urban)		-	48.43	-	48.43
Home Delivery (Rural)		-	72.64	-	72.64

Figure 6.1: *The GWP results per parcel in terms of gCO_2-eq for the PL system setups and conventional HD in an urban & rural setting*

Figure 6.1 represents the total GWP emissions of the PL system and HD in an urban and rural setup in terms of $kgCO_2$-eq emissions per parcel. It can be seen from Figure 6.1 above that in general, that the majority share of the GWP emissions are from the PL distributors in case of PL systems in urban setup. While the PL distributor emissions per parcel are fixed, the share of emissions caused by LSP per parcel dominate the PL distributor emissions in case of PL systems in rural setup.

Further insights can be drawn from Figure 6.2 and Figure 6.3, which display the percentage emissions for the different life cycle phases of the PL system in different setups by means of a stacked column chart. The most negatively impacting phase can be interpreted to be the use phase accounting for 79.02% of the total emissions (*refer to Figure 2.6 to see what is included in each phase*) in PL systems in urban setting. Additionally the use phase accounts for 86.86% of the total emissions in PL systems in rural setting when customer use bike to travel to PL locations and a substantial 99.1% when customers use car. These emissions figures are computed assuming all customers use the same mode of transport to access PL locations. This is followed by the production phase accounting for 11%-17.02% of the total emissions,while 0.73% in the rural setting where customers use car as their mode choice. The end-of-life phase makes up for 1.92%-3.09% for the total emissions regarding the different setups of PL systems and 0.13% in the rural case with car as the customer mode choice. Finally, compared to the other phases, the packaging and the transport phase have little to negligible contribution towards the environmental impact of the PL system.

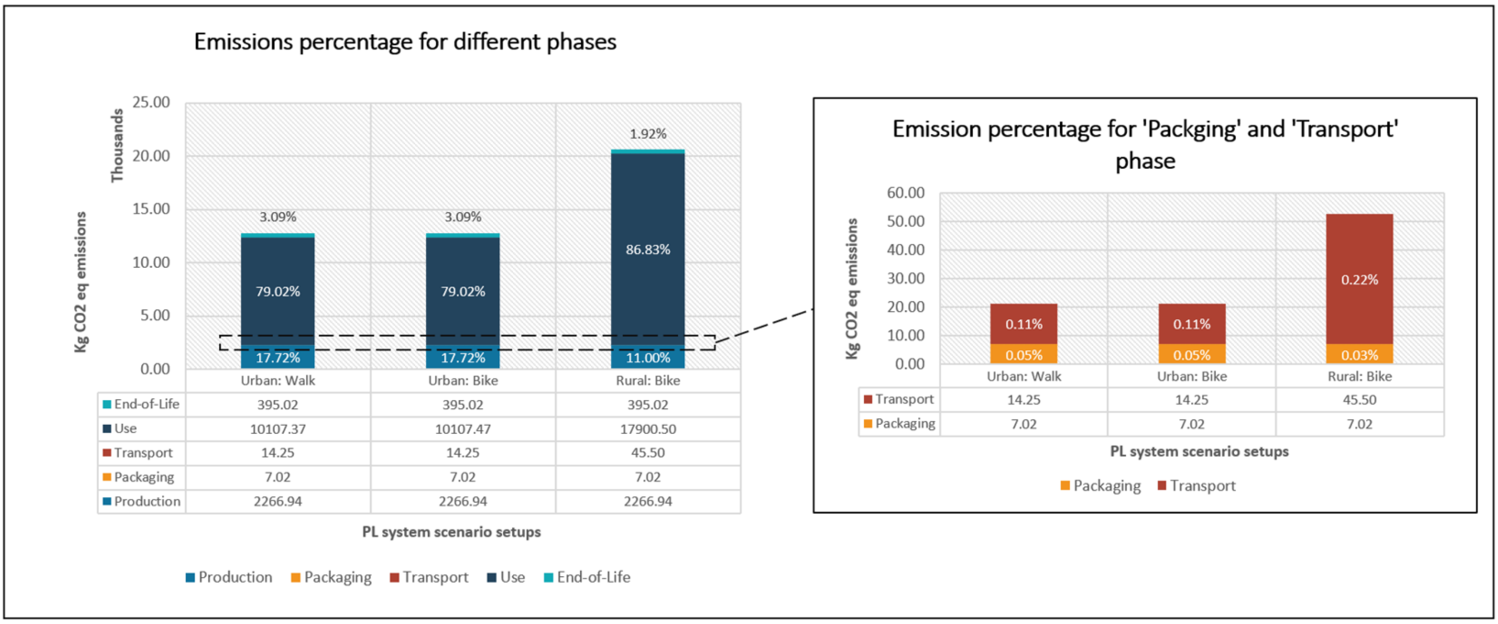


Figure 6.2: *Emissions percentage for different life cycle phases of the PL system in urban setting where customers use bike and walk, additionally the rural setting where customers bike to PL locations*

The majority of use phase emissions (99.1%) shown in Figure 6.3 can be accounted for the reason that over 15 years, if all the number of assumed customers use car to access PL locations, then these emissions are significantly huge and amount to this percentage of the total emissions.

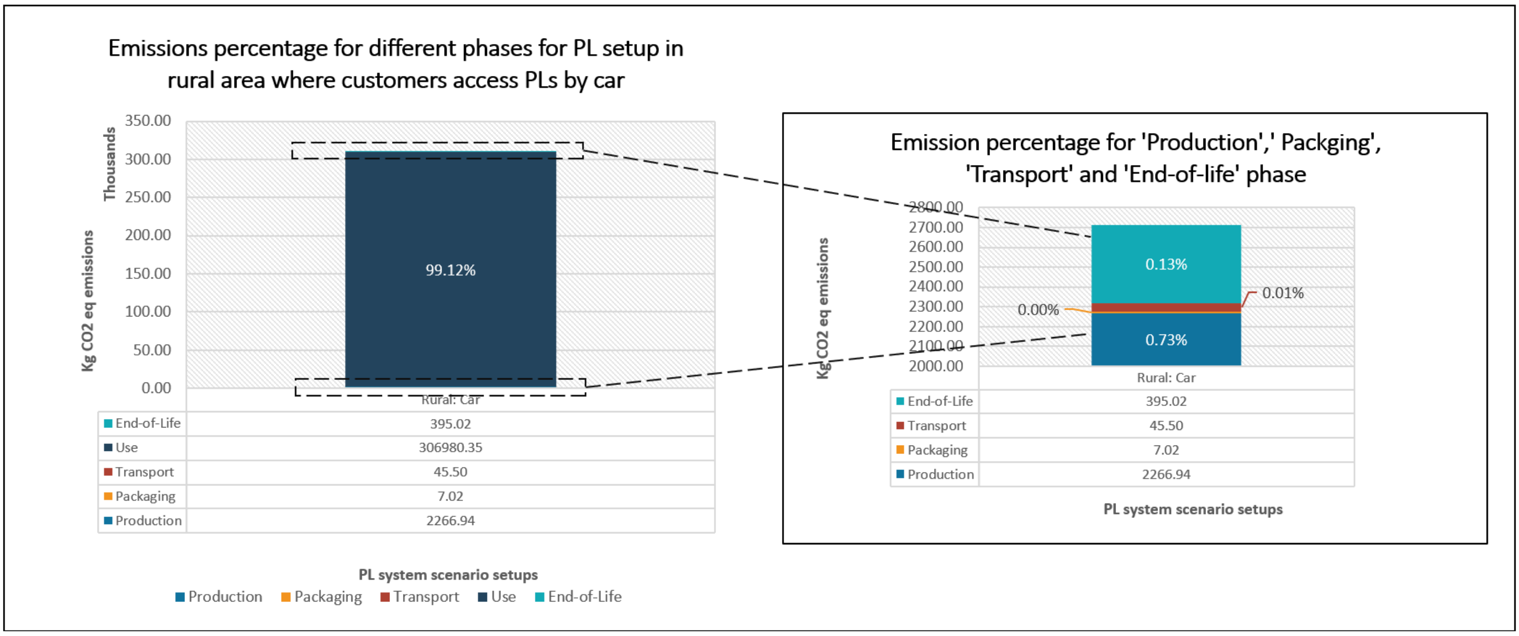


Figure 6.3: *Emissions percentage for different life cycle phases of the PL system in rural setting where customers use car to access PL locations*

While for conventional HDs, all the emissions are incurred by the LSPs which deliver parcels to the customer's residence or an address chosen by them. HD in rural areas results in higher emissions when compared to urban areas due to larger amount of VKT by the parcel delivery truck in rural areas. The primary reason for this is because the sorting center that serves the demand of urban area (De Pijp) is located more closer to it than the rural area (Ten Boer). Emissions are expressed in terms of $kgCO_2$-eq emissions highly depend on the type of delivery truck deployed by the LSP and their load.

According to a study conducted in 2021 and the Ecoinvent 3.8 database, urban delivery trucks emitted on average $167gCO_2/t-km$ or $0.17KgCO_2/t-km$ [35]. Hence, the goods transport for the HD setup is translated into in $kgCO_2$ (0.167 $kgCO_2$ eq per tkm of goods transport) by multiplying this factor by the amount of goods transported (tkm)

$$87326.25\ tkm \text{ of goods transport} \times 0.167kg\ CO_2 \text{ eq} = 14596.4kg\ CO_2 \text{ eq}$$
$$130989\ tkm \text{ of goods transport} \times 0.167kg\ CO_2 \text{ eq} = 21894.39kg\ CO_2 \text{ eq}$$

The transport emissions by LSP delivery trucks in urban and rural settings per parcel are (*also see Figure 6.1*):

$$\frac{(14596.4kgCO_2)}{(55*365*15)parcels} = 0.0484kg\ CO_2 \text{ eq}$$
$$\frac{(21894.39kgCO_2)}{(55*365*15)parcels} = 0.0726kg\ CO_2 \text{ eq}$$

6.1.1. Parcel Locker System: Urban scenario

- **Mode choice - Bike**

  For the scenario where the PL is setup in the urban area of De Pijp and the customer uses bike to access the PL location, the total climate change impact in terms of $kgCO_2$-eq emissions is found to be 1.28×10^4 (12790.7) $kgCO_2$-eq as shown in Figure 6.4.

  The figure below presents a sunburst view which provides several dimensions (*life cycle stages in this case*) into a traditional pie chart. For instance in the figure above, it can be seen that the inner pie chart represents the life cycle phases of the PL system, out of which the use phase contributes the most to the environmental impact. While the outer pie chart shows exactly which aspect of each of the life cycle phases contributes what percentage to the environmental impact. In this case *'Electricity Netherlands'* contributes the most in the 'use' phase of the PL system. Similar sunburst views are presented in the rest of section 6.1 which can be interpreted similarly to Figure 6.4.

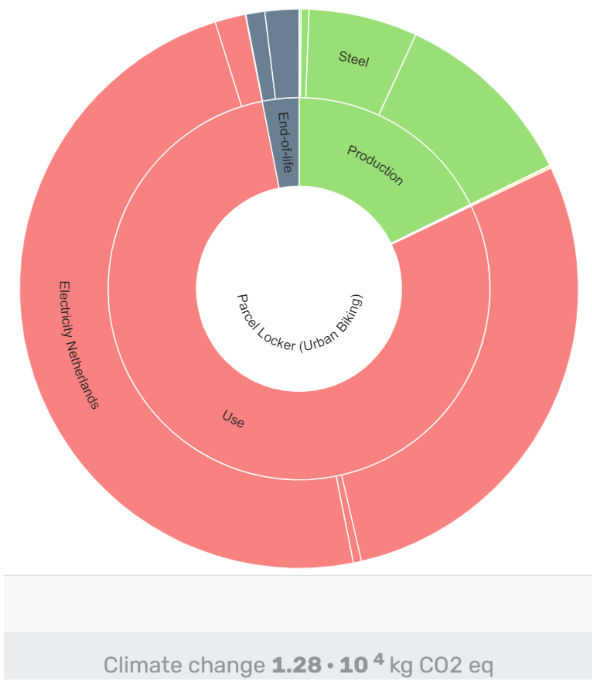


Figure 6.4: *Sunburst view of the PL system life cycle in an urban setup where customers access the PL locations by biking*

Figure E.4 (*Appendix E*) illustrates the calculated climate change impact that also denotes the GWP for all of the life cycle phases considered in this study. The results indicate that the electricity consumption, especially for the use phase has the highest GWP and therefore emit the most $kgCO_2$-eq emissions. This accounts for almost 61.1% of all the climate change emission, 48.3% of which is consumed in the 'use phase' of the PLs, 10.9% in the 'production phase' and the rest is consumed for end of life phase to recycle the PLs for next life cycle as can be seen from the sunburst view as can be seen from the sunburst view. Other significant contributing factors are accessing the PL locations by LSPs which account for 28.5% of the total emissions, steel production (6.3%), travelling of trucks for maintenance and (1.8%) respectively (*see Figure E.3, Appendix E*). Biking alone to access the PL locations have a very insignificant impact on the climate change in terms of $kgCO_2$-eq emissions, accounting for only about 0.1 $kgCO_2$-eq.

- **Mode choice - Walk**
  Similarly, according to Figure 6.5, for the scenario where the PL is setup in the urban area of De Pijp and the customer walks and accesses the PL location, the total climate change impact is found to be 1.27×10^4 (12790.7) $kgCO_2$-eq. Since biking emissions in previous case are negligible and walking does not result in any emissions as it is a green and an environment friendly mode, the emissions are nearly identical to the biking scenario.

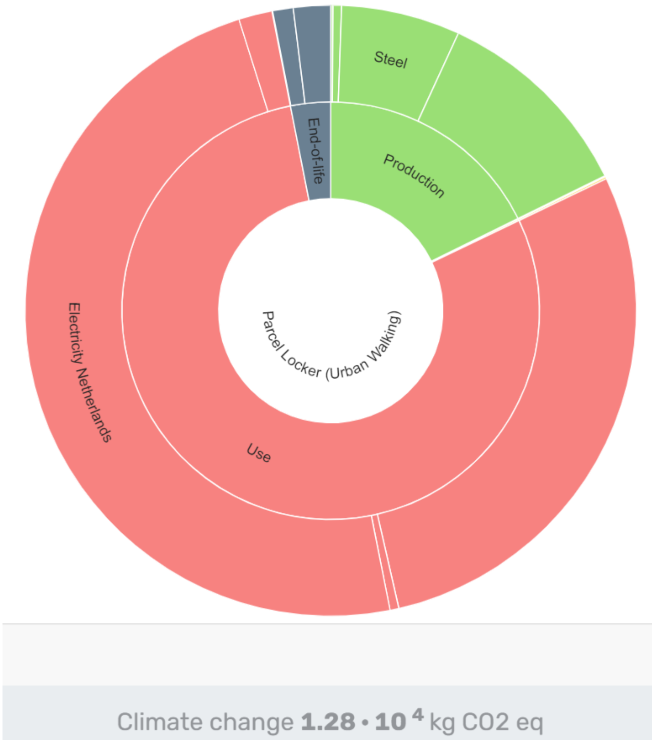


Figure 6.5: *Sunburst view of the PL system life cycle in an urban setup where customers access the PL locations by walking*

Figure E.2 (*Appendix E*) illustrates that the electricity consumption, especially for the 'use phase' has the highest GWP and therefore emit the most $kgCO_2$-eq emissions. This is similar to urban scenario where the mode choice by the customers to access PLs is bike. One benefit of this mode choice is that it leads to zero emissions when accessing the PLs for collecting or returning the parcels. Since the bike emissions in the use phase were found to be negligible in the first place, the results of this scenario are highly similar as the scenario discussed above.

6.1.2. Parcel Locker System: Rural scenario

- **Mode choice - Bike**
  For the scenario where the PL is setup in the rural area of Ten Boer and the customer uses bike to access the PL location, the total climate change impact in terms of $kgCO_2$-eq emissions is found to be 2.06×10^4 (20614.983) $kgCO_2$-eq as shown in Figure 6.6

Figure E.6 (*Appendix E*) indicates that the access by LSP trucks when they travel from sorting center in Hoogeveen to Ten Boer on a daily basis, have the maximum contribution in total GWP emissions of about 53.1%. Next to this electricity consumption also has a significant GWP impact of about 37.9% eq of total emissions. 29.9% of this electricity is consumed in the use phase of the PLs, 6.7% in the production phase and the rest is consumed for recycling of PLs for next life cycle as can be seen from the sunburst view. Other significant contributing factors towards the environmental impact are production of steel and travelling of trucks for maintenance which account for 4.6% and 3.5% of the total climate change emissions respectively (*see Figure E.5, chapter 6*).

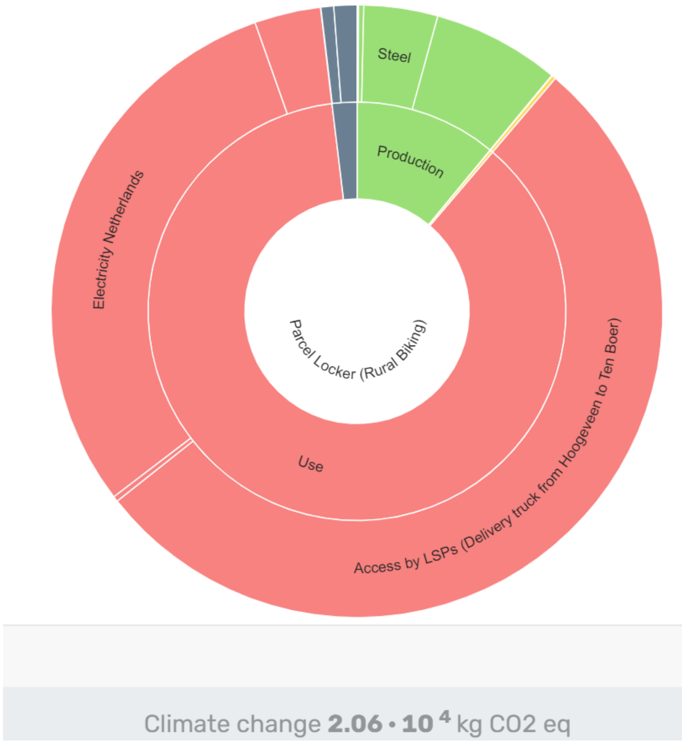


Figure 6.6: *Sunburst view of the PL system life cycle in an rural setup where customers access the PL locations by biking*

- <u>**Mode choice - Car**</u>
  For the scenario where the PL is setup in the rural area of De Pijp and the customer uses bike to access the PL location, the total climate change impact in terms of $kgCO_2$-eq emissions is found to be 3.09×10^5 (309694.83) $kgCO_2$-eq as shown in Figure 6.7

  It can be seen from Figure E.8 (*Appendix E*) that in this scenario, accessing the PLs by car has the highest GWP impact on the total climate change impact category accounting for about 93.3% of the total emissions. Majority of the emissions in this scenario originate from all the customers using cars for an average travel distance of 5 kms in rural area to access PLs. It is interesting to see that access by LSPs for parcel delivery and electricity consumption, as compared to other scenarios have significantly low impacts of about 3.5% and 2.5% respectively (*see Figure E.7, Appendix E*).

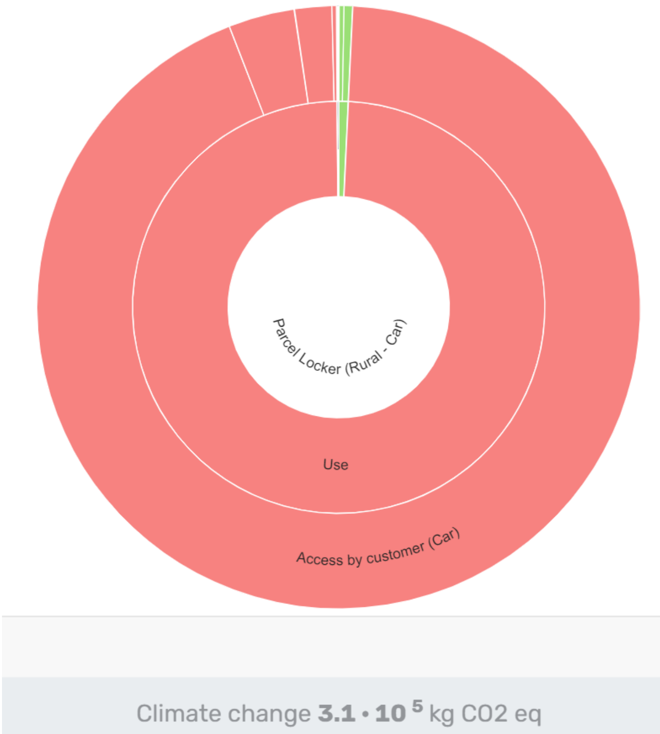
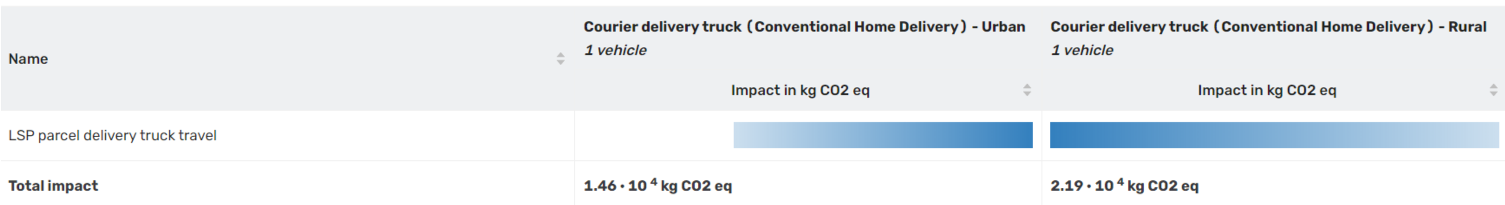


Figure 6.7: *Sunburst view of the PL system life cycle in an rural setup where customers access the PL locations by car*

6.1.3. Conventional Home Delivery

- **Urban setup**
  For the HDs in urban areas where the parcels are collected and returned by customers at their place of residence, the total climate change impact in terms of $kgCO_2$-eq emissions is found to be 1.44×10^4 (14596.68) $kgCO_2$-eq as shown in Figure 6.8. Since only the delivery truck travel is considered for the HD system, 100% of the climate change impact emissions are generated by the tonnes-km (tkm) of goods transport (*see Figure E.9, Appendix E*)

- **Rural setup**
  For HD in rural areas, the total emissions is found to be 2.14×10^4 (21894.95) $kgCO_2$-eq as shown in Figure 6.8. The emissions are higher is case of rural areas due to higher number of VKT by parcel delivery trucks from the sorting center Hoogeveen to Ten Boer in comparison to the urban setup (*see Figure E.10, Appendix E*).



Name	Courier delivery truck (Conventional Home Delivery) - Urban, 1 vehicle — Impact in kg CO2 eq	Courier delivery truck (Conventional Home Delivery) - Rural, 1 vehicle — Impact in kg CO2 eq
LSP parcel delivery truck travel		
Total impact	$1.46 \cdot 10^4$ kg CO2 eq	$2.19 \cdot 10^4$ kg CO2 eq

Figure 6.8: *Sunburst view of conventional HD system in urban area of De Pijp (left) vs. rural area of Ten Boer (right)*

6.2. Results interpretation

This section briefly reflects on the overall emissions, the most contributing phase towards the environmental impact and the comparison of PL system to HD.

Overall emissions

PL system in an urban setup (De pijp) where customer access them by walking or by biking has proven to be the most efficient PL setup while the PL system in a rural area (Ten Boer) is the least efficient PL setup as seen from Figure 6.1. In both the scenario the emissions are almost identical as emissions by biking are almost negligible.

It can be seen from results discussed in section 6.1 that there is some considerable difference in the climate change impact emissions of the two different setups considered in this study. The higher population density in urban areas often necessitates a higher density of PLs. This is also supported by literature as seen from chapter 3 where the PLs in an urban setup are more easily accessible than the one is rural areas. While the PL system in a rural setup where mode choice is bike has significantly higher emissions, the case where customers only use car has immensely high emissions.

PL in De Pijp are close to the PostNL sorting center chosen for this study being located only 25 kms away from the city in Westzaan. This results in significantly low LSP truck transport emissions accounting for about 28.5% (*see Figure E.1*) in contrast to 53.1% (*see Figure E.5*) of the total climate change impact emissions for PLs situated in rural area in case of bike. This is because the nearest PostNL sorting center to Ten Boer is located about 75 kms away from it in Hoogeveen. The difference in emissions of about 7.29 tonnes of CO_2 (or 7298.4 $kgCO_2$) is a result of more tkm of goods transported in rural areas causing more CO_2 emissions. Overall there can be a maximum possible reduction of about 66.6% emission reduction if the sorting centers that are setup to serve the demand of customers in Ten Boer have a similar distance to sorting centers from De Pijp. While for mode choice as car, the LSP transport emissions amount to only about 3.5%.

Most contributing phase and factor towards the environmental impact

As seen from section 6.1, it is clear that 'use phase' (*see Figure 2.6*) for all the scenarios contribute to have the most effect on the climate change category. This can be accounted for the fact that the transport emissions by customers and LSPs for accessing PL location along with the electricity consumption in different life cycle phases of PL over the course of 15 years, results in significantly high emissions. *Electricity Consumption* in the use phase for the PL scenarios in urban setup are the most contributing factor accounting for about 48.3% of the total environmental impact consuming 13342 KWh of electricity its entire life cycle. While for PL system in rural setup where customer bike to PL locations, transport emissions by LSP are the most contributing factor (about 53.1%) towards the total emissions. Finally for PL system scenario in rural setup where customers use car to access PL locations, the transport emissions by customers are the most contributing factor (about 93.3%) towards the total emissions.

Mode choice

Location of PL system setup ultimately affects the way they are accessed by customers and thus affects their mode choice. As seen from previous literature in chapter 3 and from the case study conducted in this thesis, the difference in total climate change impact in urban scenario when the customer bikes and when the customer walks to access the PLs is a mere 0.1 $kgCO_2$ according to the software which is negligible. This can be accounted for the fact that both biking and walking are very green ways of transport and high density of PL locations in an urban setup make this possible.

While in a rural setup, since the PL density is sparse, travelling by car becomes more convenient for the customer for collection of parcels at PL location as seen from previous literature in chapter 3. However travelling by car causes significantly higher emissions as opposed to using a bike for accessing PL locations. Thus travelling by car in a rural PL system setup results in about 93.3% (289080 $kgCO_2$) in contrast to 7.04×10^{-4}% (0.1 $kgCO_2$) by bike of the total climate change impact emissions for PLs situated in rural area.

Transport emissions caused by LSPs in PL system vs HD

It is interesting to note that the no failed delivery assumption in section 5.1, works against the PL system and is the best case scenario for HDs. Despite assuming the best case scenario for HDs and worst case scenario for PL system, the PL system performs better than the HD as can be seen from Figure 6.1. The only scenario where the PL system performs worse in the case where all the customers travel by car in order to access PLs. This is in tune with the findings from (De Maere. B, (2018) [8] where benefits of PLs are undone if the trip is made by car.

After seeing the results from section 6.1 (*see Figure 6.1*), it is clear that the transport emissions caused by the LSP trucks in case of HDs are higher when compared to a PL system. The overall emissions of the entire PL system are lower than HDs, except for the scenario when all the customers use car to access PL locations. This makes HD inefficient and thus have a higher carbon footprint in comparison to PL systems. The main reason for this is the amount of tonnes-km of goods transported between the two setups by the LSPs. This value is high in case of HD system as the courier delivery truck has to drive significantly more kms to deliver the same number of parcels during one delivery occasion. This includes the LSP trucks driving from sorting centers to urban and rural areas plus the additional distance to deliver each parcel as mentioned in section 5.1.

Figure 6.9 compares the transport emissions of the LSPs in PL system and HDs. It can be seen that PL system in an urban setup can reduce about 74.9% of the emissions while about 49.9% of emissions in a rural setup per parcel. It is also interesting to note that the benefits in terms of $g\ CO_2$ reduction are somewhat similar in case of urban and rural areas. Although the percentage emissions reduction in urban areas is more as compared to rural areas, the amount of carbon footprint reduced is similar to about $36.3g\ CO_2$ eq per parcel in case of PL systems.

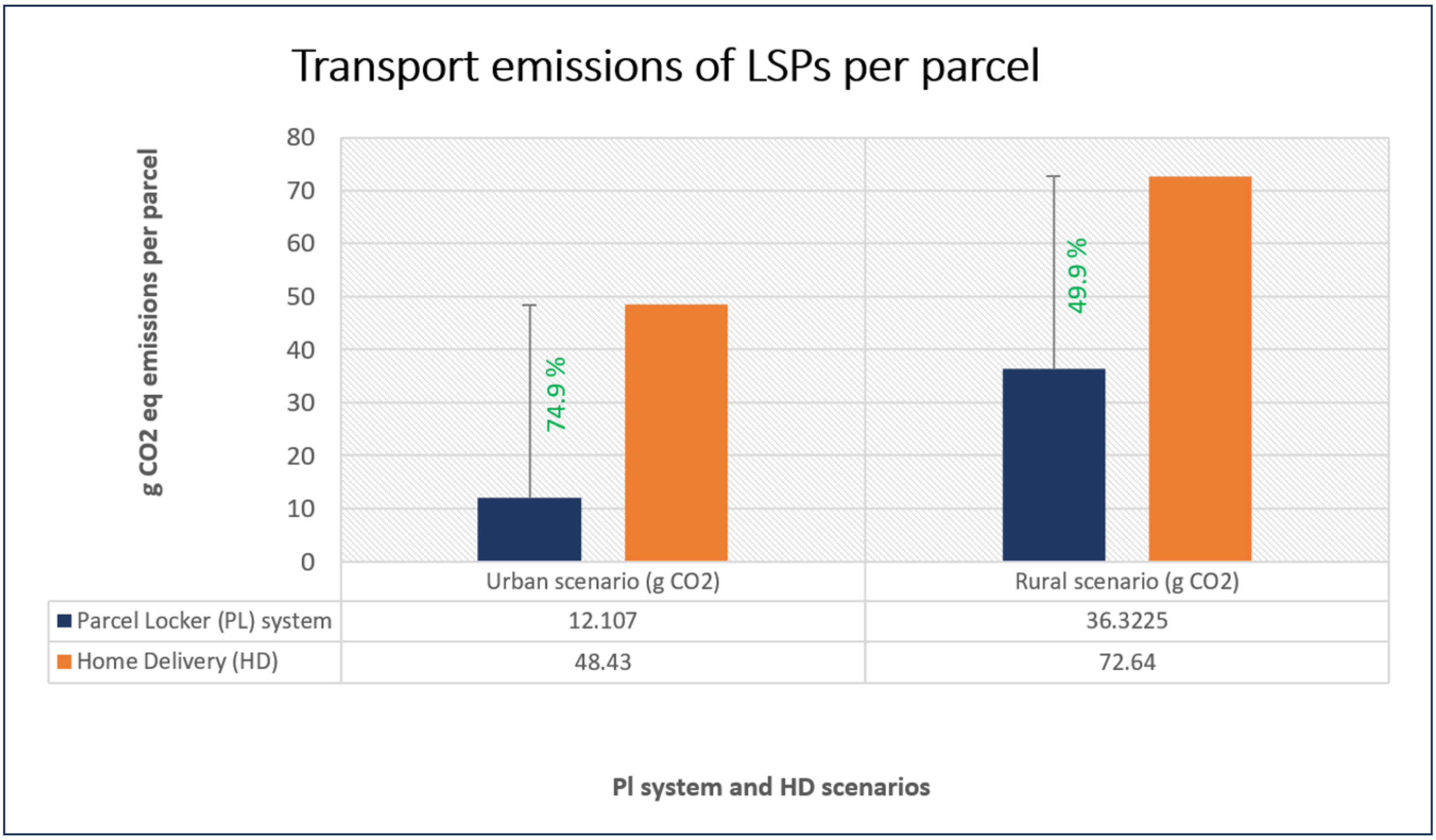


Figure 6.9: *Stacked column chart representing the $KgCO_2$ eq emissions per parcel of the PL system and conventional HD in different scenarios*

Hence from carefully analyzing the PL system and HD setups as a last mile delivery, the analysis suggests that the installation of PLs in urban and rural areas yields significant environmental benefits in terms of transport emissions by LSPs. This can be attributed to the advantage in PL systems where the reduction in the VKT by the LSP parcel delivery trucks out benefits the customer travel to retrieve their parcels for last mile delivery operation. However, this gain in environmental impact is undone if all the trips are entirely made by car as seen in section 6.1 in the PL system rural scenario. Then the PL system performs worse in terms of $KgCO_2$ eq emissions per parcel owing to huge emissions by car travel on a daily basis.

6.3. Sensitivity Analysis

In the base case scenario already discussed in this thesis where all the external factors for both PL system and HD are same, it can be seen from section 6.2, how generally the PL system is more environment friendly and sustainable solution than the conventional HD as a last mile delivery. A sensitivity analysis that is conducted in this section, a reflection on the effect of more sustainable practices in the future and convenience of the solution for PL distributors and also LSPs is studied. Hence for this section of the thesis, most insightful factors are chosen and a sensitivity analysis would be conducted on them. For ease of computation, it is assumed that demand of parcels in urban and rural area to still be the same of about 55 parcels per day.

6.3.1. Motivation for parameters/factors selection

In order to carry out the sensitivity analysis, firstly key factors or parameters that significantly affect the environmental impact of the PL system need to identified. These factors can be broadly divided into two categories namely:

- **Scenario factors**
  Scenario factors in the context of this thesis refer to variables that characterize different scenarios or conditions under which the PL system operates. These factors encapsulate various elements that can impact the overall environmental impact of the system. They include parameters that influence customer behavior, logistics operations, and external circumstances. For instance, the delivery failure rate represents the frequency of unsuccessful delivery attempts, affecting the need for re-deliveries and potentially increasing emissions. Customer mode choice pertains to the transportation mode customers select when accessing the PLs, influencing emissions related to their travel. These scenario factors collectively reflect the intricacies of real-world scenarios and how they interact with the PL system, ultimately influencing its environmental footprint.

  As previously mentioned in section 5.1 (*see chapter 5*), no delivery failure rates are assumed which may not be the case in reality. Additionally it is assumed that customer make dedicated trips to retrieve parcels, thus no trip chaining. Hence a sensitivity analysis is done by including delivery failure rate in HDs, trip chaining and assuming PL location , i.e customers can combine other trips for different purposes with a trip to retrieve parcels from PL locations in subsection 6.3.2:

  – The *'Delivery failure rate'* of PLs: It is assumed that in real world scenario, there are parcel delivery failures to some extent in case of HDs. This can be due to reasons such as either customers not being at home when the LSP truck arrives at their residence or the customer location is not accessible. Three scenarios are considered for conducting a sensitivity analysis, namely: Low; Medium and High

  – The *'Trip Chaining'*: Based on the study done by (De Maere. B, (2018) [8], it is assumed that the average extra travel distance the customers have to make when visiting PLs when trip chaining to be 0.75 kms

  – The *'PL locations'*: It is expected in real world scenario, that the PL distribution would be different in urban and a rural setting. Thus the PL distribution varies the number of PLs based on the expansion of PL network in The Netherlands [38] and the consequent emissions are studied.

- **System design factors**
  System design factors encompass the specific attributes and configurations of the PL system itself. These factors shape the structure, efficiency, and environmental impact of the system. They include variables related to the physical aspects and operational setup of the PL infrastructure. For example, the number and size of PLs directly impact the system's capacity and accessibility. Energy consumption of PLs relates to the efficiency of energy use within the system. The frequency of deliveries, often measured as the batch size, affects transportation efficiency and emissions. System design factors are intrinsic to the functioning of the PL system and are under the direct control of the logistics service providers and designers. Analyzing these factors provides insights into how different configurations and attributes of the system can influence its environmental performance and sustainability.

  As can be seen from results in section 6.1 (*also see Appendix E*), the factors contributing the most to the climate change environmental impacts of the PL system in the urban scenarios is the 'Electricity Consumption' and 'Access by LSPs'. Hence a sensitivity analysis is done by varying parameters that directly impact decisions of the PL distributors and LSPs in subsection 6.3.3:

- The *'Electricity consumption'* of PLs: It is assumed that in the future more energy efficient PLs will be designed. Thus a range of low, medium, and high energy consumption scenarios are considered.

- The *'VKT by LSP trucks'* by LSPs to deliver parcels to PL locations: It is also assumed that in the future, more distribution centres will be deployed near rural areas that will reduce the VKT of the parcel delivery trucks. Specially for rural areas, it is assumed that these distances reduce significantly to a 'moderate' and 'low' scenarios.

6.3.2. Scenario factors

Delivery failure rate

Although the best case scenario for HDs is assumed in section 5.1 which performs worse than the PL system as seen in section 6.1, however including failed delivery rates can give important insights into real-world complexities and challenges, guiding the development of more efficient and sustainable last-mile delivery solutions. This scenario will particularly affect HDs both in urban and rural scenario. The case where there are zero delivery failures is assumed to be the base case scenario. The delivery failure rate can be defined as:

$$\text{Delivery Failure Rate} = \frac{NumberofFailedDeliveries}{TotalNumberofDeliveryAttempts} \times 100$$

Table 6.1 shows the three scenarios considered for the sensitivity analysis. As of 2020, the state of e-commerce in the Netherlands is that the parcels on average have a 95% of success rate at first delivery attempt [10]. Additionally literature shows reported rates of failed first-time deliveries of between 12% and 60% in cases in which no delivery time or arrangement had been made with the customer in advance. This high failure rate is largely the result of lifestyle changes: the growth in single-person households and flexible working patterns [52]. Thus for the 'low' scenario, out of the 55 parcels that need to be delivered in a day (*see section 5.1*), the delivery failure rate is assumed to be about 5%, i.e at most 3 out of the 55 parcels are not not delivered successfully in the first attempt. Similarly the delivery failure rates for 'medium' and 'high' scenarios are about 14.5% and 36.6% respectively.

Table 6.1: *Sensitivity analysis: Delivery failure rate*

Scenario	Number of failed deliveries	Number of delivery attempts	Delivery failure rate
Scenario 1 (Low)	3	55	5.45%
Scenario 2 (Medium)	8	55	14.45%
Scenario 3 (High)	20	55	36.36%

This means that the number of parcels that are not delivered (number of failed deliveries), would need to be delivered to the customers the following day thus resulting in additional trips by LSP delivery trucks to deliver the unfulfilled customer parcels and thus increasing VKT. It is here assumed that the delivery failure rate in all the three scenarios occur daily, hence the trucks travel next day with undelivered parcels to deliver them to the customers. This consequently will result in higher emissions compared to the base case scenario.

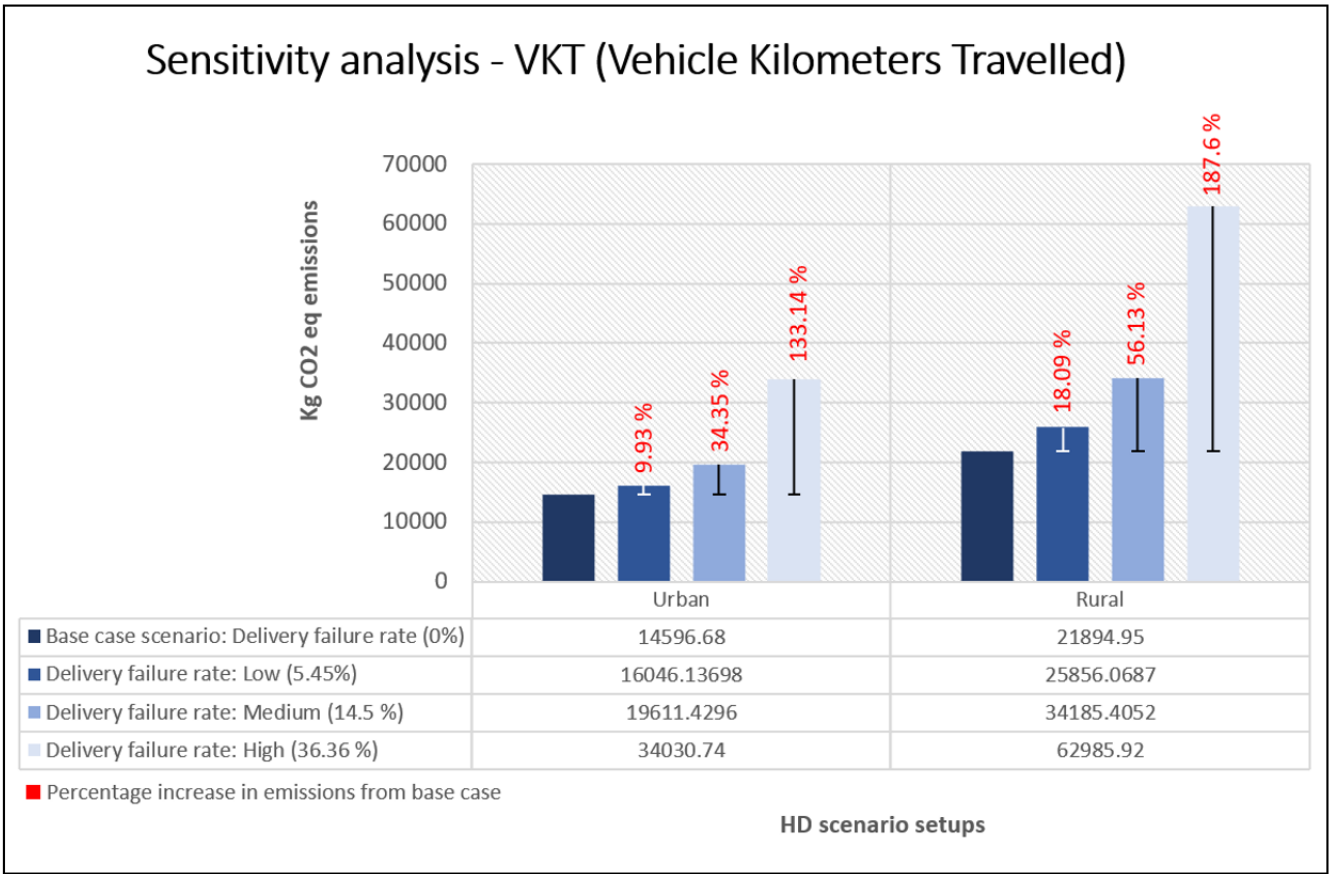


Figure 6.10: *Sensitivity Analysis: Delivery failure rate with Low, Medium and High scenarios*

It can be seen from Figure 6.10 that the overall increase in $KgCO_2$ emissions are almost exponential with increasing parcel delivery failure rates. Also it is interesting to note that increase in emissions in rural areas is more compared to urban areas with increasing delivery failure rates. This can be accounted for the fact that the sorting center that serves the demand of rural area are located further than the sorting center that serves the urban area. This ultimately leads to increased VKT per parcel in rural areas thus leading to higher emissions.

When delivery failure rate is about 5.45%, a 9.9% increase in the total emission can be observed in urban HDs and an 18% increase in rural HDs. Emissions increase by a factor to 2.3 (133.1%) in urban HDs and 2.8 (187.6%) in rural HDs when the parcel delivery failure rate becomes high, to about 36.3% meaning that about 20 out 55 parcels are not delivered successfully in a single delivery attempt. The HD emissions are also poor when the delivery failure rates are moderate (about 14.5%) translating to 8 failed deliveries out of 55 on a single occasion. In this scenario the percentage increase in emissions are 34.3% in urban HDs and 56.1% in rural HDs respectively.

It can be therefore concluded that factor delivery failure rate is a significantly sensitive factor and can lead to increased emissions by up to two to three folds if it becomes high. Hence the delivery failure rate should be kept as low as possible, which is the present situation in the Netherlands [10] with average successful delivery first time delivery rates of 95%, to ensure efficient transport and delivering of goods.

Trip chaining

This scenario will affect the environmental impacts of PL system more in rural setup. The reason behind this is that walking and biking are very eco-friendly transport modes. Although the extra travel distance to access PLs during their trip chain would be less that a dedicated trip using these modes, the emissions caused by biking or walking can be considered negligible or zero. Hence trip chaining is only applied to the PL system in the rural setup where the emissions per km of car travel are significant and a reduction in distance to access PLs would consequently result in overall decreased environmental impact. The case where there is no trip chaining (i.e. dedicated trips by customer) is assumed to be the base case scenario. If the the collection of the parcel is combined with another activity, the point of interest is the extra distance and the transport mode used during that particular distance [8].

Table 6.2: *Sensitivity analysis: Trip chaining*

Scenario	Trip characteristic	Avg. customer travel distance by car
Scenario 1	Dedicated trip	5 km
Scenario 2	Trip chaining	0.75 km

It is assumed that the average extra travel distance the customers have to make when visiting PLs when trip chaining to be 0.75 kms, the same distance chosen based on the study by (De Maere. B, (2018) [8]. Similar to the emissions computation considering the customer travel emissions to PL location in rural area of Ten Boer via car, this is translated into in $g\ CO_2$ per parcel which now becomes:

$$\frac{(192gCO_2/km \times 0.75kmsofaveragedrivingdistance) \times 365days \times 15years \times 55customers}{(55 * 365 * 15)parcels} = 144g\,CO_2$$

eq per parcel

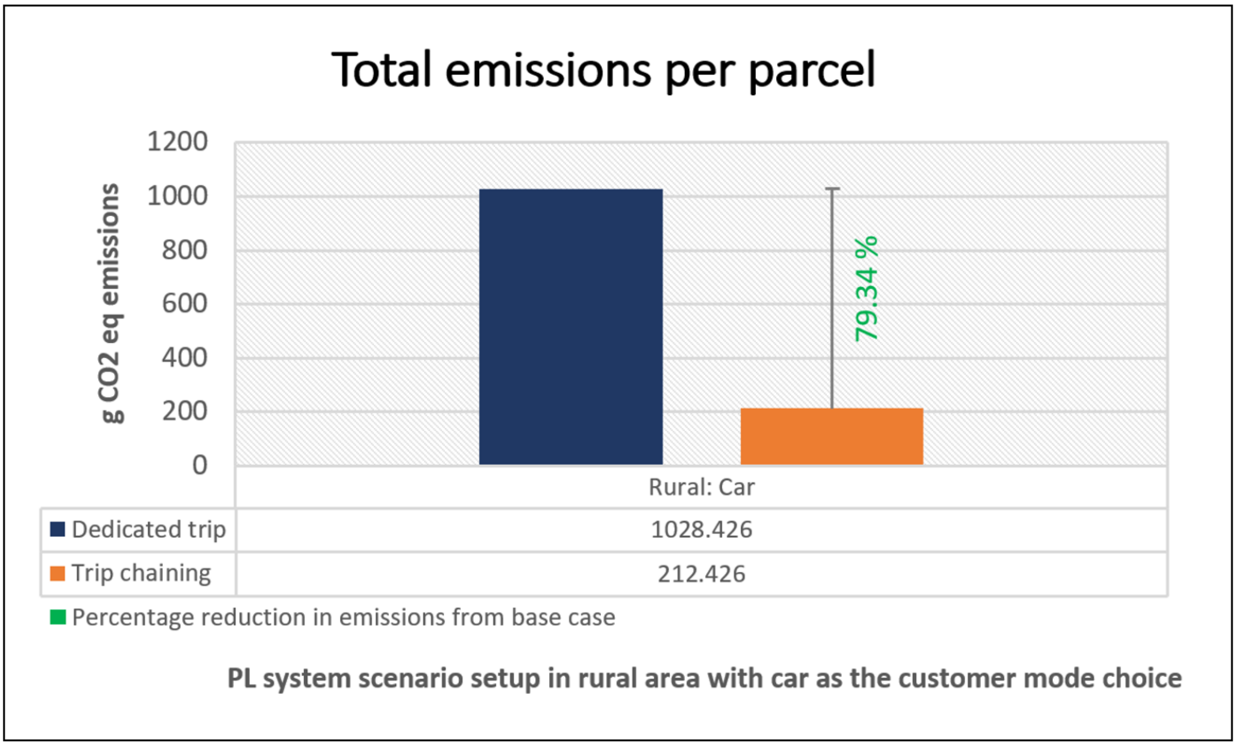


Figure 6.11: *Scenario analysis: Average trip chaining distance of 0.75 km assumed*

Figure 6.11 shows that when trip chaining is considered, only the emissions caused by the customers are reduced in the entire PL system. Referring Figure 6.1, the emissions caused by LSPs and PL distributor remain the same, resulting the total PL system emissions for the rural setup where customers use car as their mode choice to be 212.426 $g\ CO_2$ eq per parcel. This results in 79.34% lower emissions per parcel in case of trip chaining. Thus it can be concluded that trip chaining is an important aspect of the PL system and can result in significant reduction of overall emissions per parcel.

PL Locations

This scenario affects the PLs in both the rural and urban setups. According to PostNL, there are more than 400

PostNL lockers in the Netherlands currently and their goal is to reach about 1500 lockers installed by the end of 2024 [38] (see section 3.4). This will be done to ensure that everyone can use a PL nearby. Hence two scenario for the increase in PL locations are discussed as shown in Table 6.3.

Table 6.3: *Sensitivity analysis: PL locations*

Scenario	Trip characteristic	VKT by LSPs and Customers	PL life cycle emissions
Scenario 1	2024 beginning	40% decrease	40% increase
Scenario 2	2024 end	60% decrease	60% increase

Additional lockers installed would mean reduced VKT by customers and LSPs. For conducting this scenario analysis, a medium or moderate increase in PL network is assumed all over resulting in an assumed 40% decrease in the VKT of LSPs and customers. Similarly a high increase in PL network density scenario is assumed where the customer and LSP VKT reduce by 60%. Thus for instance the distance travelled by car in a rural setup for a dedicated trip would be 2 kms instead of 5 kms.

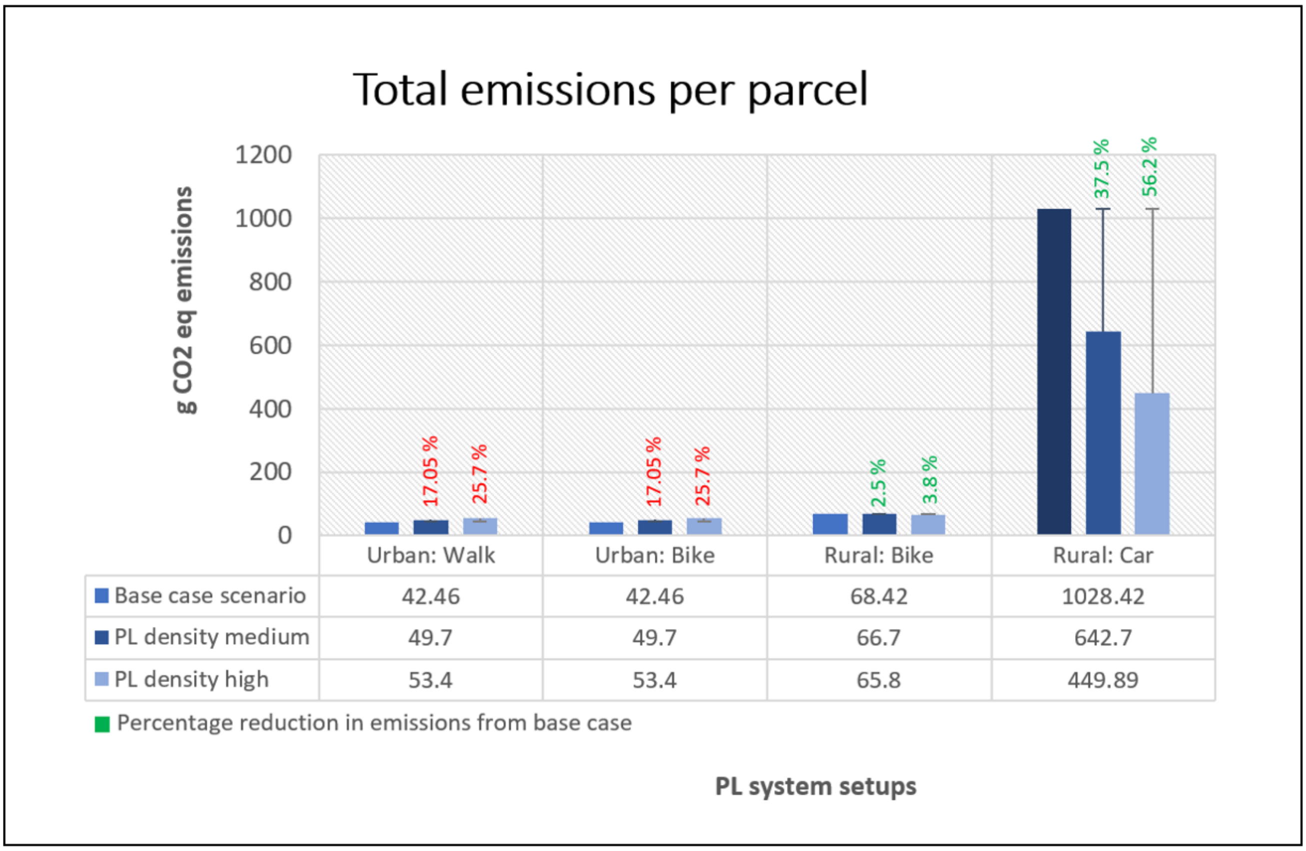


Figure 6.12: *Sensitivity Analysis:more PLs with Medium and High scenarios*

In contrast, it is assumed that the PL emissions per parcel by the PL distributor will increase due to increased life cycle emissions as more PLs are installed (more emissions per each life cycle stage). Figure 6.12 shows that the scenario where the reduced VKT and PL life cycle emissions are moderately high due to moderate increase in PL locations, an 17.05% increase in emissions in urban area and about 2.5%-37.5% reduction in rural setup's overall emissions of the PL system per parcel can be observed. This can be accounted for the fact that the environmental gain from reduced VKT of customer travel and LSPs outweighs the negative impact of increased PL life cycle emissions due to increase in PL density in rural areas. This is not the case in urban areas where the PL life cycle emissions per parcel have a more negative impacts and outweigh the emissions reductions by reduced VKT of customers and LSPs. Similarly in the case of high increase in PL locations, the emission reductions per parcel are about 3.8%-56% in rural setup of PL systems. While for urban areas this results in increased overall emissions by upto 25%.

It is interesting to note that the PL system most affected by this scenario analysis is the rural setup where all the customers use cars to access PL locations. Thus for instance, if the travel to PL locations by car is reduced from 5 kms to 3 kms, an emission reduction of 385 gCO_2 is observed. This is because the other PL system setups considered in this study have zero customer emissions as the mode chosen are either bike or on foot which are very green ways of mobility. It can also be inferred that it is beneficial to increase the PL locations in rural areas but not in urban areas. The increased PL life cycle emissions in this case outweigh the reduced VKT by LSPs and customers.

Thus increasing PL locations and therefore their density becomes highly beneficial in decreasing the overall emissions per parcel especially in cases where the customer transport emissions are significantly high, which implies the use of non-green ways of mobility on their part.

6.3.3. System design factors

Electricity consumption

This scenario will affect the PLs in both the rural and urban setups. It can be seen from section 6.2, this factor is most significant contributor towards the environmental impacts in PL systems in urban setting and also has a significant contribution in rural setting where customers use bike as their mode choice. Since the emissions in case of urban setting where mode choices are bike and walking are fairly similar, only the bike scenarios in urban and rural settings are chosen for this analysis. The PL system in rural setup where customer use cars is not considered here as electricity consumption makes up for a very small percentage of total emissions of that scenario. The case where the PL system consumes about 0.08 KWh electricity is assumed to be the base case scenario. Three scenarios are considered for conducting a sensitivity analysis, namely: Low; Medium and High as shown in Table 6.4.

Table 6.4: *Sensitivity analysis: Electricity consumption*

Scenario	Electricity consumption
Scenario 1	Low (0.03 KWh)
Scenario 2	Medium (0.05 KWh)
Scenario 3	High (0.1 KWh)

As mentioned in chapter 4, Most PL systems have an electricity consumption of around 80-100 watts per hour. The base case that is also modelled into this case study is an electricity consumption of 80 watts per hour. For high PL electricity consumption scenario, it is assumed that all the components are in use and the PL consumes 100 watts per hour. For medium PL electricity consumption scenario, it is assumed that only the necessary components the PL are in use to have more efficient operation than the base case scenario while not compromising parcel safety. Hence an electricity consumption of 50 watts per hour is assumed for the medium scenario. Finally, for low PL electricity consumption scenario, it is assumed that due to future development in technology, a highly efficient operation of PL takes place resulting in electricity consumption of 30 watts per hour.

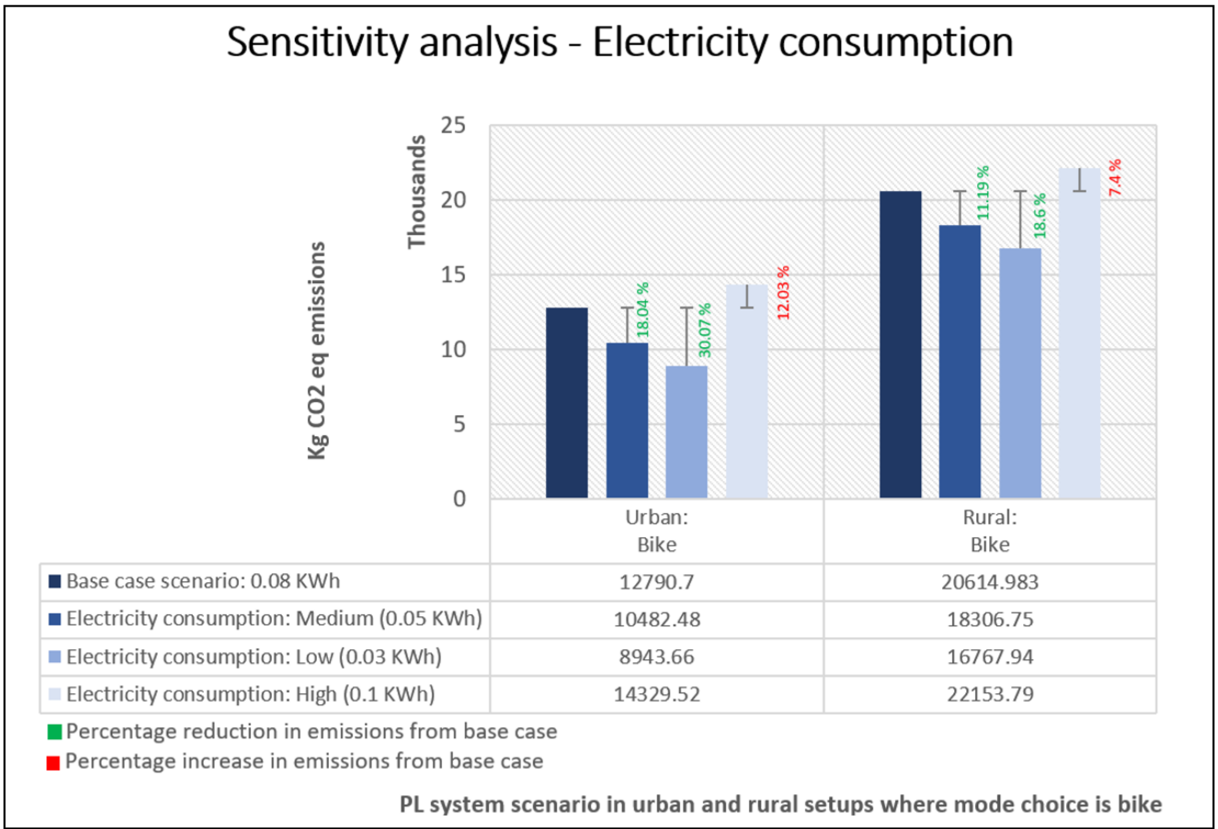


Figure 6.13: *Sensitivity Analysis: Electricity consumption with Low, Medium and High scenarios*

It is observed from Figure 6.13 that for the assumed scenario when the PL consumes only 0.03 KWh of electricity due to an assumed efficient production of PL by their distributors in future, emissions reduction can range from anywhere between 18.04% to 30%. This could result in up to 3.84 $tonnes$ of CO_2 emission reduction in the PL system life cycle.

Similarly when the electricity consumption if reduced from 0.08 Kwh to 0.05 KWh due to efficient operation by only use of necessary components for PL without compromising its intended use and safety, the resulting emissions by the PL system results in emission reduction from a minimum of 11.19% to a maximum of 18%. This results in 2.3 $tonnes$ of CO_2 reduction that is produced less during the life cycle of the PL system. Finally for the case where all the components and auxiliaries of the PL are in complete use, the resulting electricity consumption is assumed to be 100 watts per hour which results in increased emissions by up to 7.4%-12%. This accounts for an increase of 1.53 $tonnes$ of CO_2 emissions.

The scenario where PL uses 0.03 KWh electricity may be possible but would require a significant technological advancement. Hence, it can be concluded that the scenario where the PL consumes 0.05 KWh of electricity proves to be more beneficial as compared to other scenarios due to its assumed feasibility for a short time horizon in the future.

VKT by LSP delivery trucks

As mentioned in chapter 4, the logistics operation of delivering parcels are dependent on the location of sorting centers that also ultimately affect the environment. This scenario in contrast to the amount of electricity consumed, affects the PLs more in rural than urban setups as the amount of VKT by LSP delivery trucks is more in rural areas. This is because the PostNL sorting center where the LSP delivery trucks start their journey to PL locations is about 75 kms for the Ten Boer (sorting center in Hoogeveen) compared to only 25 kms for De Pijp (sorting center in Westzaan). The case where the LSP trucks travel 75 kms to PL locations in rural area of Ten Boer is assumed to be the base case scenario. Two scenarios are considered for conducting a sensitivity analysis, namely:

Low and Moderate as shown in Table 6.5.

Table 6.5: *Sensitivity analysis: VKT by LSP delivery trucks*

Scenario	VKT
Scenario 1	Moderate (50 kms)
Scenario 2	Low (25 kms)

As mentioned in section 5.1, the base case that is also modelled into this case study is the distance of 75 kms from sorting center to the rural area of Ten Boer. For moderate VKT scenario, it is assumed that the LSP parcel delivery trucks travel a distance of 50 kms. Additionally it is assume that in the future due to more demand and increasing online e-commerce, more sorting centres will be developed and thus increase their density over time. This would mean they would be able to service the demand of more areas easily and might potentially be located close to rural areas. Hence for the low VKT scenario, it is assumed the travel distance by LSP trucks to PL locations is assumed to be 25 kms. For this scenario, it is assumed that sorting center is equidistant from both rural and urban areas.

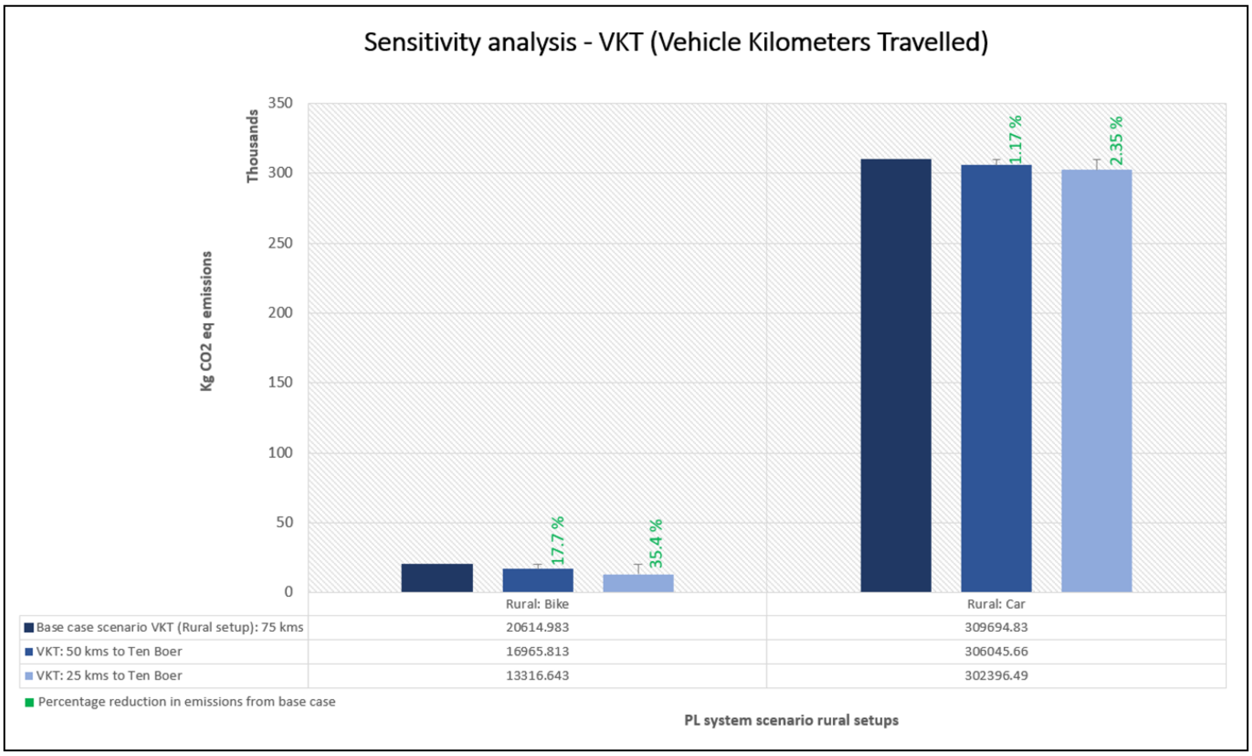


Figure 6.14: *Sensitivity Analysis: VKT by LSP delivery trucks with two (Moderate and Low) improvement scenarios in rural setups*

It is observed from Figure 6.14 that when the amount of VKT is reduced from 75 kms to 50 kms by LSP trucks in rural setup, that it results in the reduced emissions of CO_2 by up to $3649.1kgs$ which translates to 1.1% of overall reduced CO_2 emissions in rural setup with car as the mode choice and 17% of overall reduced CO_2 emissions in rural setup with bike as the mode choice. Additionally, in the future scenario where the sorting centers are almost identically situated from rural areas as the urban areas, the reduced VKT of 25 kms by LSP delivery trucks for a single delivery occasion, results in 2.3%-35% emission reductions accounting for about $7298.3kgs$ of overall reduced CO_2 emissions.

The growing trend of situating distribution centers in closer proximity to rural areas represents a strategic shift in logistics and supply chain management. It can be concluded that placing distribution centers closer to rural areas can reduce the last-mile delivery distances, enabling quicker delivery times to consumers in those regions. This is particularly relevant given the challenges of delivering to remote or sparsely populated locations.

6.3.4. Brief overview of Sensitivity Analysis

As mentioned in chapter 5, the case study setup in this thesis initially considers the most positive case where PLs are fully used and all assumptions listed in section 5.1. The different scenario and system design factors reflected in section 6.3 takes the uncertainties and real world situations into account. The sensitivity analysis that is conducted for this thesis is a crucial component of research of this topic, as it allows for exploration of variations in specific factors of the PL system and their impact related to the environment.

Furthermore, conducting a sensitivity analysis sets the ground for drawing the reflection on the robustness of the conclusions. Additionally this aids in identifying areas for potential improvements in the PL system in the future. The insights gained from this analysis contribute significantly to make informed recommendations for optimizing the environmental performance of the PL system in various scenarios which will be discussed in chapter 7.

7

Conclusion & Discussion

This marks the final chapter of this thesis which, first starts by concluding the core findings and presenting the crux of this study in section 7.1. It is then followed by section 7.2 which explores the underlying meaning of this research and its possible implications in other areas of study. Finally it also reflects on the limitations and the possible improvements that can be made i the future, in order to further develop the of quality of research or an interesting research gap.

7.1. Conclusion

The emergence of PLs as an innovative solution to address the challenges of conventional home deliveries presents a dynamic opportunity for redefining the efficiency and sustainability of logistics networks. The exploration of the environmental impact of PL systems through a comprehensive LCA sheds light on a relatively novel technology that holds significant potential in shaping the landscape of last-mile delivery operations. However, as this technology gains traction and finds its place within the broader context of supply chain operations, it becomes increasingly imperative to critically evaluate its environmental implications. While PLs offer promising advantages, it is essential to recognize that this new paradigm also brings about a range of emission implications across various stages of its life cycle.

The aim of this study is to gain insights into the environmental implications of PL systems. By employing LCA, a systematic and holistic approach is adopted to assess the overall environmental performance of PL systems. This approach takes into account the different life cycle stages, the inputs and outputs involved, and the potential environmental impacts associated with each stage. This research contributes to the resolution of the ongoing debate by offering a scientific response to the following research question:

"What are the environmental impacts of implementation of parcel locker system?"

In order to answer this main research question, three sub-questions are addressed. Initially, the different ways in which the PL system can be setup are identified by studying previous works in the literature. Consequently an urban and a rural setting in which the PL system can be setup are determined. The locations chosen for the urban and rural settings are De Pijp and Ten Boer respectively. Additionally important factors that influence the use of PLs are studied. It can be concluded that PL location and customer mode choice are the most crucial factors when it comes to utilizing the PL system as it affects the customer mobility behaviour and ultimately the environmental impact of PL systems.

By considering these factors and identifying the key aspects of a PL system via literature, a conceptual model is developed by means of a system diagram that helps determine the potential environmental impacts of PL system and conventional HDs. A key difference is observed in the mobility behaviour of LSPs in conceptual model where the LSP only need to travel to PL locations in PL systems compared to travelling to individual customer residence in HDs. This also leads to the potential environmental impacts in form of various emissions caused by the actors in PL system and HDs eventually answering the second sub-question. The Global Warming Potential (GWP) indicator is selected which is a comprehensive indicator that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in $KgCO_2$-eq and gCO_2-eq per parcel.

The final sub-question is answered by means by quantifying of the potential impacts of the PL systems through a full LCA. The different life cycle phases of the PL system starting from the production all the way to end of life phase are modelled into the Ecochain Mobius software. This also includes the setting of PL system in an urban and a rural scenario .

The three sub-questions in combination answer the main research question by presenting the environmental impacts in terms of climate change emissions of the PL system in different setups. It is found that the PL systems are most efficient in urban areas owing to use of green mobility ways by customers and reduced VKT by LSPs. Electricity consumption by the PLs in urban area is the 'hot-spot' or the most negatively impacting phase of the PL system accounting for 48.3% of total emissions while for rural setup where customer bike to PL location have the LSP transport emissions as the highest. Finally it is seen that customer travel causes most emissions when they travel to PL locations by means of a car. In conclusion, the environmental impact of PL system implementation are more in rural areas where the vehicle kilometers travelled (VKT) increase both by the LSPs and the customers.

The research is extended further by comparing the transport emissions caused by LSPs (*transport emissions*) in PL system to HDs. It is concluded that the PL systems are generally beneficial and produce up to 49.9% less CO_2 emissions in rural setup (12.1 $g\ CO_2$ eq per parcel for PLs compared to 48.43 $g\ CO_2$ eq per parcel for HDs) and 74.9% less CO_2 emissions per parcel in urban setup (36.3 $g\ CO_2$ eq per parcel for PLs compared to 72.6 $g\ CO_2$ eq per parcel for HDs) over a life cycle time of 15 years considered in this study. However, it is evident from the case study that overall PL system performs worse only in the case where all the customers travel by car in order to access PLs. This is in tune with the findings from (De Maere. B, (2018) [8] where benefits of PLs are undone if the trip is made by car.

Finally, a sensitivity analysis on two categories of factors namely: scenario and system design factors is conducted to gain insights into the effects of most impactful factors and more sustainable practices in the future. It is seen that emissions grow exponentially when delivery failure rate in HDs are increased. Hence it is concluded that the parcel delivery failure rate should be kept as low as possible (below 5%) to avoid additional and unnecessary VKT by LSPs. Trip chaining can result in reduced emissions by up to 79.34% due to reduced overall extra distance to travel to PL locations by the customers. Only the extra detour distance is considered which result in fairly low emissions per parcel. Finally scenarios involving more PL locations in the future is implemented where it is concluded that majority of reduced emissions are seen in the case of PL system in rural setup where customers use cars for travel to PL locations. A 40% increase in PL locations can result in a reduction of 385 gCO_2 eq per parcel. The primary reason for this is the environmental gain in reduced VKT by customers and LSPs outweigh the increase in emissions of the PL life cycle.

System design factors where less energy is consumed by PLs due to possible policy regulations or technological advancements in the future can results in about 18.04%-30% emissions reduction. Whereas setup of additional sorting centers, especially near rural areas in the future results in less amount of VKT by LSP delivery trucks. This can have a positive impact on the environment by reducing emissions upto 17.7%-35% in rural areas where customer use bike to travel to PLs.

One of the primary conclusions of this thesis lies in the distribution of benefits between customers and LSPs. While customers need to travel to reach PL locations for package retrieval, this inconvenience is offset by the substantial gains achieved in the efficiency of logistics operations. This pivotal benefit lies in the significant reduction of vehicle kilometer traveled (VKT) by delivery trucks. As LSPs consolidate multiple deliveries into a single trip to replenish PLs, fewer vehicles cover more deliveries, resulting in an overall decrease in the VKT. This contrasts with conventional HDs, where customers receive packages at their doorstep without needing to travel, but LSPs face the challenge of higher VKT due to dispersed destinations. This distribution of advantages underscores the role of PLs in optimizing logistics operations while acknowledging the trade-off customers make in traveling to access their parcels.

Overall, it can be concluded that PLs can offer a convenient, efficient, and sustainable solution for package delivery, given that the transport used by customer is green (either walk or bike) and they combine trips as much as possible. This will benefit both recipients and delivery service providers by decreasing number of failed deliveries and emissions from delivery vehicles.

7.2. Discussion

Through a meticulous analysis and comparison with conventional HDs, this study not only underscores the environmental benefits offered by PLs but also highlights the need for ongoing scrutiny and adaptation to ensure their alignment with sustainable practices. As we navigate the evolving landscape of urbanization, e-commerce, and environmental efficiency, the pursuit of solutions like PLs show that the industry is working hard to create new and better ways of last mile delivery by trying to strike a balance between technological advancements and being environmentally mindful.

Policy Implications

In light of the LCA conducted on the environmental impact of the PL system, several crucial policy implications emerge that can significantly influence sustainable urban logistics and last-mile delivery practices. As the world increasingly moves toward more sustainable practices, the findings of this study hold significant relevance for shaping logistics policies. The LCA findings highlight the most negatively contributing aspect of the PL system's life cycle, especially in urban areas is the consumption of electricity throughout its different phases. This creates an opportunity for policy makers to consider offering incentives to PL manufacturers and distributors to use energy efficient technology that enables them to offer PL operation by customers at minimal electricity.

Combined with more energy efficient technology, electrification of delivery fleets by LSPs emerges as a critical external factor. Policymakers should encourage the adoption of electric vehicles (EVs) within the context of PL systems. Moreover the use of electric cars by customers to access PL locations can also bring in substantial benefits environmentally. Transitioning to electric fleets can further minimize emissions, enhancing the overall environmental benefits of the PL system. This involves not only offering incentives for EV adoption but also building charging infrastructure to support the transition. Furthermore, the surge in e-commerce and the growing demand for faster deliveries raise the importance of sustainability in the last-mile journey. The policy landscape should consider incentivizing more sustainable delivery methods, such as the PL system, over traditional home deliveries. This can be achieved by close collaboration between the different stakeholders such as the government, the Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving) and the LSPs.

The environmental benefits of implementing PLs compared to traditional HDs are also seen, particularly in terms of reduced greenhouse gas emissions. Policymakers should consider incentivizing the adoption of PL systems by LSPs in their service in last mile delivery. This can be done through a combination of access to infrastructure, regulatory support, green procurement policies, awareness campaigns, and research and development support. Offering grants, subsidies, or tax benefits can offset initial setup costs of LSP sorting centers in rural areas. This can lead to reduced VKT by parcel delivery trucks, faster delivery time and push the same day delivery initiatives.

Public awareness campaigns and R&D funding advance technology, leading to greener last-mile delivery practices and achieving environmental objectives. Implementing policies that promote collaboration between stakeholders, such as LSPs and PL distributors, can foster shared responsibility in improving the system's environmental performance. Furthermore, raising awareness among customers about the ecological advantages of utilizing PLs could lead to increased consumer preference for this sustainable delivery option. In the long term, comprehensive policies might include guidelines for strategic placement of PL locations. By ensuring accessible and strategically positioned lockers, policymakers can promote user adoption and minimize the travel distance customers need to cover.

How parcel collection from PLs relates to theory of constant travel time

The theory of constant travel time, often referred to as Marchetti's constant, suggests that on average humans tend to budget and allocate approximately one hour per day for their daily commute or travel activities [29]. In essence, this theory implies that when people allot a certain budget of travel time each day, they adjust their modes of transportation, distances traveled, or even their choice of residence to accommodate this fixed time budget.

In the context of this thesis, understanding Marchetti's constant could be valuable in exploring how individuals adapt their travel behaviors when using PLs. This may be seen as that when people choose to visit PLs for collecting their parcels, they are making a conscious decision to allocate part of their daily travel time budget for this purpose. This choice might mean they are willing to substitute it for another activity, like going to a coffee shop. This choice of substitution, however may depend on several factors such as time allocation, personal convenience, prioritization, cost considerations and scheduling flexibility.

For instance, if the PLs are located close to the customer and if parcel collection at the PLs takes only a couple of minutes, individuals may choose to allocate some of their travel time to this task instead of an other activity. On the other hand, if travel to PLs comes with additional costs such as transportation or parking costs, or if collecting parcel is not a priority for a customer, then the customer might not want to retrieve the parcel at the moment.

Thus, understanding how parcel collection fits into an individual's travel time budgets can provide valuable insights into the adoption and acceptance of PL systems and, their potential impact on daily routines and behaviors. Thus for a large group of people, use of PLs can contribute to optimizing how they allocate their travel time for parcel pickup while minimizing disruptions to their overall travel patterns.

Limitations

While the LCA provides valuable insights into the environmental impact of the PL system, it is essential to acknowledge the limitations that might have influenced this study's outcomes. First is the availability and accuracy of data used in the assessment, since the reference data is extrapolated to make it suited to this case study. This could impact the reliability of the results.

The lack of comprehensive and up-to-date data on certain life cycle stages might have introduced uncertainties as the data is reference from an EPD report for a different model of locker. Moreover, the scope of the study might has been limited to specific geographical areas in the Netherlands. Assumptions on certain aspects of the PL system, like the customer order frequency and modal split might affect the PL usage behaviour which, as a result might affect the accuracy of results and potentially influence the generalisation of the findings. Additionally trip combining by customer for parcel retrieval is also not considered in the base case scenario of this study.

Finally the assumptions made during the LCA where a base case scenario was developed keeping the external factors constant could also affect the accuracy of the results. The factors (mentioned in section 5.1) are not included in the case study, either due to lack of data on them or due to the complexity of implementing them in the software. It is vital to recognize and address these limitations transparently, to provide a comprehensive perspective on the environmental impact of PL systems.

Future recommendations

To advance the understanding of the environmental impact of PL systems and promote sustainable logistics practices, several future recommendations arise from this research. First and the most important being conducting more extensive data collection and collaborating with key stakeholders, such as LSPs and PL distributors, can enhance the accuracy and reliability of the LCA results.

Although a lot of research and surveys exist on customer preference when it comes to usage of PLs, it is recommended to have an additional customer stated choice survey to enhance the quality of the results and make the research more relevant to this specific case study based on geographical factors as well. This will especially help gain detailed insights how customers access the PL network either through dedicated trips or combining trips.

It is recommended to include aspects such as failed delivery rates, trip chaining and customer order patterns in the base case or initial stages of similar research in the future. Future research should also consider expanding the scope of the study to include broader geographical regions and different types of PL systems to capture a more diverse representation of their environmental impacts. Integrating social and economic dimensions into the LCA can provide a more holistic assessment, considering the overall sustainability of the PL system. Furthermore, exploring innovative technologies and renewable energy sources to power the PLs could contribute to further reducing the system's environmental footprint. Continued research and evaluation of the environmental impact of PL systems will be instrumental in driving sustainable logistics practices and fostering greener last-mile delivery solutions.

It can be seen from the sections above that The PL distributor emissions are consistent, irrespective of the number of parcels delivered. These can vary based on the area (urban or rural) they are located in, however all the PL distributor emissions would remain fairly consistent if a specific area is being studied. The is because the different phases of ’production’, ’packaging’, ’transport’ and ’end-of-life’ remain consistent in this case. Hence based on the geographical area the PL systems are being implemented in, these emissions would remain fairly robust.

Transport emissions by LSP and customers on the other hand, are majorly based on assumptions on the number of parcels being delivered and VKT by LSP trucks. These are reflected in the ’use’ phase of the PL system, which make them vary according to the research context. Furthermore, the conclusions discussed above in general are externally consistent, where PL systems are generally beneficial if the customers uses green ways of mobility for accessing PLs, meaning mean they align with previous research.

Hence for future researchers, it is recommended that with the input data for the PL distributor emission mentioned and reflected upon in this thesis, the PL distributor emissions can be replicated in the future. For the emissions concerning customer and LSPs, future study should look into more elaborate inclusion of data and aspects regarding customer order patterns, modal split and LSP travel behaviour. Nonetheless, the environmental impacts of PL system are only one aspect of this new last mile delivery innovation. To fully assess the overall impact of PL systems in a large geographical location or a country, additional research is needed to investigate other implications that are related to PL systems.

Thesis contribution

Despite its limitations, this thesis contributes towards the holistic understanding of PL systems. Academically, this thesis addresses the research gap, through literature review, development of a conceptual model, and consequently quantifying the potential impacts of the PL systems. Inclusion of scenario and system design factors in the analysis adds depth to the academic discussion. This approach allows for a nuanced understanding of how various variables affect the overall environmental footprint of PL systems. Practically, this thesis can influence policy makers to take actions that promote sustainable behaviour among customers and PL distributors for reducing the overall environment footprint of PL systems. Additionally this thesis can raise awareness among logistics companies and consumers about the environmental advantages of using PLs. Combined with previous research, this thesis can potentially contribute to enhancing the efficiency of last mile delivery operations and current use of PL systems.

References

[1] AB, E. I. (2020). Environmental product declaration - lockers. https://api.environdec.com/api/v1/EPDLibrary/Files/08445d3f-4cd6-4171-b691-08da4d16d787/Data

[2] Allen, J., Piecyk, M., Piotrowska, M., McLeod, F., Cherrett, T., Ghali, K., Nguyen, T., Bektas, T., Bates, O., Friday, A., et al. (2018). Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas: The case of london. *Transportation Research Part D: Transport and Environment*, *61*, 325–338. https://www.sciencedirect.com/science/article/pii/S136192091730305X

[3] Bautista Carrera, J. (2022). *Integrated circularity and environmental sustainability assessment for in place pavement recycling techniques* (B.S. thesis). University of Twente. http://essay.utwente.nl/92251/1/Bautista-Carrera-Jhean.pdf

[4] Boysen, N., Fedtke, S., & Schwerdfeger, S. (2021). Last-mile delivery concepts: A survey from an operational research perspective. *Or Spectrum*, *43*(1), 1–58.

[5] Buser, M. A. (2021). *Willingness to use parcel lockers. a comparative case study of groningen and ten boer.* (Doctoral dissertation). https://frw.studenttheses.ub.rug.nl/id/eprint/3637

[6] Corporation, I. P. (2020). Delivery choice - parcel lockers: 2020 overview. https://www.ipc.be/sector-data/e-commerce/articles/2020-parcel-lockers

[7] Corporation, I. P. (2023). Cross-border e-commerce shopper survey 2022. https://www.ipc.be/services/markets-and-regulations/cross-border-shopper-survey/2020

[8] De Maere, B. (2018). *Economic and ecological impact of automated parcel lockers vs home delivery.* (Doctoral dissertation). https://www.researchgate.net/publication/326723312_Economic_and_ecological_impact_of_automated_parcel_lockers_vs_home_delivery

[9] Deutsch, Y., & Golany, B. (2018). A parcel locker network as a solution to the logistics last mile problem. *International Journal of Production Research*, *56*(1-2), 251–261. https://www.tandfonline.com/doi/pdf/10.1080/00207543.2017.1395490?casa_token=Kn-vzbD_hmMAAAAA:-XySs_3GaPmQF50RMrzPWWLx2YuGKuI7bvSJlsKh16EPUVbQ54HACbiBDcBHkS2W91L5oODh52oSAQ

[10] Events, S. (2021). State of e-commerce in the netherlands. https://www.savant-events.com/parcel-monitor-state-of-e-commerce-in-the-netherlands/

[11] Faugere, L., & Montreuil, B. (2017). Hyperconnected pickup & delivery locker networks. *Proceedings of the 4th International Physical Internet Conference*, *6*, 1–14. https://www.researchgate.net/profile/Louis-Faugere/publication/318260861_Hyperconnected_Pickup_Delivery_Locker_Networks/links/595f494da6fdccc9b18c5d37/Hyperconnected-Pickup-Delivery-Locker-Networks.pdf

[12] Gatta, V., Marcucci, E., Nigro, M., Patella, S. M., & Serafini, S. (2019). Public transport-based crowdshipping for sustainable city logistics: Assessing economic and environmental impacts. *Sustainability*, *11*(1). https://doi.org/10.3390/su11010145

[13] Gevaers, R., Van de Voorde, E., & Vanelslander, T. (2011). Characteristics and typology of last-mile logistics from an innovation perspective in an urban context. In *City distribution and urban freight transport*. Edward Elgar Publishing. https://doi.org/https://doi.org/10.4337/9780857932754.00009

[14] Giuffrida, M., Mangiaracina, R., Perego, A., Tumino, A., et al. (2016). Home delivery vs parcel lockers: An economic and environmental assessment. *Proceedings of the 21thSummer School Francesco Turco, Naples, Italy*, 13–15. http://www.summerschool-aidi.it/edition-2016/cms/extra/papers/final_43.pdf

[15] global services, S. (n.d.). Environmental product declarations. https://www.scsglobalservices.com/services/environmental-product-declarations#:~:text=An%5C%20Environmental%5C%20Product%5C%20Declaration%5C%20(EPD,across%5C%20its%5C%20entire%5C%20life%5C%20cycle.

[16] Gonzales, S. (2023). How much co2 does a car emit per mile: List by type, size, energy source. https://8billiontrees.com/carbon-offsets-credits/how-much-co2-does-a-car-emit-per-mile/#:~:text=CO2%5C%20emissions%20can%20also,of%5C%20CO2%5C%20per%5C%20km.

[17] Guide, L. C. A. (.-. C. B. (2023). Life cycle assessment (lca) – complete beginner's guide. https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/

[18] Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life cycle assessment*. Springer. https://link.springer.com/content/pdf/10.1007/978-3-319-56475-3.pdf

[19] Hillege, L. (2019). Environmental cost indicator (eci) – overview. https://ecochain.com/knowledge/environmental-cost-indicator-eci/#:~:text=The%5C%20Environmental%5C%20Cost%5C%20Indicator%5C%20(short,of%5C%20a%5C%20product%5C%20or%5C%20project.

[20] Hillege, L. (2023). Life cycle assessment software tools – overview. https://ecochain.com/knowledge/life-cycle-assessment-software-overview-comparison/

[21] Hofer, K., Flucher, S., Fellendorf, M., Schadler, M., & Hafner, N. (2020). Estimation of changes in customer's mobility behaviour by the use of parcel lockers [22nd EURO Working Group on Transportation Meeting, EWGT 2019, 18th – 20th September 2019, Barcelona, Spain]. *Transportation Research Procedia*, *47*, 425–432. https://doi.org/https://doi.org/10.1016/j.trpro.2020.03.118

[22] industrial automation, A. (2023). Exploring the advantages of outdoor parcel lockers with solar panels. https://www.arkarobot.com/blog/articles/exploring-the-advantages-of-outdoor-parcel-lockers-with-solar-panels

[23] Iwan, S., Kijewska, K., & Lemke, J. (2016). Analysis of parcel lockers' efficiency as the last mile delivery solution–the results of the research in poland. *Transportation Research Procedia*, *12*, 644–655. https://core.ac.uk/download/pdf/81971393.pdf

[24] Jeroschewski, A. (2019). How parcel lockers will transform last mile delivery (a parcel perform perspective). https://www.linkedin.com/pulse/how-parcel-lockers-transform-last-mile-delivery-arne-jeroschewski/

[25] Lemke, J., Iwan, S., & Korczak, J. (2016). Usability of the parcel lockers from the customer perspective – the research in polish cities [The 2nd International Conference "Green Cities - Green Logistics for Greener Cities", 2-3 March 2016, Szczecin, Poland]. *Transportation Research Procedia*, *16*, 272–287. https://doi.org/https://doi.org/10.1016/j.trpro.2016.11.027

[26] Lisa. (2020). Features and benefits of parcel lockers. https://myparcellocker.com/news/features-and-benefits-of-parcel-lockers/

[27] Lyu, G., & Teo, C. (2021). Last mile innovation: The case of the locker alliance network. https://doi.org/10.2139/ssrn.3471166

[28] macrovector. (n.d.). Isometric post terminal infographic with image of parcel locker delivery [[Online; accessed February 21, 2023]]. https://www.freepik.com/free-vector/isometric-post-terminal-infographic-with-image-parcel-locker-delivery_13749528.htm

[29] Marchetti, C. (1994). Anthropological invariants in travel behavior. *Technological forecasting and social change*, *47*(1), 75–88.

[30] Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., & Finkbeiner, M. (2022). Relevance of impact categories and applicability of life cycle impact assessment methods from an automotive industry perspective. *Sustainability*, *14*(14), 8837. https://doi.org/10.3390/su14148837

[31] Mitrea, I. A., Zenezini, G., De Marco, A., Ottaviani, F. M., Delmastro, T., & Botta, C. (2020). Estimating e-consumers' attitude towards parcel locker usage. *2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC)*, 1731–1736. https://doi.org/10.1109/COMPSAC48688.2020.000-5

[32] Molin, E., Kosicki, M., & van Duin, R. (2022). Consumer preferences for parcel delivery methods: The potential of parcel locker use in the netherlands. *ejtir*, *2022*(2.6427), 2–6427. https://research.tudelft.nl/files/123400740/6427_Manuscript_21833_2_10_20220614.pdf

[33] Peppel, M., & Spinler, S. (2022). The impact of optimal parcel locker locations on costs and the environment. *International Journal of Physical Distribution & Logistics Management*, (ahead-of-print). https://doi.org/https://doi.org/10.1108/IJPDLM-07-2021-0287

[34] Pham, H. T., & Lee, H. (2019). Analyzing the costs and benefits of installing unmanned parcel lockers: Focusing on residential complexes in korea. *Journal of International Logistics and Trade*, *17*, 43–54. https://doi.org/10.24006/jilt.2019.17.2.002

[35] Pierre-Louis Ragon, F. R. (2021). Co2 emissions from trucks in the eu: An analysis of the heavy-duty co2 standards baseline datas. https://theicct.org/publication/co2-emissions-from-trucks-in-the-eu-an-analysis-of-the-heavy-duty-co2-standards-baseline-data/

[36] Post, C. (2022). Locky': Ctt launches a new brand of lockers open to any delivery operator. https://www.ctt.pt/grupo-ctt/media/noticias/locky-ctt-launches-a-new-brand-of-lockers-open-to-any-delivery-operator?language_id=1

[37] Posti. (2020). Summary of the ipc cross-border shopper survey. https://minun.posti.fi/hubfs/Tutkimukset/IPC-survey-2020-Posti.pdf

[38] PostNK. (2022). Postnl opens parcel machines. https://www.postnl.nl/over-postnl/pers-nieuws/nieuws/postnl-stelt-pakketautomaten-open/

[39] PostNL. (n.d.[a]). Locationfinder [Retrieved on 12th of June from:]. https://www.postnl.nl/locatiewijzer/?f=36

[40] PostNL. (n.d.[b]). Locationfinder [Retrieved on 12th of June from:]. https://www.postnl.nl/locatiewijzer/

[41] PostNL. (2021). Postnl reveals new automated parcel locker in collaboration with retailer jumbo. https://www.postnl.nl/en/about-postnl/press-news/news/postnl-reveals-new-automated-parcel-locker-in-collaboration-with-retailer-jumbo/

[42] PostNL. (2022). Postnl opens up parcel lockers. https://www.postnl.nl/en/about-postnl/press-news/news/postnl-opens-up-parcel-lockers/

[43] PostNL. (2023). Postnl opens a sustainable parcel sorting center in hoogeveen. https://www.postnl.nl/over-postnl/pers-nieuws/nieuws/postnl-opent-duurzaam-pakkettensorteercentrum-in-hoogeveen/

[44] Postnl sorting centers – a complete list. (2023). https://mailboxmaster.net/postnl-sorting-center-guide-list/

[45] PostParcel. (2022). Inpost to increase its parcel locker network. https://postandparcel.info/149079/news/e-commerce/inpost-to-increase-its-parcel-locker-network/

[46] Prandtstetter, M., Seragiotto, C., Braith, J., Eitler, S., Ennser, B., Hauger, G., Hohenecker, N., Schodl, R., & Steinbauer, M. (2021). On the impact of open parcel lockers on traffic. *Sustainability*, *13*(2). https://doi.org/10.3390/su13020755

[47] Ranjbari, A., Diehl, C., Dalla Chiara, G., & Goodchild, A. (2023). What is the right size for a residential building parcel locker? *Transportation Research Record*, *2677*(3), 1397–1407. https://journals.sagepub.com/doi/pdf/10.1177/03611981221123807

[48] Schnieder, M., Hinde, C., & West, A. (2021). Sensitivity analysis of emission models of parcel lockers vs. home delivery based on hbefa. *International Journal of Environmental Research and Public Health*, *18*(12). https://doi.org/10.3390/ijerph18126325

[49] Schwerdfeger, S., & Boysen, N. (2022). Who moves the locker? a benchmark study of alternative mobile parcel locker concepts. *Transportation Research Part C: Emerging Technologies*, *142*, 103780. https://doi.org/https://doi.org/10.1016/j.trc.2022.103780

[50] Seghezzi, A., Siragusa, C., & Mangiaracina, R. (2022). Parcel lockers vs. home delivery: A model to compare last-mile delivery cost in urban and rural areas. *International Journal of Physical Distribution & Logistics Management*. https://www.emerald.com/insight/content/doi/10.1108/IJPDLM-03-2020-0072/full/pdf?title=parcel-lockers-vs-home-delivery-a-model-to-compare-last-mile-delivery-cost-in-urban-and-rural-areas

[51] Smartbox. (2017). How parcel lockers are redefining shopping shipping. https://www.smartbox.in/blog/5-types-of-parcel-lockers/

[52] Song, L., Cherrett, T., McLeod, F., & Guan, W. (2009). Addressing the last mile problem: Transport impacts of collection and delivery points. *Transportation research record*, *2097*(1), 9–18. https://journals.sagepub.com/doi/pdf/10.3141/2097-02?casa_token=dYrkFSQb8tkAAAAA:BzxBcPvpVdt_BkZgCDRqeUYnmt2P2i8EkVmmw3am4mvjF_UHE-Z21UFkmjlm3dShrovrzez7HOfy

[53] Tsai, Y.-T., & Tiwasing, P. (2021). Customers' intention to adopt smart lockers in last-mile delivery service: A multi-theory perspective. *Journal of Retailing and Consumer Services*, *61*, 102514. https://doi.org/https://doi.org/10.1016/j.jretconser.2021.102514

[54] van Duin, J., Wiegmans, B., van Arem, B., & van Amstel, Y. (2020). From home delivery to parcel lockers: A case study in amsterdam [The 11th International Conference on City Logistics, Dubrovnik, Croatia, 12th - 14th June 2019]. *Transportation Research Procedia*, *46*, 37–44. https://doi.org/https://doi.org/10.1016/j.trpro.2020.03.161

[55] Van Wee, B. (2013). The traffic and transport system and effects on accessibility, the environment and safety: An introduction. *The transport system and transport policy. An introduction*, 4–16.

[56] Waterland, G. (2022). First postnl parcel machine in the municipality of waterland. https://www.waterland.nl/nieuws/eerste-postnl-pakketautomaat-in-gemeente-waterland

[57] Wee, G., Annema, J., & Banister, D. (Eds.). (2013). The transport system and transport policy: An introduction. Edward Elgar Publishing. https://books.google.nl/books?hl=en&lr=&id=_UwJWfgoOeEC&oi=fnd&pg=PA101&dq=Transport+resistance+factors:+Time,+money+and+effort.&ots=4gp0JBSVZP&sig=HplAMx3z_ivH1lbMXs2PXFGe1sA&redir_esc=y#v=onepage&q=Transport%5C%20resistance%5C%20factors%5C%3A%5C%20Time%5C%2C%5C%20money%5C%20and%5C%20effort.&f=false

[58] Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th international conference on evaluation and assessment in software*

engineering, 1–10. https://dl.acm.org/doi/pdf/10.1145/2601248.2601268?casa_token=hjJg2pvQVBMAAAAA:gG3RT47WAtnFRjy1Gl_bYpC_yPPTjlDQwAq6AwtzM4FQoLfJzb45vUHiFhNZqNak1A9E89aLW76WEA

A

Scientific Paper

Analysing the environmental effects of the Parcel Locker System

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Abstract

Problem definition - The escalating trends in e-commerce have led to a surge in parcel delivery demands, necessitating innovative solutions for efficient and environment friendly last-mile deliveries. Parcel Lockers (PLs) in the recent years, have emerged as a potential answer to address the environmental impact of traditional delivery methods. However, a research gap exists concerning the assessment of the environmental implications of PL systems holistically which comprise the customers, the LSPs and the PL distributors.

Aim - This paper aims to bridge this gap by conducting a comprehensive life cycle assessment (LCA) of a PL system via the Environment Footprint (EF) methodology.

Methodology - Firstly extensive literature research is undertaken to understand the various aspects of the PL system and the factors influencing PL use, leading to the development of a conceptual model encompassing its key components. The Environment Footprint method in the LCA methodology is applied to analyze the GWP climate change impacts in both urban and rural setups, specifically in De Pijp and Ten Boer areas respectively. The method considers relevant characteristics, such as customer travel behavior and mode choice. The GWP impacts of the PL system are compared to conventional home deliveries (HDs) to identify the more environmentally friendly option for last-mile parcel distribution. Furthermore, a sensitivity analysis is conducted based on different scenarios and system design factors to evaluate the potential impacts of future policy implications and developments on the environmental performance of the PL systems.

Findings - The total environmental impact in the rural setup, where customers utilized cars to access the PL, is found to be the highest leading to 1028 $g\ CO_2$ eq emissions per parcel produced. The urban setting has the least overall environmental impact, due to customers walking to the PLs which amounts to 42.46 $g\ CO_2$ eq emissions per parcel. Furthermore it is found that the PL systems generally perform better than conventional HDs given that the customers minimze the use of cars to access PLs as much as possible.

Research limitations - This research is limited to the available data from an Environment Product Declaration (EPD) report of steel lockers that is referenced for PLs. Additionally factors such as failed delivery rates, trip chaining and customer order patterns are not included in the base case scenario, which could also affect the accuracy of the results.

Implications - LCA analysis of PL systems allows for holistic understanding of various aspects of PL system. Furthermore the insights from this research can potentially influence policy makers to take actions that promote sustainable behaviour among customers and PL distributors.

Key words: Last-mile delivery, Parcel Lockers (PLs), Innovation, Life Cycle Assessment (LCA), Environmental effects

I. INTRODUCTION

There has been a significant growth in the business to customer (B2C) market in recent years in countries all across the world as a result of digitization of services. In 2015, roughly 7.5% of all retail sales were conducted online, while in 2024 this number is expected to increase to 21.8%. According to the International Post Corporation

(IPC) cross-border survey conducted in 2022 across 39 countries researching over 33000 people, 33% of people order at least once per week and 83% once a month [1]. With the rise of e-commerce, the amount of HDs has also increased [2], especially during the Covid-19 pandemic, which resulted in about 334.9 million parcel deliveries in the Netherlands. This accounts for an increase of 27% compared to 2019. The last mile delivery is the most inefficient process of the entire logistic supply chain [3] and can account for 41–50% of shipment costs [4].

Traditional delivery methods may struggle to cope with the higher demand regarding the direct delivery to consumers. This leads to several challenges such as delivery delays, missed deliveries, and increased transportation congestion. This also accounts for congestion, pollution, and other negative effects on the environment, safety, and health[5]. The majority of delivery vehicles are still powered by internal combustion engines that contribute to these adverse effects [4]. In addition to these effects, problems such as lack of economies of scale, slow identification of handover points, long walking distances, and the not-at-home problem still persist in the logistic supply chain [6] [7].

Public Lockers or Parcel Lockers (PLs) as shown in Figure 1 are an innovation to these issues where customers can pick up their orders at any time of their convenience, thus making them highly flexible. When a customer places an order online, they can choose to have their package delivered to a nearby PL location instead of their home or office. Once the package is ready for delivery, the logistics service provider (LSP) places it inside the designated locker at the chosen locker location. The customer receives a notification with a unique pickup code or QR code. To retrieve their package, the customer visits the PL location, enters the pickup code or scans the QR code to authenticate themselves, and the locker system opens the corresponding locker. The customer then collects their package from the locker, and the locker door securely closes for the next use. PLs offer convenience, security, and 24/7 accessibility, making them a popular choice for both customers and LSPs in the last-mile delivery process.

The PLs are usually located in places that are constantly visited by people such as supermarkets, transport hubs (stations) and apartment blocks [4]. These are unmanned and can be both emptied by the customer and filled by the LSP.

Fig. 1. A PostNL Parcel Locker in the municipality of Waterland, on the Graaf Willemlaan in Monnickendam [8]

Typically, the PL service starts when a customer orders a product via an online retailer. This then leads the LSP to dispatch the courier to deliver this parcel to the PL locations possibly close to the respective customers. The customers then have the flexibility to collect their parcels by deciding a convenient time and the mode of their choice to travel to these PLs. Customers that use PLs, often choose to pick up their parcels on foot, bike or car. A typical PL system is depicted in Figure 2 through a parcel joruney perspective. If the customer wants to return or exchange a parcel, they can similarly travel back to PL locations where the courier can collect their parcels and process their request.

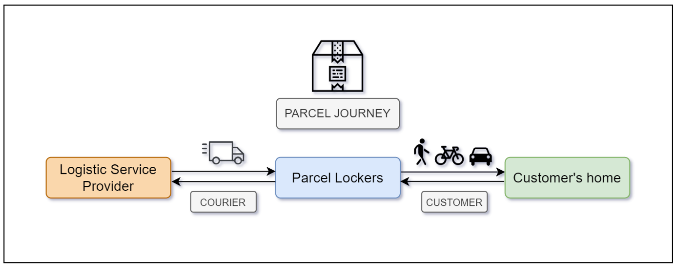


Fig. 2. *A PL system depicting parcel journey*

This type of PL system can be used by couriers and users for delivering and collecting packages. These PLs can be installed in for example neighbourhoods, supermarkets, metro stations, malls or near workplaces, which essentially act as an interface where delivering and collecting of the parcels takes place.

The aim of this paper is to analyze & assess the environmental impacts associated with implementation of PL system different setup scenarios. This will aid in identifying the parts of a PL system that contribute most to its environmental impact. This is be followed by a brief comparison of the transport emissions of LSPs in PL system to the conventional home delivery (HD) as a last mile delivery process.

II. LITERATURE REVIEW AND RESEARCH QUESTIONS

The purpose of this literature review is to analyse PLs as a novel innovation for more efficient last mile delivery and their potential impact on the environment. PLs are being used in numerous countries which owe their success to high parcel delivery rates and reduction in failed deliveries by the couriers and ultimately by the LSPs. Recently companies like InPost have announced their intention to increase their PL network with new key partnerships [9] in the UK, France, Spain and Portugal. PostNL in the Netherlands also plans to expand it PL network to 1500 lockers by end of 2024, so that everyone can have an easy and a close access to PLs. Recent years have shown that PLs have been gaining popularity as a last mile delivery innovation. Moreover, the estimation is that PLs will become a $1.6 billion industry by 2028, hence it is necessary to investigate the environmental impact of this system for its sustainable development.

The literature study is first used to explore about different aspects on the PL system and the current trends of PL use in different countries. This provides input in the ways in which a PL system can be setup. Secondly, the important factors that influence the use of PLs are studied to further explore and refine the conceptual model by showing relationship between different aspects of PL system. Additionally the literature research gives partial input in developing of a conceptual model by providing insights into what kinds of emissions are studied when PLs are studied.

The literature research strategy is based on finding the articles including keywords related to the selected topic as shown in Table 1. The search engines used are Google Scholar and Scopus for finding articles and some websites that describe the challenges in Last-Mile Delivery currently. A total of 16 research papers and articles were found relevant to this paper. Abstracts of each of the papers found initially were read briefly to get an overview followed by snowballing method on some relevant publications [10] resulting in 4 additional articles.

A brief overview of each article found is presented in Table 2 and Table 3. Some additional criteria based on the year of acceptance of articles in different conferences: Only the articles belonging to or newer than the year 2016 were selected, which allows for the most recent access and insights in the field of PL along with their environmental impact. Focusing on recent papers allows for clear identification of emerging trends and potential gaps in the existing literature relating to PLs that may have emerged in the last few years.

Table 1. *Research strategy*

Concept groups	Last-mile delivery; Parcel Lockers; Pickup points; Environment effects
Keywords	Last-mile delivery: Innovation, optimization PLs: Location, acceptance, distance, systems, customer access Pickup points: Emissions Environment effects: Emissions, traffic, sustainable city logistics, externalities
Year	Recent articles referred (2016 or newer)

These articles offer insights into diverse aspects, including customers' intentions to use such systems, their chosen modes of accessing PL locations, and the inherent advantages of these systems over conventional home deliveries. Notably, the higher delivery density and the consequential reduction in failed deliveries have been heralded as the primary benefit of these systems. It is also reflected in articles (Schnieder et al., 2021)[11] and (Giuffrida et al., 2016)[12] from the tables above, the conditions under which the PL use will prove to be beneficial over conventional deliveries. From additional studies conducted previously, it is evident that weight and size are less important attributes as data on delivery of parcels as that the vast majority of ordered parcels would fit into PLs where 85% of parcels had length smaller than 50 cm, 90% had a width smaller than 40 cm, and 80% had a height smaller than 20 cm. Based on this an assumption is also made in subsection i for the total parcel weight delivered to PLs which ultimately impacts the transport emissions.

However, the environmental implications of PL system involving all the aspects; customers, LSPs and PL distributors, have not been thoroughly researched yet and it is thus interesting to analyze CO2 emissions for such a PL system. Based on the literature reviewed in this chapter, the the KPIs from Table 2 and Table 3 of interests for this paper are the VKT by LSPs, CO_2 emissions caused by the different aspects of the PL system, distance and transport mode choice by customers and LSPs. Furthermore a comparison between the transport emissions of LSP parcel delivery trucks in PL system and conventional HDs gives interesting insights into the benefits of PL system.

Table 2. *Overview of articles*

Author	Findings
Lyu, G., & Teo, C. P. (2022) [13]	-Customers can pickup from lockers near residential areas resulting in model not always placing the lockers in the vicinity of locations with peak parcel volumes -Inclusion of 250 meters is appropriate for the LA network in Singapore
Tsai, Y. T., & Tiwasing, P. (2021) [14]	-Perceived behavioral control influences the convenience, reliability, and privacy security on Thai consumers' intention to use smart locker -Customer attitude influences the compatibility, relative advantage, and complexity -Strongest effects is shown by attitude
Seghezzi, A., Siragusa, C., & Mangiaracina, R. (2022) [15]	-PLs have lower cost of delivery than HD, key benefits mainly derive from the higher delivery density and the drastic reduction of failed deliveries -PLs are more critical in rural regions because of lower expenses, as well as higher HD costs
Gatta, V., Marcucci, E., Nigro, M., Patella, S. M., & Serafini, S. (2018) [16]	-A redcution of about 239 kg of particulate matter annually by implementing a crowd-shipping service in Rome -Economic sustainability reahed when the people are incentivized because a system is helping to reduce problems for society.
Peppel, M., & Spinler, S. (2022) [4]	-About 11% cost savings can be achieved due to placing SPL optimally -Urban areas see a positive impact on total CO2 emission savings by up to 2.5%, while less populated areas see an increase in emissions by about 4.6% due to longer travel distances for collecting parcels
Schwerdfeger, S., & Boysen, N. (2022) [17]	-Mobile lockers enable shorter travel time and long overlap times without significant cost invested into a network of stationary lockers -Mobile lockers can potentially be superior to fixed lockers
Prandtstetter, M., Seragiotto, C., Braith, J., Eitler, S., Ennser, B., Hauger, G., Hohenecker, N., Schodl, R., & Steinbauer, M. (2021) [18]	-PLs have a positive impact under specific conditions which can be easily achieved given they are promoted -No clear statement that "a PL will reduce the emitted CO2" can be made due to the individual surroundings and conditions -Important that either the rate of successful first deliveries or the utilization rate of PLs is increased
Schnieder, M., Hinde, C., & West, A. (2021) [11]	-Group of people collecting their parcels from a PL by means of car should be minimized otherwise HDs result in lower emissions
Lemke, J., Iwan, S., & Korczak, J. (2016) [19]	-Customer propose the PL placement in areas surrounding public transport stops and stations -About 600 parcels delivered in a day by courier servicing InPost PLs with travel distance of about 70 km in comparison to 60 parcels and 150 km respectively in HDs -PLs have CO2 emissions of about 1516 tons per year in comparison to 32500 tons in traditional courier service

Table 3. *Overview of articles*

Author	Findings
van Duin, J. R., Wiegmans, B. W., van Arem, B., & van Amstel, Y. (2020) [20]	-Instead of having a total of 1475 stops for the whole delivery of 1770 parcels, this alternative delivery model has only 47 stops for the PL route -The delivery costs could annually save up to €121,356 (De Pijp area)
Pham, H. T., & Lee, H. (2019) [21]	-PLs especially in residential areas have a high benefit-cost ratio of 4.89 -The most crucial factor in terms of PL benefits was time savings -Support from the government is required for setup of PLs in semi public locations that would optimize land costs
Mitrea, I. A., Zenezini, G., De Marco, A., Ottaviani, F. M., Delmastro, T., & Botta, C. (2020, July) [22]	-This service has a high potential for adoption (988 potential adopters out of the 1053) -Majority of the users prefer having PLs located close to home(80.1%) as compared to other locations -An average deviation of 5-10 minutes is acceptable to consumers for collecting their parcels
Molin, E., Kosicki, M., & van Duin, R. (2022) [2]	-It is predicted that the HDs will reduce from 71% to only 7% with increasing the HD costs by a small amount and additionally expanding PLs (close to the vicinity of households)
De Maere, B. (2018) [23]	-Courier is mainly responsible for the emissions caused by delivering the parcel (131.76 g per parcel) in the HD model -In the PL scenario, the courier only emits a small amount of CO_2 (2.56 g per parcel) due to PL parcel consolidation along with HD parcels
Faugere, L., & Montreuil, B. (2017, July) [24]	-There are several challenges to implementation of hyper-connected network such as engineering design, efficiency, operating policy and integration
Giuffrida, M., Mangiaracina, R., Perego, A., & Tumino, A. (2016) [12]	-Environmentally, PLs have a legit convenience if their reach distance does not exceed 0.94 km in a urban context and 6 km in an extra-urban one -Economically, PLs have a legit convenience if their reach distance does not exceed 3.5 km in a urban context and 9 km in an extra-urban one

i. Parcel Locker System

As briefly mentioned in section I, Parcel Lockers or PLs are automated lockable storage boxes that facilitate the delivery and collection of parcels by its couriers, delivering company and users. This is where couriers deliver parcels to the PL locations and customers travel to these locations via different modes from their residences. This system in general is comprised of 5 aspects :

- *Distribution of PLs:* This is an important aspect as the number of PLs in a certain location should be able to fulfill the demand of consumers while ensuring a low occupancy rate. This parameter is highly dependent on the spatial distribution of population in a respective area. For instance urban residential areas in the Netherlands such as 'De Pijp' have an even distribution of PLs such that the customers are able to walk or bike on average of about 5 minutes to reach a PL. Whereas in rural area of Ten Boer, PL distribution is central making their location a bit further compared to urban areas.

- *Configuration of PLs:* PL systems recently implement modular designs of PLs where their capacities and layouts can be tailored according to the requirements of the consumer. According to a study conducted in Seattle [25], a 4 tower PL was selected and installed in the Beltown neighbourhood with approx. 12000 people in a 0.3 square-mile area. The modular PL was fitted with 3 compartment sizes namele, small; medium and large. The configuration in this specific study was with 8 large, 28 medium, and 19 small cells. Cells were about 1.5 ft wide and 2 ft deep, and the heights of the small, medium, and large cells were respectively about 5, 10, and 25 inches. This 4 tower configuration is cheaper then 5 tower one and was the most ideal one for as it results in a low occupancy rate which causes less number or packages to be left outside the PL system. For ease of computation this locker configuration is also selected for this case study in subsection ii.

- *Location of PLs:* According to literature research, plenty of surveys have been conducted indicating that the majority of customers (around 80.1%) would prefer PLs close to home according to (Lemke et al., 2016)[19] and (Mitrea et al., 2020)[22] as seen from Table 2 and Table 3. This decision generally lies in the hands of the LSPs as will be discussed later during the conceptual model elaboration.

- *Customers and their mobility behaviour:* In order to eliminate failed delivers, the LSPs can deliver orders to a set PL location. Likewise, consumers enjoy the convenience of 24-hour accessibility. With parcel lockers located closer to their home than post offices, they can pick up and return items at their convenience with minimal queuing and indirectly lowering service costs at the same time [26]. For this paper, it is assumed that customers pick their parcels through a dedicated trip and within 24 hours of parcel delivery by LSPs.

  This also means taking into account the maximum distance that customers are willing to travel in order to collect their parcels from the PL stations in their neighbourhood or vicinity. According to (Mitrea et al., 2020)[22], majority of e-consumers are available to deviate from usual daily trips (e.g. home-workplace or home-university), between 5 to 10 minutes to collect their parcel [22]. Additional literature research, PLs can influence and change the activity chains, number of trips, as well as modal split and the travelled distances for pick-up/drop-off parcels. Based on this study conducted by (Hofer et al., 2020)[27], results shown in

Figure 3 depict the average acceptable travel time by consumers to PL locations by different modes.

Accepted Indicators	Walk	Bicycle	Public Transport	Car
Travel time [min]	10.3	7.5	9.1	7.2
Travel distance [km]	0.7	1.9	1.2	3.6

Fig. 3. *Accepted average travel time and distance to reach a PL [27]*

- *Logistic service providers:* From the perspective of Logistic Service Providers (LSPs), a PL system offers a flexible and efficient alternative for parcel delivery and pickup. The usage of the PL system varies based on customer preferences and service offerings. Typically, customers have the freedom to retrieve their parcels whenever convenient, leading to the potential for multiple uses per day. This adaptability allows customers to align their parcel collection with their schedules, optimizing convenience. Time windows for parcel retrieval can vary, accommodating diverse customer preferences.

  The usage pattern influences the required number of lockers within a system. For efficient operations, LSPs must balance the number of lockers with the expected parcel volume. An optimal ratio is sought between the number of lockers, the anticipated frequency of usage, and the number of parcels being serviced. Factors such as the density of customers, delivery schedules, and locker accessibility play a role in determining the appropriate locker quantity. An assumption on all these factors are discussed in subsection i.

These 5 aspects can be amalgamated into 3 key aspects which form the PL system: the customer; the LSPs and the PL distributor. The LSPs make decisions on PL locations and then consequently deliver parcels to the lockers based on demand and number of lockers. The customer access PLs in order to collect or return their parcels. Their choice of mode choice depends on the location of PLs. PL distributors are in charge of the life cycle emissions for the PLs and make decisions on the configuration of PLs.

The primary benefits of PLs arise from high parcel delivery rates and reduction in failed deliveries. Additionally, reduction in failed deliveries can have an overall reduction in emissions and congestion in certain network areas which can have a considerable positive effect on the environment. It can be concluded that the utilisation rates of PLs is closely related to their location. Other key features of PLs are its 24/7 parcel access, secure deliveries, electronic logged deliveries and collection and provision of returning parcels [28].

However from a customer's perspective, they can also be a source of inconvenience in certain situations when parcel size is too big to fit in the compartments of a PL station. Additionally, there is the principal disadvantage for the customer to travel to the PL stations for picking up or dropping-off their parcel. This can be inconvenient to certain age groups of people who are used to getting their parcels delivered at home as the last mile delivery.

ii. Factors influencing the usage of Parcel Lockers

The adoption and utilization of PLs are governed by a multitude of complex factors that influence their usage patterns. Some of these factors include regional setups, city designs, recipient habits, attitude, convenience, privacy, security and population densities also play an important role that influence the degree of usage and adoption of PLs in certain areas [14]. In this discourse, we delve into two pivotal factors that significantly impact the usage of PLs: the strategic location of these lockers and the mode choice exercised by customers.

- **Location of PLs**
  The utilisation rates of PLs is closely related to their location. About 80% of customers prefer the PLs location close to home[22], hence PLs in residential areas could be an area of interest to be more specific. This encapsulates the core effect of customers willingness to use them and travel short distances to access their parcels. Additionally when considering the location of PLs by LSPs, there are two main approaches that can be adopted: more locations with fewer lockers or fewer locations with more lockers. Opting for more locations with fewer lockers entails spreading out the lockers across a larger geographic area. This approach aims to provide customers with easy access to a PL within close proximity to their homes or workplaces. It encourages a higher frequency of use, as customers find it convenient to drop off or retrieve parcels on a regular basis. This approach may require smaller lockers in terms of size and capacity but enables greater flexibility in parcel management. More locations with fewer lockers may suit densely populated urban areas where convenience and quick access are essential. This factor affects the VKT as more PL locations with fewer lockers lead to shorter travel distances for customers but more by logistic service providers.

  Alternatively, having fewer locations with larger, bulkier lockers focuses on consolidating the locker presence in key strategic areas. Customers might have to travel a bit farther to access these lockers, potentially resulting in less frequent usage but a higher parcel volume per visit. This approach aims to reduce the number of locker installations while accommodating higher demand at centralized points. Fewer locations with more lockers might be favored in rural areas with lower population density, where optimizing resource allocation becomes critical. This factor affects the VKT as fewer PL locations with large lockers lead to shorter travel distances for LSPs but further distances for customers.

- **Mode choice of customers**
  Additionally, findings from other authors have shown that the benefits of a parcel machine will be undone if these trips are done by car[23]. This means that PLs should be reached with eco-friendly modes, either by bike or foot, by its users to have a positive environmental impact. However if the PL location is far from the customer, especially in rural areas where the PL density is low, then travelling via car can become a necessity. An assumption based on mode choice of the customers based on their location from PLs is made in subsection i.

iii. PL system setup: Urban vs Rural

Urban

As highlighted in subsection i which highlights the key aspects of a PL system, in an urban area PLs would be potentially placed at various locations throughout the city to serve the high population density and meet the demand for convenient access. They would be strategically distributed in areas such as residential complexes, office buildings, shopping centers, and transportation hubs. These could be integrated with existing infrastructure, such as apartment buildings, retail stores, or transportation hubs.Additionally since urban areas generally have higher parcel volumes, a larger number of modular lockers and compartments would be necessary. Due to superior internet connectivity in urban areas, customers have the provision to utilize features like real-time monitoring, remote access control, and notification systems for parcel pick-up and drop-off.

In an urban setting of a dense network of PLs, most preferred mode of transports for accessing the PLs are by walking and biking [29]. If PL are stationed at a 5-minute walk range from a home address, then inhabitants are more willing to collect a parcel on foot [20]. Majority of the respondents in a survey conducted in the Netherlands are willing to travel 5-10 minutes, resulting in buffer zone of approximately 400 to 800 metres for walking [29]. This also translates into a zone of about 2000 meters for biking.

Rural

In contrast to a setup in an urban area, the PL system in a rural area would typically have a centralized location to serve multiple nearby communities. It would be located in a village or town center, making it accessible to residents within a larger geographic area. This system should preferably be integrated with local facilities like post offices, community centers, or retail stores, leveraging existing infrastructure and providing additional services to the community.

In rural areas, where access to electrical infrastructure may be limited, the locker system might incorporate alternative power sources such as solar panels or battery systems to ensure a reliable power supply. These areas may additionally face challenges with internet connectivity, requiring efforts to ensure reliable connectivity for the PL system. Maintenance and support services would be provided for both urban and rural PL systems. However, in rural areas, special considerations might be needed due to longer travel distances for service personnel. Regular maintenance visits and prompt response times are essential to ensure the smooth operation of the lockers in rural areas.

Similarly, in a rural setting of a network of PLs, most preferred mode of transports for accessing the PLs are by biking and by car [29]. The travel distances in rural area are about 10 mins on average which translate to about 2.8 kms by biking and 5 kms for driving a car to PL locations.

iv. Conventional HD

Traditional HD involves direct shipment of packages to the customer's residential or business address. Extensive literature underscores a multitude of benefits associated wih this method. It offers a high level of convenience and a personalized experience, as packages are brought directly to the customer's preferred location. Studies indicate that this convenience plays a pivotal role in customer satisfaction and retention. Furthermore, conventional HD is known to contribute to enhanced accessibility for a diverse range of consumers, including those with limited mobility or residing in remote areas. Moreover, some sources suggest that centralizing deliveries to residential addresses could potentially lead to fewer vehicles on the road, aligning with sustainability goals.

However, the literature also underscores certain environmental drawbacks. The increased use of delivery vehicles, particularly in densely populated urban areas, has been associated with elevated emissions and air quality concerns.

Research Question

As mentioned above, the aim of this paper is achieved by answering the following main research question:

"What are the environmental impacts of implementation of parcel lockers system?"

In order to answer the main research question, the following three sub-questions need to be answered first:

- *SQ1: What are the different ways in which the PL system can be setup?*
- *SQ2: What are the potential factors that determine the environmental impacts of PL system?*
- *SQ3: How can the potential impacts of the different ways that the PL system is setup be quantified?*

III. METHODOLOGY

Methodology provides detailed information about the methods used to answer the main research question in this research which are also shown briefly in Figure 4. Literature review conducted in the previous section is used to answer the first sub-question, while the other two sub-questions will be discussed here. The second sub-question is answered by developing a conceptual model while the third sub-question is answered by conducting a comprehensive LCA of PL system.

Subquestion	*Methodology*
SQ1: What are the different ways in which the PL system can be setup?	Literature Research
SQ2: What are the potential factors that determine the environmental impacts of PL system?	Literature Research & Conceptual Model
SQ3: How can the potential impacts of the different ways that the PL system is setup be quantified?	Life-Cycle Assessment

Fig. 4. Methodologies for the sub-questions

i. Conceptual Model

A conceptual model is developed in this research to provide a visual representation of the PL system regarding its environmental impact. This model is based on the societal impact model [30] by only considering the environment aspect. The development of such a societal impact model was taught in the curriculum of the masters programme of Transport, Infrastructure and Logistics (TIL) in the course *"Innovations in Transport and Logistics"*.

The conceptual model as shown in Figure 5 is developed by means of a system diagram that provides a general framework to identify and understand potential environmental impacts associated with the life cycle of PLs. This model is based on a novel last-mile delivery innovation, the PL system which comprises 3 aspects: the Logistic Service Provider (LSP), the Customers and the Distributors. These components of the PL system are displayed in blue colour. One of the aspects of the PL system is also involved in HDs; the LSP which is also highlighted in blue colour. The different decisions variables that are manipulated by the key actors of the PL system are depicted by white boxes. These include the decisions on different life cycle stages of the PL by the distributor, determination of PL locations by the LSPs , the mobility behaviour of the customers and the logistics operations by the LSPs for instance. The yellow coloured boxes are used to depict the effects of the decision variables. The other factors that are related to the LSP and customers are depicted in grey boxes. The different types of emissions from all the three components of the PL system are depicted by orange colour boxes which are discussed in detail below. These emissions from the different aspects of the PL system ultimately have impacts on the environment which is depicted by the red box. For the clarity of the reader, all the factors and aspects of the conceptual model are discussed in detail first and then followed by stating what exactly is included in the scope of this paper and carries over to the case study in section IV.

Scope of PL system and its purpose

It is previously mentioned in section I that as e-commerce trend is accelerating, the demand for the number of parcel being delivered continues to grow. Consequently the demand for efficient and convenient delivery options has also increased. In the recent years PLs have emerged as a viable solution to address the challenges associated with the last-mile delivery of online purchases. This benefits both the customers and the LSPs as it results in convenient delivery, 24/7 accessibility, reduced delivery attempts, consolidated deliveries, sustainable delivery option and cost savings. These benefits in turn creates the need for customers and LSPs to travel to PL locations for parcel delivery and collection. The PL systems described in this section comprise of 3 aspects: Customers, LSPs and PL distributors.

Conventional HD

The conventional HDs involve the LSP delivering parcels to the individual customers by travelling to their place of residence or a chosen address of their preference. The distance travelled by LSP trucks in real world scenarios would vary on a daily basis, it is assumed to be a constant number of VKT by the vehicle which includes the distance between the sorting center and the respective area plus the distance covered by LSP trucks when travelling to individual customer residences which is further elaborated in subsection i.

PL locations

The PL locations themselves can have considerable effects on the environment. Strategic placement of PLs in convenient and accessible locations can contribute to more efficient delivery routes and reduced overall transportation distances thus increasing transport efficiency. Determination of PL locations that ultimately have an affect on accessibility of this system in done by LSPs, thus influencing mobility behaviour of customers to some extent.
Although as mentioned in subsection ii, that urban and rural areas have different PL distribution, for ease of computation it is assumed that the combined PL demand and capacity, irrespective of their distribution, is a fixed number in urban and rural settings which is also reflected later in subsection i.

Transport Resistance

Factors which affect the PL system and ultimately the environment are travel time, cost and effort. These are the resisting factors which obstruct the need to travel to these PL locations [31]. Low resisting factors results in high amount of transport and vice-versa. This in turn also can potentially reflect in the mobility behaviour of the customer.
These factors are a results of the LSPs that determine the deployment of PL locations. For the HDs there are potentially high and varying number of kilometers travelled by the parcel delivery vehicle expressed as VKT. For PL systems on the other hand, the VKT are potentially low and fixed as the LSP trucks travel only to the PL locations.

Customer location and their mobility behaviour

The customer location or residence can be broadly classified into two categories: urban or rural. These locations have a considerable affect on their mobility behaviour which ultimately impacts their mode choice to access the PL systems. As mentioned in subsection iii, customers residing in rural areas prefer to access PL locations via bike or car. Whereas in an urban setting the more preferred mode choice are walking and biking. Other customer behavior characteristics such as dedicated trip by driving to and from PLs or combining parcels pickup with other trips can contribute to additional vehicle emissions and traffic congestion.
While customer behaviour depends on several factors, it is assumed that customer mode choice will solely depend on the distance to PL location in this paper. The choices of modes by customers are also limited to three in this paper namely; on foot, bike and car respectively. Furthermore customer purpose of package collection is solely assumed to be a dedicated trip initially for the case study.

Logistics operations

The LSPs make important decisions that relate to the logistical operations. These decisions are influenced by the transport resistances discussed previously. The logistic operation decisions result in choice of mode transport, routing, scheduling and parcel handling for both PL systems and HDs. Usually all of these decisions are important when considering the entire logistical chain.
However for this paper, the point of interest in only the environmental impact for which only VKT by the LSP trucks is considered. The key difference in the effect of the decision is LSPs target destination being customer residence in HD scenario and PL locations in a PL systems. The VKT is also highly dependent on the respective sorting center that serves the demand of the PL locations and customers.

Vehicle emissions

The vehicle emissions which have an impact on environment are influenced by mode choice by the LSPs to deliver or collect the parcels and the customer that use specific modes to access PL locations. Some of the most common emissions caused by vehicle are carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), and other air pollutants. Accessing PL locations via walking has no environmental impacts.
Although there are many emissions caused by vehicle travel, but due to reasons mentioned in subsection iii, the GWP or the climate change impact category is selected for this paper which is expressed in kg $CO2$-eq or g $CO2$-eq.

PL life cycle phases

The decision on the different life cycle phases of the PLs that are made by the distributor ultimately reflect on the various emissions that affect the environment. Some of the relevant factors and impacts to this study are:

- Production: This phase consumes fossil fuels and begins with the extraction of raw material needed for PL construction. This is followed by processing and assembly of components. As a result GHGs, metallic oxides, silicates, fluorides and wastes are produced. The different materials and their quantities are referenced from the EPD report [32] and the emission factors are referenced from the Ecoinvent v3.8 database in Mobius.
- Packaging: For safe and undamaged transport of PLs to its installation sites, proper packaging needs to be done. This phase involves extraction and production of packaging materials such as cardboard, paper and polyethylene etc. As a result the emissions produced are GHGs.
- Transport: This phases involves the activity of transporting the

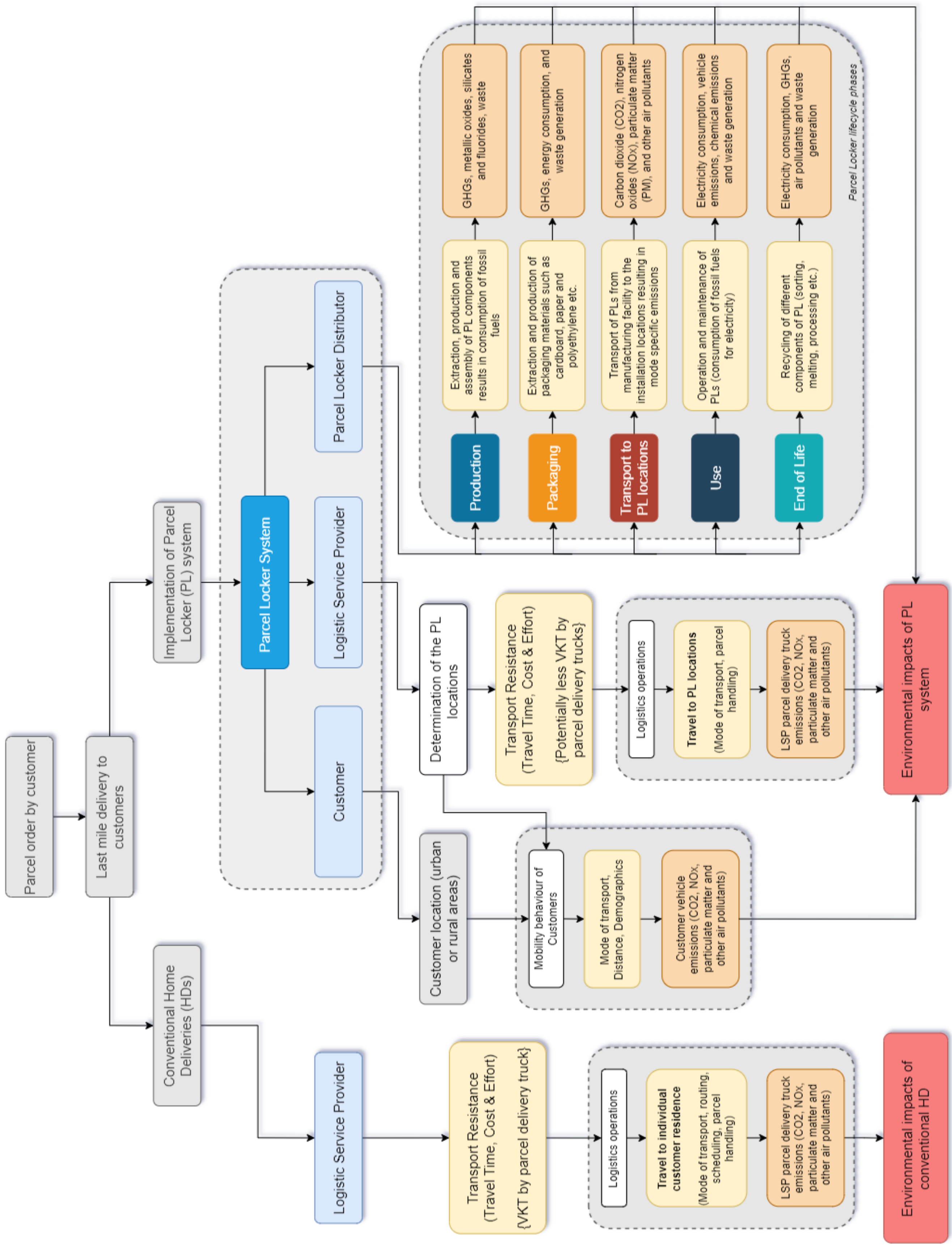


Fig. 5. Conceptual Model for potential environmental impacts of PL system and conventional HD

assembled and packaged PLs to their installation sites which results in mode specific emissions which are mainly carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), and other air pollutants. The transport emissions factors considered for this case study is 192 gCO_2 per km [33] for cars used by customers to access the PL locations. All the Other emission factors are referenced from the Ecoinvent v3.8 database in Mobius.

- Use: This phases includes the PL use by the customers and the LSPs delivering their parcels. Operation and maintenance of PLs are a crucial part of this phase which requires significant energy consumption. It is necessary in order to power their operation, including features such as lighting, display screens, and electronic locks. This electricity could be generated from fossil fuels such as coal or natural gas resulting in GWP emissions. Other emissions include vehicle emissions, chemical emissions and waste generation that are related to the maintenance of the PLs.
  In a PL system, continuous electrical supply is essential for the proper functioning of various components. These components comprise primary elements like the electric motor and control board, as well as secondary elements like lights, sensors, and cameras. The electric motor serves to power the locking mechanism, with power consumption reaching up to 20 watts per hour during operation. The control board, responsible for managing system functions, consumes approximately 10 watts per hour while in use. Ensuring safety and security, lights and sensors operate at an energy consumption rate of 5-10 watts per hour each. Moreover, the integration of cameras within the system results in an additional 40-50 watts per hour of power consumption when activated [34].
- End-of-Life: This phase comprises the recycling of different components of PLs by sorting, melting, processing etc. which can be further utilised for its next life cycle. In order to carry out these processes electricity is consumed, which as stated above could be from use of fossil fuels. Other emissions that negatively impact the environment are GHGs, air pollutants and waste generation which mainly occur due to material treatment and certain non-recyclable by products.

Although the different life cycle phases have various types of emissions, only the GHG emissions expressed in kg $CO2$-eq or g $CO2$-eq are relevant to this paper and are considered for the case study in section IV. Assumptions based on life cycle phases are further carried over in subsection i.

The conceptual model facilitates a structured approach to quantify the impacts under different scenarios. This methodological approach enhances the depth of analysis and supports the overarching goal of understanding and optimizing the environmental sustainability of the parcel locker system.

ii. Quantification of potential environmental impacts using LCA

The utilization of the Environmental Footprint (EF) method in conjunction with the Ecoinvent v3.8 database within Life Cycle Assessment (LCA) is applied in this paper. Life Cycle Assessment (LCA) is a systematic and comprehensive methodology used to evaluate the environmental impact of a product, process, or system throughout its entire life cycle. The full LCA for PL systems is done in the Ecochain Mobius software (see Figure 6) which considers all stages, including raw material extraction, production, distribution, use, and end-of-life disposal or recycling. LCA involves the quantification and analysis of various environmental aspects, such as energy consumption, greenhouse gas emissions, water use, and waste generation. By assessing the inputs and outputs at each life cycle stage, LCA allows for informed decision-making by identifying areas where environmental improvements can be made. As a valuable tool for sustainability assessment, LCA plays a crucial role in supporting environmentally conscious choices and fostering the development of greener and more eco-friendly practices [35].

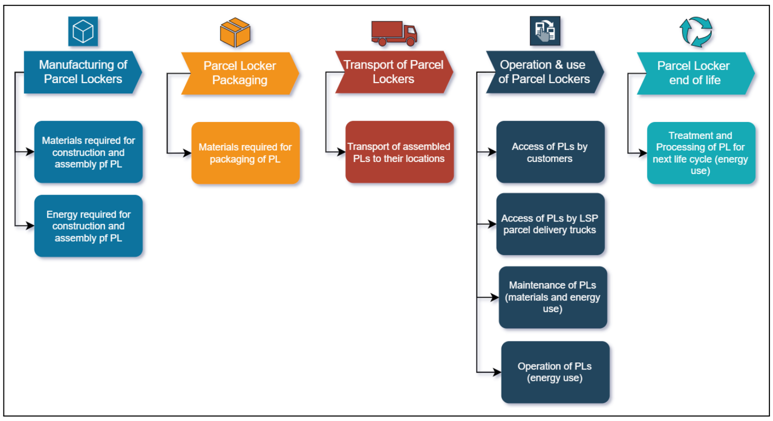


Fig. 6. *The different life cycle stages of the PL system and their components in Ecochain Mobius software*

<u>**Motivation for PL location choices**</u>

This section describes the motivation for choosing an urban and a rural location for this case study.

De Pijp

For this paper the urban location chosen for the PL system setup is 'De Pijp', an urban neighbourhood in Amsterdam. This choice is made due to the easy availability of demographics and city characteristics. Since there are a larger number of PostNL PLs for parcel collection available in the area of the De Pijp as shown in figure Figure 7, the inhabitants of Amsterdam can choose the nearest collection point [36]. Moreover previous research findings regarding last mile delivery efficiency has been been done which concluded that the usage of PLs is beneficial concerning the location of De Pijp [20].

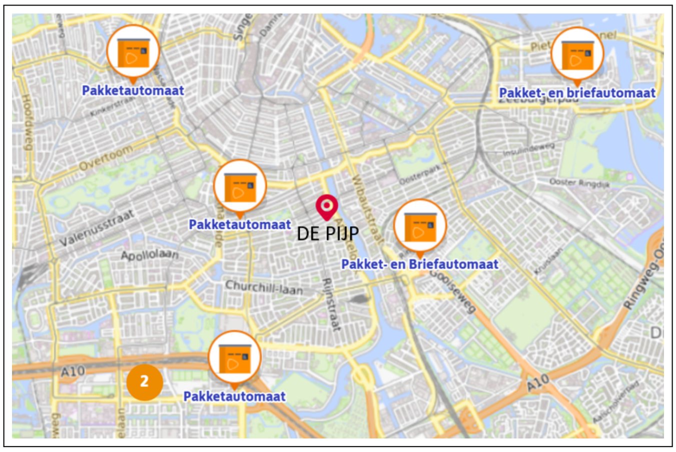


Fig. 7. Parcel Machine network in De Pijp [36]

Ten Boer

The rural location for the PL system setup is chosen to be 'Ten Boer', a village and a former municipality in the northeastern Netherlands, in the province of Groningen. PostNL currently has over 400 PLs across the Netherlands in a whole host of municipalities, including Almere, Tilburg and Breda. PostNL in addition to this is also in communication with different municipalities across the Netherlands to achieve 1,500 PostNL PLs in 2024 [37]. Similar to the urban location setup, previous research has been done on willingness to use PLs in Ten Boer which throws light on travel behaviour of the residents of the location. This proves to be beneficial for this study [29]. PostNL parcel collection points distribution in Ten Boer and the surrounding area is shown in Figure 8 which shows that the PL network distribution is very limited when compared to an urban setup [38].

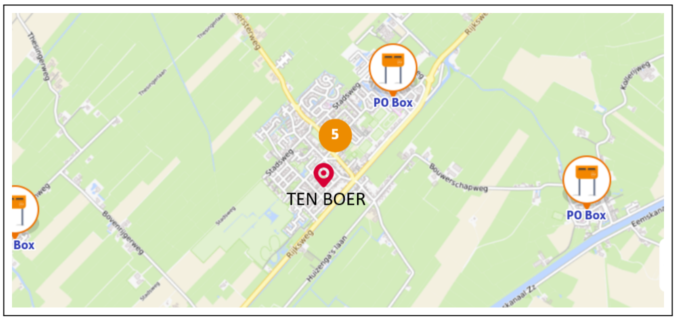


Fig. 8. Parcel Machine network in Ten Boer [36]

iii. Impact category

The emission involved in different aspects of the this PL system can contribute to varying environmental impacts which are discussed in Figure 5. Their characterization into impact categories can be used to quantify the ability of each of the assigned elementary flows to impact the indicator of the category.

Typically, the 'Climate Change' environmental impact category is used due to its high relevance amongst stakeholders [39] according to Mikosch, N (2022). In order to represent this impact, the Global Warming Potential (GWP) or the climate change impact category is selected for this paper. The GWP is a comprehensive indicator that accounts for the impact of all greenhouse gas (GHG) emissions, expressed in kg $CO2$-eq.

IV. CASE STUDY

This section of this paper presents the setting up of the case study to assess the environmental effects of PLs using LCA. This section will follow a structured format, beginning with a list of assumptions for this paper in subsection i. This is followed by subsection ii that provides a detailed description explanation of the different aspects and values for each of the phase of the PL system life cycle and the PL system setups. Finally, a brief description of the setting up of the conventional HD is also presented in this section. The system setup will be supported by relevant data and figures to enhance the clarity and visual representation.

This section enables the reader to gain detailed understanding of how the phases are modelled into Ecochain Mobius. Based on this section, the findings of the case study are discussed in section section V.

i. Assumptions

Several assumptions are made for ease of modelling the different phases of the PL system in this case study listed below and as shown in Table 4:

- Lets start the assumptions from an LSP perspective, where they setup PL system in either urban or rural areas. It is assumed that the total number of PLs that are situated in both the settings (urban and rural) have around one truck load capacity such that the trucks can drive there once per day.
- It is assumed that the LSP trucks have a capacity of 55 parcels. It is also assumed that the demand of parcels is high in both the settings also about 55 parcels per day and the number of parcels delivered to the PLs and the customers by the LSPs are 55 each day for both PL systems and HDs.
- For this paper and also the case study in subsection ii, although there is an expected difference in PL location and density, the total demand of parcels in PLs in urban and rural areas is assumed to be the same irrespective of their numbers for ease of computation. However this difference will be reflected later in subsection iii where the distribution of lockers will be varied.
- It is assumed that the PLs in case of PL systems and parcel delivery trucks by LSPs in case of HDs serve demand of different customers each day. A single customer order frequency is assumed to be once a month as mentioned in section I. But since the customer orders are not synchronized and it is difficult to pin point each customer order placement patterns, it is assumed that the daily overall order frequency by customers in total belonging to the urban and rural settings in this case study to be 55. Hence on a daily basis 55 customers in total travel to retrieve a total of 55 parcels per day, meaning about 1 parcel per customer per day.
- Since PLs give its users flexibility to collect parcel at their preferred times during a day, for ease of computation it is assumed that a maximum retrieval time of parcels from PLs is 24 hrs, i.e lockers can be used once per day or the lockers have to be emptied by the customer (parcel collection) so that trucks come to empty lockers the next day.
- Failed deliveries in case of conventional HDs are not included in this case study. This is due to lack of data and although, this works to the disadvantage of the PL systems, the failed deliveries will be later discussed in the subsubsection iv.1 and be reflected upon in subsection ii in the discussion. Hence for now it is assumed that 100% of the parcels are delivered on the first try by the couriers.
- All the emissions are expressed per parcel in terms in Kg CO_2-eq. While Figure 19, reflects these emissions per parcels in g CO_2-eq for ease of interpretation and comparison to HDs
- It is assumed that the customers make a dedicated trip for collection of their parcel from PLs in urban and rural area. This means that combining trips with other purposes such as work, leisure is out of the scope of this study. This is to make the base case scenario as simple as possible, however trip chaining for the purpose of parcel collection by customers, especially in rural setup will be reflected upon in subsubsection iv.1 and in section VII.
- It is assumed that all the customers use the same mode of transport to access PL locations as specified in different scenarios. This means that in urban setting, if the PL locations are close by to the customers from their location, all of them would walk about an average of 0.8 km. Similarly if the PLs are located a bit further from their location, all of the customers would bike and average distance of 2 kms. Consequently for rural setting where the PL density is low, customers travel larger distances as compared to urban setting to access PL locations. This means that customers

are more inclined to take the bike for distances around 2.8 km and more inclined to take the car for distances around 5 km.

- The time horizon for which the total climate change emissions are calculated is assumed to be 15 years. This means delivering 55 parcels to PLs everyday for 15 years for PL systems. Additionally this also translates to delivering 55 packages to customers everyday for 15 years for the conventional HDs.
- In the HDs, the delivery trucks travel to individual customer residence location for parcel delivery. This results in more VKT by parcel delivery trucks compared to PL systems. It is assumed that the VKT travelled by delivery trucks in both the urban and the rural setting to be 75 kms plus the respective distance they have to travel from their sorting centers [40].
- For urban setting, the sorting center in Westzaan is 25 kms away from De Pijp, hence the total VKT by LSP trucks is:
  25 km (distance from sorting center in Westzaan to De Pijp) + 75 km (assumed VKT by LSP trucks to serve 55 customer order) = 100 kms VKT which translates to 1.81 kms travelled per parcel in urban setting.
- For rural setting, the sorting center in Hoogeveen is 75 kms away from Ten Boer, hence the total VKT by LSP trucks is:
  75 km (distance from sorting center in Hoogeveen to Ten Boer) + 75 km (assumed VKT by LSP trucks to serve 55 customer order) = 150 kms VKT which results in 2.72 kms travelled per parcel in rural setting

Base case scenario

This case study starts by setting up of the base case scenario where both in PL system and HD, all the aspects and external factors are assumed to be the same as discussed above. To be more elaborate it is assumed that number of parcels delivered over the entire time horizon of 15 years are same in both the cases. It also means that the sorting centers that serve the demand of customers in urban and rural regions in both the cases are also assumed to be the same. Scenarios where some factors change in the PL system or the HD in the future will be discussed and reflected upon in section V (subsection iii).

ii. Case study

For this study, an urban region in the Netherlands chosen is 'De Pijp', which is a neighborhood and a former borough of Amsterdam. On the other hand a rural region in the Netherlands chosen is 'Ten Boer', a village and a former municipality in the northeastern Netherlands as mentioned in subsection iii. The data from the EPD of the Steel Case Lockers can be extrapolated as PLs are self service lockers which will be in use for a longer duration throughout the day and all the weekdays throughout the year. In addition to this the configuration found in this study to be the most effective for residential areas is the 4-tower configuration according to the study conducted by Ranjbari, A., (2023) [25].

Hence, the materials required for production of the 4 tower PL as mentioned in subsection i are referenced from the EPD conducted for a steel locker. This steel locker had different dimensions (H1645mm D450mm W1200mm; 3 columns) from the one proposed in this study as shown in Figure 9, hence the amount of materials required (kg) in production and packaging have been extrapolated accordingly (see Figure 23) and assumed in the software Mobius Ecoinvent v3.8 database as shown in Figure 10 and Figure 11.

PL locations

Since 2021, the new automated PLs in Utrecht are the product of a collaboration with retailer Jumbo and distributor Dujardin-Remmers [42]. Dujardin Remmers is an innovative security solutions company based in Gorinchem, Netherlands located about 73.6 kms from the urban region of De Pijp area. For transport of PLs from Gorinchem to the rural area of Ten Boer, they need to be transported over a distance of about 235 kms via road.

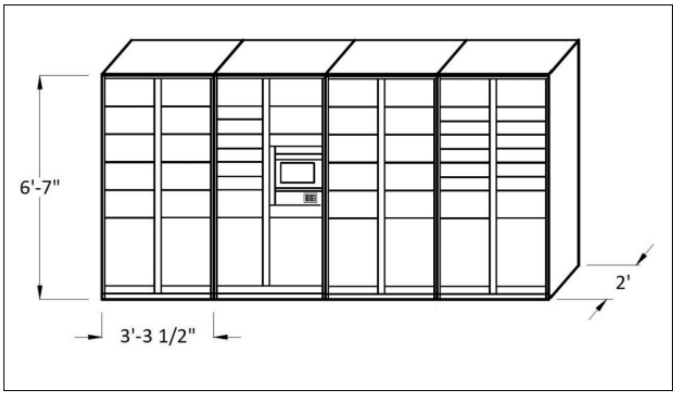


Fig. 9. 4PL tower configuration [25]

Sorting center locations

The delivery trucks need to only travel to PL locations from the nearest sorting centers in case of PL systems. The PostNL sorting center that serves the demand of customers in the urban PL system scenario is assumed to be in Westzaan [41] which is 25 kms from De Pijp in Amsterdam. Similarly, the location Hoogeveen is chosen for the PostNL sorting center that serves the demand of customers in rural PL system scenario, which is about 75 kms from Ten Boer [43].

Production phase

All the materials required for the construction of PLs are firstly modelled into the first phase. All the reference data for emissions are embedded itself in the software (Ecoinvent v3.8) which includes databases for all kinds of process and products. Hence the emissions related to the amount of materials used in the production of PLs such as Aluminium, Steel, Polypropylene, ABS (Acrylonitrile Butadiene Styrene), ZAMAK and Paint shown in Figure 10 are modelled into the Mobius software. For more clarity, see Figure 25 which shows the climate change impact category for instance the material *ABS* used in PL production. Other materials are also referenced similarly from the database.

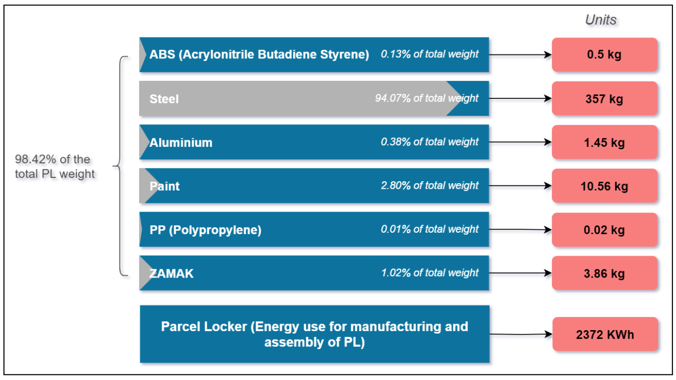


Fig. 10. *Production phase describing input of amount of materials and energy required for PL production*

Packaging phase

Table 4. *Assumption for this case study*

Assumption(s)	***Urban scenario***	***Rural scenario***	***home delivery***	***Source/Reference of assumption***
Customer order frequency	Everyday	Everyday	Everyday	As mentioned in section I, the frequency of order by a customer is assumed to be everyday PL systems and home deliveries as the orders are not synchronized.
Average parcel weight	2.9 Kgs	2.9 Kgs	2.9 Kgs	Since about 75% of the parcels weigh less than 2kg [2], the average parcel weight is assumed to be 2.9 kgs as shown in *Figure 24*
Multiplication factor for amount of material and energy required for PLs	Material: 3.3 Energy: 4.2	Material: 3.3 Energy: 4.2	Not applicable/ Not required	For the different amount of materials required for the considered PL in this paper, a multiplication factor of 3.3 is chosen as shown in *Figure 23*
Impact category	GWP	GWP	GWP	The indicator GWP, expressed in CO_2 is chosen for this study as it allows for comparisons of the global warming impacts of different emissions involved.
Lifecycle duration for which impact is considered	15 years	15 years	15 years	This is same the lifetime considered in the EPD reference report [32]
Sorting center location for modelling access of PLs by LSPs	Westzaan	Hoogeveen	Urban: Westzaan Rural: Hoogeveen	The PostNL sorting centers chosen in Westzaan and Hoogeveen will serve the demand of the PL placed in urban and rural settings [41]
Number of packages delivered at once	55	55	55	Since the PL design considered in this case study can accommodate 55 packages of three varying sizes, the parcel delivery truck capacity is assumed to be 55 parcels
Electricity consumption by PL	80 watts per hour/ 0.8 KW per hour	80 watts per hour/ 0.8 KW per hour	Not applicable/ Not required	The electricity consumed by a PL on average is assumed to be 0.08 KWh [34] of which about 0.05-0.06 kilo watts per houris consumed by camera and security systems
Maintenance of PLs and electricity consumption	Every 3 months, 0.5 KWh	Every 3 months, 0.5 KWh	Not applicable/ Not required	Self assumption
Vehicle-Kilometers Traveled (VKT) by delivery truck	25 kms	75 kms	Urban: 100 kms Rural: 150 kms	Self assumption and literature research on location of PostNL sorting centers in the Netherlands [41]

The next phase modelled for the PL system is the packaging phases where the different quantities and materials are fed into the software. Figure 11 shows the materials in kg used for a packaged PL that will be installed in either an urban or a rural setting are Cardboard, Low-density Polyethylene (LDPE), Paper, Polyethylene and Polypropylene. The different materials used for packaging of PLs for their safe and undamaged transport are input in the software as shown in Figure 11.

For more clarity, see Figure 26 which shows the climate change impact category for instance the material *Kraft paper* used in PL packaging. Other materials are also referenced similarly from the Ecoinvent v3.8 database.

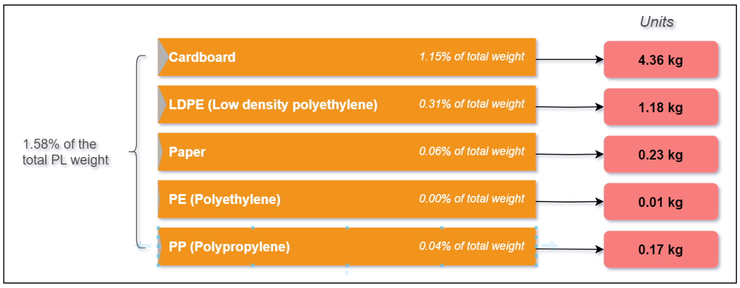


Fig. 11. *Packaging phase describing input of amount of materials required for PL packaging*

Transport phase

The transport of finished PLs will take place from Gorinchem to the areas of De Pijp and Ten Boer respectively via Lorry. This phase models the transport of the assembled and packaged PLs to their respective installation locations. The emissions related to this phase are initially expressed in t*km (mass*distance) of goods transport by road which are then translated into kg CO_2 eq emissions. In the content declaration section of the EPD report [32], the total product weight is first computed by multiplying the reference locker weight by the multiplying factor of 3.3 resulting in the PL weight being 373 kg. The weight in tonnes (10^3 kg) is computed and then multiplied by the distance between the distributor and installation locations.
For urban and rural setups, the distance between the PL distributor is 73.6 kms from De Pijp and 235 kms from Ten Boer respectively. Hence this results in

$(379.3kg \times 73.6km)/1000 = 27.9tkm$ and,
$(379.3kg \times 235km)/1000 = 89.1.9tkm$ of goods transport respectively

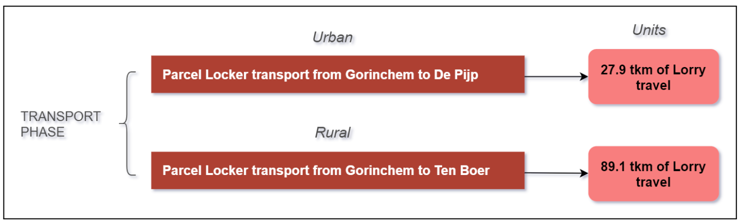


Fig. 12. *Transport phase describing input of amount of tonnes-km travelled by lorry to transport the finished PLs to their installation location*

Figure 12 shows the transport emissions of the PLs that is modelled in the software by taking into account the emissions per tonnes per km (tkm) produced. Also refer to Figure 27, which shows the climate change impact category for transport of 1 t-km of PL transport from distributor to installation location.

Use phase

This is the most crucial stage in order to get insights of how the use of the PL system varies in different settings. This stage includes the operation and maintenance and use of electricity by the PLs at respective locations. Additionally this phases also incorporates the emissions involved when the PLs are accessed by the LSPs and customer. Hence for this phases, the amount of electricity for operation & maintenance used, the distance from the sorting centers of PostNL to the PL locations and the average customer travel in order to access PLs are some of the parameters that will be modelled in the software. For both the cases, it is assumed that maintenance of PLs requires about 2 kg of disinfectant (isopropanol) to clean the surface for a life cycle of 15 years.

Urban
For urban setting, the preferred mode choice for accessing the PL locations are either by walking or by using bike as discussed in sub-section iii. Modelling of this phases can be seen in Figure 14 and Figure 13 where the average travel distance by walking is assumed to be 0.6 kms and about 2 kms by bike which translates to about 5 mins of travel times with both of these modes. The distance from the sorting centre in Westzaan to De Pijp is 25 kms and the along with the computed average weight of the parcels, it is translated in tonnes per km.
According to Figure 14, it can be seen that there is no climate change impact when the customer walks to the PL location which is to be expected as walking is a green mobility behaviour and for customer travelling to PL location by bike(electric) as seen in Figure 13:

- Access by customer input parameters
  $(2kms$ of bike travel $\times$ $55(numberofcustomerstravellingdaily)$ $\times$ $365(days)$ $\times$ $15(years))$ = $602250kms$ of biking

  $(0.8kms$ of walking $\times$ $55(numberofcustomerstravellingdaily)$ $\times$ $365(days)$ $\times$ $15(years))$ = $240900kms$ of walking

- Access by LSP input parameters
  $(25kms$ of LSP truck travel $\times$ 0.1595 tonnes $\times$ $365(days)$ $\times$ $15(years))$ = $21831.56tkm$ of LSP truck travel

- Maintenance input parameters
  $(2kg$ of disinfectant $\times$ $15(years))$ = $30kg$ of disinfectant required

  $(0.5KWh$ of energy required $\times$ $4(Maintenance/year)$ $\times$ $15(years))$ = $30KWh$ of energy required

  $(73.6kms$ of truck travel for maintenance $\times$ 0.1 tonnes supplies for maintenance $\times$ $4(Maintenance/year)$ $\times$ $15(years))$ = $441tkm$ of PL distributor truck travel

- Energy use input parameters
  $(0.08KWh$ of energy required $\times$ $24(hours)$ $\times$ $365(days)$ $\times$ $15(years))$ = $10512KWh$ of energy required

Rural
For the PL system setup in a rural setting, the preferred mode choice for accessing the PL locations are either by bike or by using car similarly

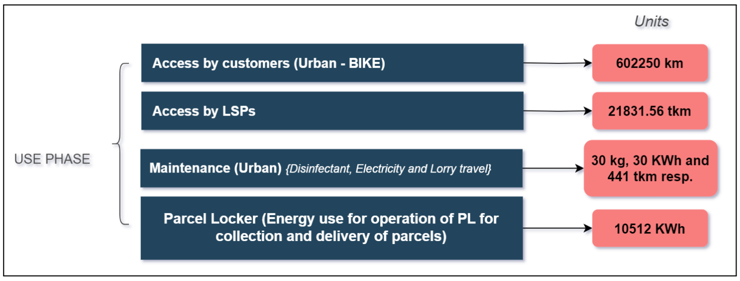


Fig. 13. *Use phase (Bike - Urban) describing input of amount of the kms travelled by customers by bike, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

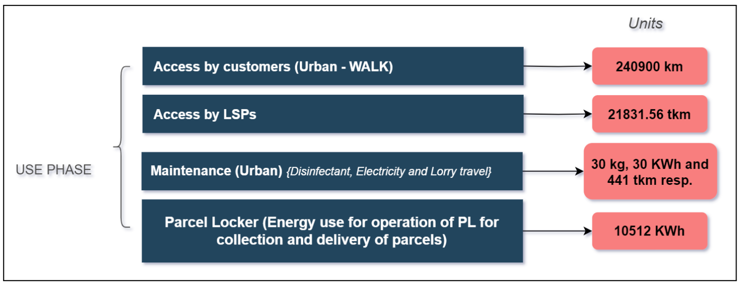


Fig. 14. *Use phase (Walking - Urban) ddescribing input of amount of the kms travelled by customers by walking, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

mentioned in subsection iii. Figure 15 and Figure 16 show the different attributes of the use phase of the PL system by bike and car in rural setting. The average distance for bike is assumed to be 2.8 kms for bike and 5 kms for car which translates to about 10 mins of travel by both of these modes. The average medium gasoline-powered car emission per km is assumed to be 0.192 g per km [33]. Similarly the distance between the sorting center in Hoogeveen and Ten Boer is 75 kms via road.

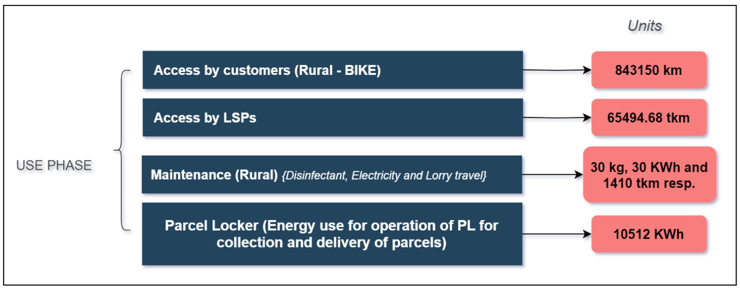


Fig. 15. *Use phase (Bike - Rural) describing input of amount of the kms travelled by customers by bike, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

- Access by customer input parameters
  $(2.8kms$ of bike travel $\times$ $55(number of customers travelling daily)$ $\times$ $365(days)$ $\times$ $15(years))$ = $843150kms$ of biking

  $(5kms$ of car travel $\times$ $55(number of customers travelling daily)$ $\times$ $365(days)$ $\times$ $15(years))$ = $15050625kms$ of driving

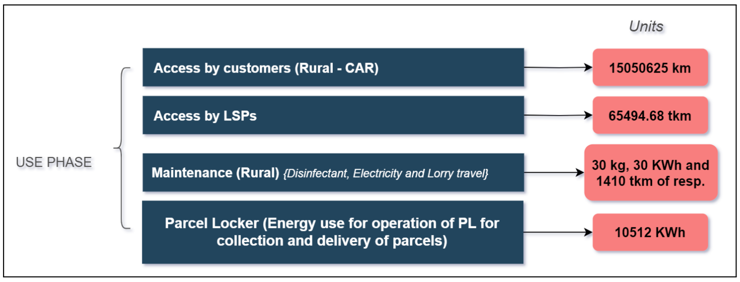


Fig. 16. *Use phase (Car - Rural) describing input of amount of the kms travelled by customers by driving car, tonnes-km travelled by LSP trucks to access PLs, maintenance and energy use for operation of PL use*

- Access by LSP input parameters
  $(75kms$ of LSP truck travel $\times$ 0.1595 tonnes $\times$ $365(days)$ $\times$ $15(years))$ = $65494.68tkm$ of LSP truck travel

- Maintenance input parameters
  $(2kg$ of disinfectant $\times$ $15(years))$ = $30kg$ of disinfectant required

  $(0.5KWh$ of energy required $\times$ $4(Maintenance/year)$ $\times$ $15(years))$ = $30KWh$ of energy required

  $(235kms$ of PL distributor truck travel for maintenance $\times$ 0.1 tonnes supplies for maintenance $\times$ $4(Maintenance/year)$ $\times$ $15(years))$ = $1410tkm$ of PL distributor truck travel

- Energy use input parameters
  $(0.08KWh$ of energy required $\times$ $24(hours)$ $\times$ $365(days)$ $\times$ $15(years))$ = $10512KWh$ of energy required

End of Life phase

Figure 17 shows the input parameters for the software. About 17% of the product that is the PL itself and 74% of the packaging is recycled which has been included in the 'End-of-Life' stage of the PL system. This results in about 4.4 kgs and 64 kgs of the packaging and PL being recycled respectively, and available for use in its next life cycle phase. In addition to this certain energy is also required for treatment and processing of the PLs for its next life cycle.

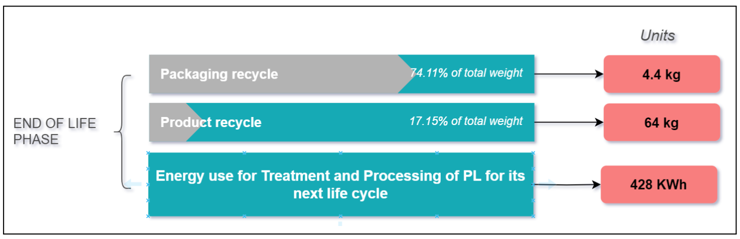


Fig. 17. *End of Life phase describing input of amount of materials and energy required for PL recycle*

Conventional home delivery

Rural

For the conventional HD scenario in rural areas, similar parameters as the PL setup are modelled. According to previous research conducted in Poland, the courier servicing InPost PLs is able to deliver about 600 parcels in just one day, with travel distance of about 70 km in comparison to respectively 60 parcels and 150 km in traditional delivery system [40]. 60 parcels is somewhat similar to the maximum number of parcels that can be accommodated in the PL considered for this case study.

Hence a rough calculation of The emissions related to this phase similar to the PL case, are initially expressed in t*km (mass*distance) of goods transport by road which are then translated into kg CO_2 eq emissions. The weight of the parcels carried by a delivery truck in tonnes (10^3 kg) is computed and then multiplied by the distance between the distributor and installation locations.

For urban and rural setups, the delivery truck is assumed to be at similar load capacity as that of the trucks thats are used by the LSPs in the PL case. Hence the number of parcels in a delivery truck is considered to be 55 with average parcel weight of 2.9 kgs. The distance covered on average by a delivery truck is assumed to be 150 kms during one day of delivering parcels [40]. Hence delivering parcels twice a month this results in:

$(2.9kg \times 55parcels)1000 \times 150km$ daily travel $\times$ $365days \times 15years$= 130989.375 tkm of goods transport

Figure 18 shows the amount of tonnes-km that are travelled in the conventional HD trucks. These are modelled in the software by taking into account the emissions per tonnes per km (tkm) produced. The emission factor of delivery truck is $0.167KgCO2/t-km$ which has been taken into account with tkm of goods transport.

Urban
For HD in urban areas, all the parameters are same except the VKT bt the parcel delivery truck, which in this case is assumed to be about 100 kms during one occasion of delivering parcels. Hence from the assumption that in the HD case, the trucks also deliver twice a month, this results in:

$(2.9kg \times 55parcels)1000 \times 100km$ daily travel $\times$ $365days \times 15years$= 87326.25 tkm of goods transport

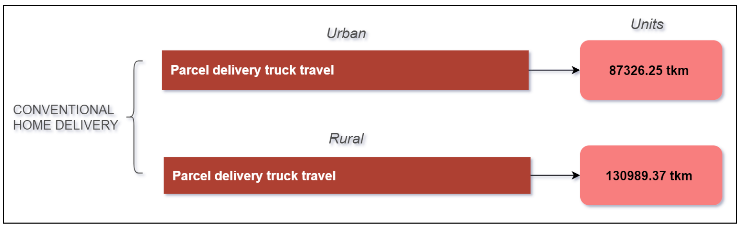


Fig. 18. *Use phase (HD truck emissions in urban and rural setting) describing input of amount of tonnes-km travelled by LSP trucks deliver parcels to customers at their home*

The outputs of the input parameters discussed in subsection ii will be reflected upon in section V.

V. Results

This section presents the GWP results of the considered PL system setup scenarios as discussed in subsection iii. Specifically, section provides a comparison of GWP values across different transport mods, while section breaks down the GWP for each transport mode to the LCA components and discusses their respective contributions. All the emissions expressed in Figure 19 are expressed per parcel.

i. Climate Change Impact: GWP results

This section presents the GWP results of the considered PL system setup scenarios as discussed in subsection iii. Specifically, section provides a comparison of GWP values across different transport mods, while section breaks down the GWP for each transport mode to the LCA components and discusses their respective contributions. All the emissions expressed in Figure 19 are expressed per parcel.

- **Transport emissions caused by Customers**
  These emissions expressed in $kgCO_2$ eq represent the transport emissions caused by customers when they travel to access the PL location for retrieval or return of their parcel. For the mode choice biking or walking, the emissions are negligible and thus can be considered as having no environmental impact. While considering the customer travel emissions to PL location in rural area of Ten Boer via car, this is translated into in $kg\ CO_2$ [33] per parcel:

  $(192gCO_2/km \times 15050625kmsofdriving)1000 \times (55*365*15)parcels$
  $= 0.96kg\ CO_2$ eq per parcel

- **Transport emissions caused by LSPs**
  These emissions expressed in $kgCO_2$ eq represent the transport emissions caused by LSP parcel delivery trucks. These are caused when these trucks travel to the PL locations from the sorting center serving the demand of respective customer locations (urban or rural) and customer's residence in case of HD. The transport emissions by LSP delivery trucks to PLs in urban area per parcel are:

  $(167gCO_2/t-km \times 0.1595tonnes \times 25kmsofdriving \times 365days \times 15years)$
  $= 0.0121kg\ CO_2$ eq

  Similarly, the transport emissions by LSP delivery trucks to PLs in urban area per parcel are:

  $(167gCO_2/t-km \times 0.1595tonnes \times 75kmsofdriving \times 365days \times 15years)$
  $= 0.0363kg\ CO_2$ eq

- **Emissions caused by PL distributor**
  These emissions expressed in $kgCO_2$ eq represent the environmental impact caused by the PL distributor that is responsible for the different life cycle phases of the PL itself and thus the emissions caused during the phases that include:
  (1) Production, (2) Packaging, (3) Transport, (4) Operation & Maintenance: and (5) Recycle of PLs.

  The emissions caused by these life cycle are fixed in urban and rural settings, for urban area per parcel being:

  $9141.5KgCO_2(emissionsforlifecyclephases)(55*365*15)parcels$
  $= 0.0303kg\ CO_2$ eq per parcel

  Similarly for rural setting, the emissions per parcel are:

$9667.32KgCO_2(emissions for life cycle phases)(55*365*15)parcels$
$= 0.0321kg\ CO_2$ eq per parcel

SCENARIO ↓ / EMISSIONS →	Customer mode choice	Transport emissions caused by Customers per parcel (g CO_2 eq)	Transport emissions caused by LSPs per parcel (g CO_2 eq)	Emissions caused by PL distributor per parcel (Life cycle phase of PL) (g CO_2 eq)	Total emissions per parcel (g CO_2 eq)
PL system Urban Setup	Walk	0	12.1	30.35	42.46
	Bike	0	12.1	30.35	42.46
PL system Rural Setup	Bike	0	36.32	32.10	68.42
	Car	960	36.32	32.10	1028.42
Home Delivery (Urban)		-	48.43	-	48.43
Home Delivery (Rural)		-	72.64	-	72.64

Fig. 19. *The GWP results per parcel in terms of gCO_2-eq for the PL system setups and conventional HD in an urban & rural setting*

Figure 19 represents the total GWP emissions of the PL system and HD in an urban and rural setup in terms of $kgCO_2$-eq emissions per parcel. It can be seen from Figure 19 above that in general, that the majority share of the GWP emissions are from the PL distributors in case of PL systems in urban setup. While the PL distributor emissions per parcel are fixed, the share of emissions caused by LSP per parcel dominate the PL distributor emissions in case of PL systems in rural setup.

While for conventional HDs, all the emissions are incurred by the LSPs which deliver parcels to the customer's residence or an address chosen by them. HD in rural areas results in higher emissions when compared to urban areas due to larger amount of VKT by the parcel delivery truck in rural areas. The primary reason for this is because the sorting center that serves the demand of urban area (De Pijp) is located more closer to it than the rural area (Ten Boer). Emissions are expressed in terms of $kgCO_2$-eq emissions highly depend on the type of delivery truck deployed by the LSP and their load.

According to a study conducted in 2021 and the Ecoinvent 3.8 database, urban delivery trucks emitted on average $167gCO_2/t-km$ [44]. Hence, the goods transport for the HD setup is translated into in $kgCO_2$ (0.167 $kgCO_2$ eq per tkm of goods transport) by multiplying this factor by the amount of goods transported (tkm)

87326.2 tkm goods transport $\times$ 0.167$kg\ CO_2$ = 14596.4$kg\ CO_2$ eq
130989 tkm goods transport $\times$ 0.167$kg\ CO_2$ = 21894.39$kg\ CO_2$ eq

The transport emissions by LSP delivery trucks in urban and rural settings per parcel are (*also see Figure 19*):

$(14596.4kgCO_2)/(55*365*15)parcels = 0.0484kg\ CO_2$ eq

$(21894.39kgCO_2)/(55*365*15)parcels = 0.0726kg\ CO_2$ eq

ii. Results interpretation

This section will briefly reflect on the overall emissions, the most contributing phase towards the environmental impact and the comparison of PL system to HD.

Overall emissions

PL system in an urban setup (De pijp) where customer access them by walking or by biking has proven to be the most efficient PL setup while the PL system in a rural area (Ten Boer) is the least efficient PL setup as seen from Figure 19. In both the scenario the emissions are almost identical as emissions by biking are almost negligible.

It can be seen from results discussed in subsection i that there is some considerable difference in the climate change impact emissions of the two different setups considered in this study. The higher population density in urban areas often necessitates a higher density of PLs. This is also supported by literature as seen from section II where the PLs in an urban setup are more easily accessible than the one is rural areas. While the PL system in a rural setup where mode choice is bike has significantly higher emissions, the case where customers only use car has immensely high emissions.

PL in De Pijp are close to the PostNL sorting center chosen for this study being located only 25 kms away from the city in Westzaan. This results in significantly low LSP truck transport emissions accounting for about 28.5% in contrast to 53.1% of the total climate change impact emissions for PLs situated in rural area in case of bike. This is because the nearest PostNL sorting center to Ten Boer is located about 75 kms away from it in Hoogeveen. The difference in emissions of about 7.29 tonnes of CO_2 (or 7298.4 $kgCO_2$) is a result of more tkm of goods transported in rural areas causing more CO_2 emissions. Overall there can be a maximum possible reduction of about 66.6% emission reduction if the sorting centers that are setup to serve the demand of customers in Ten Boer have a similar distance to sorting centers from De Pijp. While for mode choice as car, the LSP transport emissions amount to only about 3.5%.

Most impacting phase and factor towards the environmental

As seen from subsection i, it is clear that 'use phase' (*see Figure 6*) for all the scenarios contribute to have the most effect on the climate change category. This can be accounted for the fact that the transport emissions by customers and LSPs for accessing PL location along with the electricity consumption in different life cycle phases of PL over the course of 15 years, results in significantly high emissions. *Electricity Consumption* in the use phase for the PL scenarios in urban setup are the most contributing factor accounting for about 48.3% of the total environmental impact consuming 13342 KWh of electricity its entire life cycle. While for PL system in rural setup where customer bike to PL locations, transport emissions by LSP are the most contributing factor (about 53.1%) towards the total emissions. Finally for PL system scenario in rural setup where customers use car to access PL locations, the transport emissions by customers are the most contributing factor (about 93.3%) towards the total emissions.

Mode choice

Location of PL system setup ultimately affects the way they are accessed by customers and thus affects their mode choice. As seen from previous literature in section II and from the case study conducted in this paper, the difference in total climate change impact in urban scenario when the customer bikes and when the customer walks to access the PLs is a mere 0.1 $kgCO_2$ according to the software which is negligible. This can be accounted for the fact that both biking and walking are very green ways of transport and high density of PL locations in an urban setup make this possible.

While in a rural setup, since the PL density is sparse, travelling by car becomes more convenient for the customer for collection of parcels at PL location as seen from previous literature in section II. However travelling by car causes significantly higher emissions as opposed to using a bike for accessing PL locations. Thus travelling by car in a rural PL system setup results in about 93.3% (289080 $kgCO_2$) in contrast to 7.04×10^{-4}% (0.1 $kgCO_2$) by bike of the total climate change impact emissions for PLs situated in rural area.

Transport emissions caused by LSPs in PL system vs HD

It is interesting to note that the no failed delivery assumption in subsection i, works against the PL system and is the best case scenario for HDs. Despite assuming the best case scenario for HDs and worst case scenario for PL system, the PL system performs better than the HD as can be seen from Figure 19. The only scenario where the PL system performs worse in the case where all the customers travel by car in order to access PLs. This is in tune with the findings from (De Maere. B, (2018) [23] where benefits of PLs are undone if the trip is made by car.

After seeing the results from subsection i (*see Figure 19*), it is clear that the transport emissions caused by the LSP trucks in case of HDs are higher when compared to a PL system. The overall emissions of the entire PL system are lower than HDs, except for the scenario when all the customers use car to access PL locations. This makes HD inefficient and thus have a higher carbon footprint in comparison to PL systems. The main reason for this is the amount of tonnes-km of goods transported between the two setups by the LSPs. This value is high in case of HD system as the courier delivery truck has to drive significantly more kms to deliver the same number of parcels during one delivery occasion. This includes the LSP trucks driving from sorting centers to urban and rural areas plus the additional distance to deliver each parcel as mentioned in subsection i.

Figure 20 compares the transport emissions of the LSPs in PL system and HDs. It can be seen that PL system in an urban setup can reduce about 74.9% of the emissions while about 49.9% of emissions in a rural setup per parcel. It is also interesting to note that the benefits in terms of $g\ CO_2$ reduction are somewhat similar in case of urban and rural areas. Although the percentage emissions reduction in urban areas is more as compared to rural areas, the amount of carbon footprint reduced is similar to about 36.3$g\ CO_2$ eq per parcel in case of PL systems.

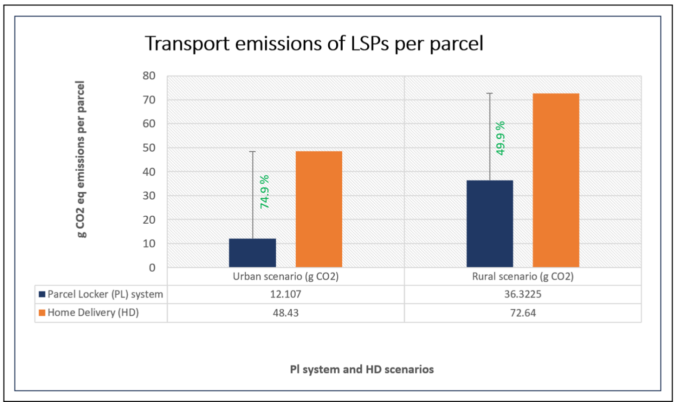


Fig. 20. *Stacked column chart representing the $KgCO_2$ eq emissions per parcel of the PL system and conventional HD in different scenarios*

Hence from carefully analyzing the PL system and HD setups as a last mile delivery, the analysis suggests that the installation of PLs in urban and rural areas yields significant environmental benefits in terms of transport emissions by LSPs. This can be attributed to the advantage in PL systems where the reduction in the VKT by the LSP parcel delivery trucks out benefits the customer travel to retrieve their parcels for last mile delivery operation. However, this gain in environmental impact is undone if all the trips are entirely made by car as seen in subsection i in the PL system rural scenario. Then the PL system performs worse in terms of $KgCO_2$ eq emissions per parcel owing to huge emissions by car travel on a daily basis.

iii. Sensitivity Analysis

In the base case scenario already discussed in this paper where all the external factors for both PL system and HD are same, it can be seen from subsection ii, how generally the PL system is more environment friendly and sustainable solution than the conventional HD as a last mile delivery. By means of sensitivity analysis that will be conducted in this section, a reflection on the effect of more sustainable practices in the future and convenience of the solution for PL distributors and also LSPs will be studied. Hence for this section of the paper, most insightful factors will be chosen and a sensitivity analysis would be conducted on them.

iv. Parameters selection

In this paper, one parameter each from the scenario and the system design factor will be chosen in order to carry out the sensitivity analysis:

- **Scenario factors**
  Scenario factors in the context of this paper refer to variables that characterize different scenarios or conditions under which the PL system of HDs function. These factors encapsulate various elements that can impact the overall environmental impact of the system. For instance, trip chaining implying that the customers can combine parcel delivery trip with other purposes which reflect the intricacies of real-world scenario.

  As previously mentioned in subsection i (*see section IV*), it is assumed that customer make dedicated trips to retrieve parcels, thus no trip chaining.

  - The *'Trip Chaining'*: Based on the study done by (De Maere. B, (2018) [23], it is assumed that the average extra travel distance the customers have to make when visiting PLs when trip chaining to be 0.75 kms

- **System design factors**
  System design factors encompass the specific attributes and configurations of the PL system itself. These factors shape the structure, efficiency, and environmental impact of the system. They include variables related to the physical aspects and operational setup of the PL infrastructure. For example, the energy consumption of PLs relates to the efficiency of energy use within the system. Analyzing this factors provides insights into how different configurations technological advancements in the system can influence its environmental performance and sustainability.

  As can be seen from results in subsection i, the factor contributing the most to the climate change environmental impacts of the PL system in the urban scenarios is the 'Electricity Consumption'.

- The *'Electricity consumption'* of PLs: It is assumed that in the future more energy efficient PLs will be designed. Thus a range of low, medium, and high energy consumption scenarios are considered.

iv.1. Scenario factor

Trip chaining

This scenario will affect the environmental impacts of PL system more in rural setup. The reason behind this is that walking and biking are very eco-friendly transport modes. Although the extra travel distance to access PLs during their trip chain would be less that a dedicated trip using these modes, the emissions caused by biking or walking can be considered negligible or zero. Hence trip chaining is only applied to the PL system in the rural setup where the emissions per km of car travel are significant and a reduction in distance to access PLs would consequently result in overall decreased environmental impact. The case where there is no trip chaining (i.e. dedicated trips by customer) is assumed to be the base case scenario. If the the collection of the parcel is combined with another activity, the point of interest is the extra distance and the transport mode used during that particular distance [23].

Table 5. *Sensitivity analysis: Trip chaining*

Scenario	Trip characteristic	Avg. customer travel distance by car
Scenario 1	Dedicated trip	5 km
Scenario 2	Trip chaining	0.75 km

It is assumed that the average extra travel distance the customers have to make when visiting PLs when trip chaining to be 0.75 kms, the same distance chosen based on the study by (De Maere. B, (2018) [23]. Similar to the emissions computation considering the customer travel emissions to PL location in rural area of Ten Boer via car, this is translated into in $g\ CO_2$ per parcel which now becomes:

$(192gCO_2/km \times 0.75kms of averaged riving distance) \times 365days \times 15years \times 55customers)/(55 * 365 * 15)parcels = 144g\ CO_2$ eq per parcel

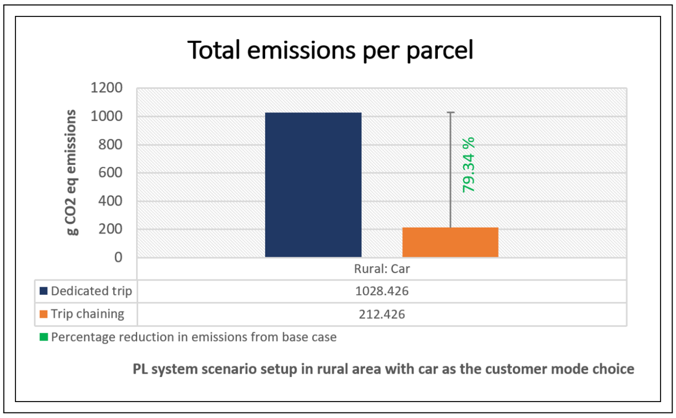


Fig. 21. *Scenario analysis: Average trip chaining distance of 0.75 km assumed*

Figure 21 shows that when trip chaining is considered, only the emissions caused by the customers are reduced in the entire PL system. Referring Figure 19, the emissions caused by LSPs and PL distributor remain the same, resulting the total PL system emissions for the rural setup where customers use car as their mode choice to be 212.426 $g\ CO_2$ eq per parcel. This results in 79.34% lower emissions per parcel in case of trip chaining. Thus it can be concluded that trip chaining is an important aspect of the PL system and can result in significant reduction of overall emissions per parcel.

iv.2. System design factors

Electricity consumption

This scenario will affect the PLs in both the rural and urban setups. It can be seen from subsection ii, this factor is most significant contributor towards the environmental impacts in PL systems in urban setting and also has a significant contribution in rural setting where customers use bike as their mode choice. Since the emissions in case of urban setting where mode choices are bike and walking are fairly similar, only the bike scenarios in urban and rural settings are chosen for this analysis. The PL system in rural setup where customer use cars is not considered here as electricity consumption makes up for a very small percentage of total emissions of that scenario. The case where the PL system consumes about 0.08 KWh electricity is assumed to be the base case scenario. Three scenarios are considered for conducting a sensitivity analysis, namely: Low; Medium and High as shown in Table 6.

Table 6. *Sensitivity analysis: Electricity consumption*

Scenario	Electricity consumption
Scenario 1	Low (0.03 KWh)
Scenario 2	Medium (0.05 KWh)
Scenario 3	High (0.1 KWh)

As seen previously from the conceptual model, most PL systems have an electricity consumption of around 80-100 watts per hour. The base case that is also modelled into this case study is an electricity consumption of 80 watts per hour. For high PL electricity consumption scenario, it is assumed that all the components are in use and the PL consumes 100 watts per hour. For medium PL electricity consumption scenario, it is assumed that only the necessary components the PL are in use to have more efficient operation than the base case scenario while not compromising parcel safety. Hence an electricity consumption of 50 watts per hour is assumed for the medium scenario. Finally, for low PL electricity consumption scenario, it is assumed that due to future development in technology, a highly efficient operation of PL takes place resulting in electricity consumption of 30 watts per hour.

It is observed from Figure 22 that for the assumed scenario when the PL consumes only 0.03 KWh of electricity due to an assumed efficient production of PL by their distributors in future, emissions reduction can range from anywhere between 18.04% to 30%. This could result in up to 3.84 *tonnes* of CO_2 emission reduction in the PL system life cycle.

Similarly when the electricity consumption if reduced from 0.08 Kwh to 0.05 KWh due to efficient operation by only use of necessary components for PL without compromising its intended use and safety, the resulting emissions by the PL system results in emission reduction from a minimum of 11.19% to a maximum of 18%. This results in

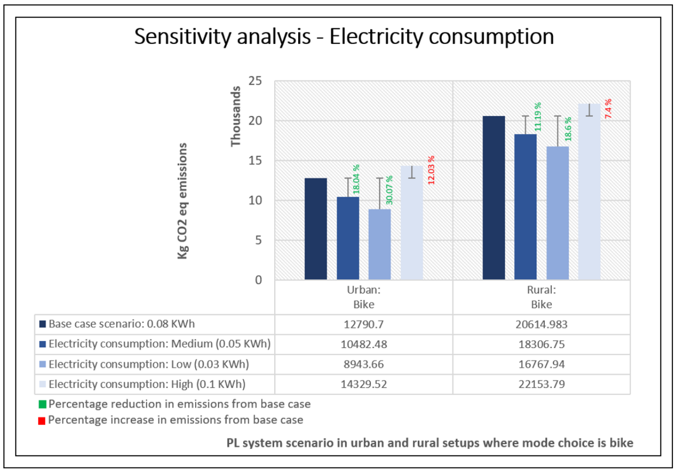


Fig. 22. *Sensitivity Analysis: Electricity consumption with Low, Medium and High scenarios*

2.3 *tonnes* of CO_2 reduction that is produced less during the life cycle of the PL system. Finally for the case where all the components and auxiliaries of the PL are in complete use, the resulting electricity consumption is assumed to be 100 watts per hour which results in increased emissions by up to 7.4%-12%. This accounts for an increase of 1.53 *tonnes* of CO_2 emissions.

The scenario where PL uses 0.03 KWh electricity may be possible but would require a significant technological advancement. Hence, it can be concluded that the scenario where the PL consumes 0.05 KWh of electricity proves to be more beneficial as compared to other scenarios due to its assumed feasibility for a short time horizon in the future.

VI. LIMITATIONS

While the LCA provides valuable insights into the environmental impact of the PL system, it is essential to acknowledge the limitations that might have influenced the study's outcomes. Firstly, the availability and accuracy of data used in the assessment, since the reference data is extrapolated to make it suited to this case study could impact the reliability of the results.

The lack of comprehensive and up-to-date data on certain life cycle stages might have introduced uncertainties as the data is referenced from an EPD report for a different model of locker. Moreover, the scope of the study might has been limited to specific geographical areas in the Netherlands. Certain aspects of the PL system, like the assumed customer order frequency which might affect their PL usage behaviour might affect the accuracy of results and potentially influence the generalisation of the findings. Additionally trip combining by customer for parcel retrieval is also not considered in the scope of this study.

Finally the assumptions made during the LCA where a base case scenario is developed keeping the external factors constant could also affect the accuracy of the results. Some of the factors (see subsection i) were not included in the case study, either due to lack of data on them or due to the complexity of implementing them in the software. It is vital to recognize and transparently address these limitations to provide a comprehensive perspective on the environmental impact of PL systems.

VII. CONCLUSIONS & FUTURE RESEARCH

This marks the final chapter of this paper which, first starts by concluding the core findings and presenting the crux of this study in subsection i. It is then followed by subsection ii which explores the underlying meaning of this research and its possible implications in other areas of study. Finally it also reflects on the limitations and the possible improvements that can be made i the future, in order to further develop the of quality of research or an interesting research gap.

i. Conclusion

The emergence of PLs as an innovative solution to address the challenges of conventional home deliveries presents a dynamic opportunity for redefining the efficiency and sustainability of logistics networks. However, as this technology gains traction it is essential to recognize that this new paradigm also brings about a range of environmental emission implications across various stages of its life cycle.

The aim of this paper is to therefore address this research gap by employing LCA, a systematic and holistic approach is adopted to assess the overall environmental performance of PL systems. This approach takes into account the different life cycle stages, the inputs and outputs involved, and the potential environmental impacts associated with each stage.

The study begins initially by analyzing the different ways in which the PL system can be setup through previous works in the literature. Consequently an urban and a rural setting in which the PL system can be setup are determined. The locations chosen for the urban and rural settings are De Pijp and Ten Boer respectively. Additionally important factors that influence the use of PLs are studied. It can be concluded that PL location and customer mode choice are the most crucial factors when it comes to utilizing the PL system as it affects the customer mobility behaviour and ultimately the environmental impact of PL systems. Based on this review, a conceptual model is developed by means of a system diagram that helps determine the potential environmental impacts of PL system and conventional HDs. Consequently the conceptual model leads to the potential environmental impacts in form of various emissions caused by the actors in PL system and HDs. The Global Warming Potential (GWP) indicator is selected for this study and the emissions are expressed in $KgCO_2$-eq and gCO_2-eq per parcel. Finally, the potential impacts of the PL systems through a full LCA are quantified. This includes the different life cycle phases of the PL system and its setting in an urban and a rural area.

It is found that the PL systems are most efficient in urban areas owing to use of green mobility ways by customers and reduced VKT by LSPs. Electricity consumption by the PLs in urban area is the 'hot-spot' or the most negatively impacting phase of the PL system accounting for 48.3% of total emissions while for rural setup where customer bike to PL location have the LSP transport emissions as the highest. Finally it is seen that customer travel causes most emissions when they travel to PL locations by means of a car.

The research is extended further by comparing the transport emissions caused by LSPs (*transport emissions*) in PL system to HDs. It is concluded that the PL systems are generally beneficial and produce up to 49.9% less CO_2 emissions in rural setup (12.1 g CO_2 eq per parcel for PLs compared to 48.43 g CO_2 eq per parcel for HDs) and 74.9% less CO_2 emissions per parcel in urban setup (36.3 g CO_2 eq per parcel for PLs compared to 72.6 g CO_2 eq per parcel for HDs) over a life cycle time of 15 years considered in this study. However, it is evident from the case study that overall PL system performs worse only in the case where all the customers travel by car in order to access PLs.

Finally, a sensitivity analysis on scenario and system design factors is conducted to gain insights into the effects of most impactful factors and more sustainable practices in the future. It can be concluded that trip chaining can result in reduced emissions by up to 79.34% due to reduced overall extra distance to travel to PL locations by the customers. Only the extra detour distance is considered which result in fairly low emissions per parcel. In future where less energy is consumed by PLs due to possible policy regulations or technological advancements, can results in about 18.04%-30% emissions reduction.

Overall, it can be concluded that PLs can offer a convenient, efficient, and sustainable solution for package delivery, given that the transport used by customer is green (either walk or bike) and they combine trips as much as possible. This will benefit both recipients and delivery service providers by decreasing number of failed deliveries and emissions from delivery vehicles.

ii. Future recommendations

To advance the understanding of the environmental impact of PL systems and promote sustainable logistics practices, several future recommendations arise from this research. First and the most important being conducting more extensive data collection and collaborating with key stakeholders, such as LSPs and PL distributors, can enhance the accuracy and reliability of the LCA results.

Although a lot of research and surveys exist on customer preference when it comes to usage of PLs, it is recommended to have an additional customer stated choice survey to enhance the quality of the results and make the research more relevant to this specific case study based on geographical factors as well. This will especially help gain detailed insights how customers access the PL network either through dedicated trips or combining trips.

It is recommended to include aspects such as failed delivery rates, trip chaining and customer order patterns in the base case or initial stages of similar research in the future. Future research should also consider expanding the scope of the study to include broader geographical regions and different types of PL systems to capture a more diverse representation of their environmental impacts. Integrating social and economic dimensions into the LCA can provide a more holistic assessment, considering the overall sustainability of the PL system. Furthermore, exploring innovative technologies and renewable energy sources to power the PLs could contribute to further reducing the system's environmental footprint. Nonetheless, the environmental impacts of PL system are only one aspect of this new last mile delivery innovation. To fully assess the overall impact of PL systems in a large geographical location or a country, additional research is needed to investigate other implications that are related to PL systems.

REFERENCES

1. I. P. Corporation, "Cross-border e-commerce shopper survey 2022," (2023).
2. E. Molin, M. Kosicki, and R. van Duin, "Consumer preferences for parcel delivery methods: the potential of parcel locker use in the netherlands," ejtir **2022**, 2–6427 (2022).
3. Y. Deutsch and B. Golany, "A parcel locker network as a solution to the logistics last mile problem," Int. J. Prod. Res. **56**, 251–261 (2018).
4. M. Peppel and S. Spinler, "The impact of optimal parcel locker locations on costs and the environment," Int. J. Phys. Distribution & Logist. Manag. (2022).
5. N. Boysen, S. Fedtke, and S. Schwerdfeger, "Last-mile delivery concepts: a survey from an operational research perspective," Or Spectr. **43**, 1–58 (2021).
6. J. Allen, M. Piecyk, M. Piotrowska, F. McLeod, T. Cherrett, K. Ghali, T. Nguyen, T. Bektas, O. Bates, A. Friday *et al.*, "Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas: The case of london," Transp. Res. Part D: Transp. Environ. **61**, 325–338 (2018).
7. R. Gevaers, E. Van de Voorde, and T. Vanelslander, "Characteristics and typology of last-mile logistics from an innovation perspective in an urban context," in *City distribution and urban freight transport,* (Edward Elgar Publishing, 2011).
8. G. Waterland, "First postnl parcel machine in the municipality of waterland," (2022).
9. PostParcel, "Inpost to increase its parcel locker network," (2022).
10. C. Wohlin, "Guidelines for snowballing in systematic literature studies and a replication in software engineering," in *Proceedings of the 18th international conference on evaluation and assessment in software engineering,* (2014), pp. 1–10.
11. M. Schnieder, C. Hinde, and A. West, "Sensitivity analysis of emission models of parcel lockers vs. home delivery based on hbefa," Int. J. Environ. Res. Public Heal. **18** (2021).
12. M. Giuffrida, R. Mangiaracina, A. Perego, A. Tumino *et al.*, "Home delivery vs parcel lockers: an economic and environmental assessment," Proc. 21thSummer Sch. Francesco Turco, Naples, Italy pp. 13–15 (2016).
13. G. Lyu and C. Teo, "Last mile innovation: The case of the locker alliance network," (2021).
14. Y.-T. Tsai and P. Tiwasing, "Customers' intention to adopt smart lockers in last-mile delivery service: A multi-theory perspective," J. Retail. Consumer Serv. **61**, 102514 (2021).
15. A. Seghezzi, C. Siragusa, and R. Mangiaracina, "Parcel lockers vs. home delivery: a model to compare last-mile delivery cost in urban and rural areas," Int. J. Phys. Distribution & Logist. Manag. (2022).
16. V. Gatta, E. Marcucci, M. Nigro, S. M. Patella, and S. Serafini, "Public transport-based crowdshipping for sustainable city logistics: Assessing economic and environmental impacts," Sustainability. **11** (2019).
17. S. Schwerdfeger and N. Boysen, "Who moves the locker? a benchmark study of alternative mobile parcel locker concepts," Transp. Res. Part C: Emerg. Technol. **142**, 103780 (2022).
18. M. Prandtstetter, C. Seragiotto, J. Braith, S. Eitler, B. Ennser, G. Hauger, N. Hohenecker, R. Schodl, and M. Steinbauer, "On the impact of open parcel lockers on traffic," Sustainability. **13** (2021).
19. J. Lemke, S. Iwan, and J. Korczak, "Usability of the parcel lockers from the customer perspective – the research in polish cities," Transp. Res. Procedia **16**, 272–287 (2016). The 2nd International Conference "Green Cities - Green Logistics for Greener Cities", 2-3 March 2016, Szczecin, Poland.
20. J. van Duin, B. Wiegmans, B. van Arem, and Y. van Amstel, "From home delivery to parcel lockers: a case study in amsterdam," Transp. Res. Procedia **46**, 37–44 (2020). The 11th International Conference on City Logistics, Dubrovnik, Croatia, 12th - 14th June 2019.
21. H. T. Pham and H. Lee, "Analyzing the costs and benefits of installing unmanned parcel lockers: Focusing on residential complexes in korea," J. Int. Logist. Trade **17**, 43–54 (2019).
22. I. A. Mitrea, G. Zenezini, A. De Marco, F. M. Ottaviani, T. Delmastro, and C. Botta, "Estimating e-consumers' attitude towards parcel locker usage," in *2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC),* (2020), pp. 1731–1736.
23. B. De Maere, "Economic and ecological impact of automated parcel lockers vs home delivery." Ph.D. thesis (2018).
24. L. Faugere and B. Montreuil, "Hyperconnected pickup & delivery locker networks," in *Proceedings of the 4th International Physical Internet Conference,* vol. 6 (2017), pp. 1–14.
25. A. Ranjbari, C. Diehl, G. Dalla Chiara, and A. Goodchild, "What is the right size for a residential building parcel locker?" Transp. Res. Rec. **2677**, 1397–1407 (2023).

26. A. Jeroschewski, "How parcel lockers will transform last mile delivery (a parcel perform perspective)," (2019).
27. K. Hofer, S. Flucher, M. Fellendorf, M. Schadler, and N. Hafner, "Estimation of changes in customer's mobility behaviour by the use of parcel lockers," Transp. Res. Procedia **47**, 425–432 (2020). 22nd EURO Working Group on Transportation Meeting, EWGT 2019, 18th – 20th September 2019, Barcelona, Spain.
28. Lisa, "Features and benefits of parcel lockers," (2020).
29. M. A. Buser, "Willingness to use parcel lockers. a comparative case study of groningen and ten boer." Ph.D. thesis (2021).
30. B. Van Wee, "The traffic and transport system and effects on accessibility, the environment and safety: an introduction," The transport system transport policy. An introduction pp. 4–16 (2013).
31. G. Wee, J. Annema, and D. Banister, eds., *The transport system and transport policy: An introduction* (Edward Elgar Publishing, United Kingdom, 2013), pp. 101–124.
32. E. I. AB, "Environmental product declaration - lockers," (2020).
33. S. Gonzales, "How much co2 does a car emit per mile: List by type, size, energy source," (2023).
34. A. industrial automation, "Exploring the advantages of outdoor parcel lockers with solar panels," (2023).
35. M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life cycle assessment* (Springer, 2018).
36. PostNL, "Locationfinder," Retrieved on 12th of June from:.
37. PostNL, "Postnl opens up parcel lockers," (2022).
38. PostNL, "Locationfinder," Retrieved on 12th of June from:.
39. N. Mikosch, T. Dettmer, B. Plaga, M. Gernuks, and M. Finkbeiner, "Relevance of impact categories and applicability of life cycle impact assessment methods from an automotive industry perspective," Sustainability **14**, 8837 (2022).
40. S. Iwan, K. Kijewska, and J. Lemke, "Analysis of parcel lockers' efficiency as the last mile delivery solution–the results of the research in poland," Transp. Res. Procedia **12**, 644–655 (2016).
41. "Postnl sorting centers – a complete list," (2023).
42. PostNL, "Postnl reveals new automated parcel locker in collaboration with retailer jumbo," (2021).
43. PostNL, "Postnl opens a sustainable parcel sorting center in hoogeveen," (2023).
44. F. R. Pierre-Louis Ragon, "Co2 emissions from trucks in the eu: An analysis of the heavy-duty co2 standards baseline datas," (2021).

Appendix

Locker type	*Specifications*	*Surface Area = 2(L*W + L*H + W*H)*
Reference Locker (SteelCase)	Height: 1645mm Depth: 450mm Width: 1200mm; 3 columns	Surface Area = 6508500.000 mm^2
Locker considered in this case study	Height: 2006.6mm Depth: 609.6mm Width: 3657.6mm; 4 columns	Surface Area = 21584472.960 mm^2
		Ratio = 3.3

Fig. 23. *Surface Area calculation and their ratio in order to obtain the multiplication factor for materials required*

<u>About 75 % of parcels weigh less than 2 kg:</u>

Hence 0.75 * 2 kg (assumed) = 1.5 kgs

<u>About 25 % more than 2 kg (also keeping in mind medium and large cells in the PL):</u>

Hence 0.25 * 5.5 kg (assumed) = 1.37 kgs

<u>Hence, average parcel weight:</u>

1.5 + 1.37 = 2.87 ~ ***2.9 kgs***

Fig. 24. *Average parcel weight calculation based on literature review and self assumption*

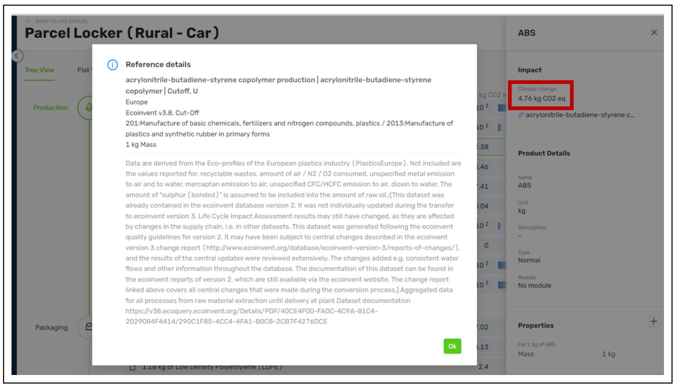


Fig. 25. *Climate change impact category in kg CO_2 equivalent (4.76 kg CO_2 eq) from production of 1 kg of acrylonitrile-butadiene-styrene (ABS) copolymer that is used in the parcel locker production*

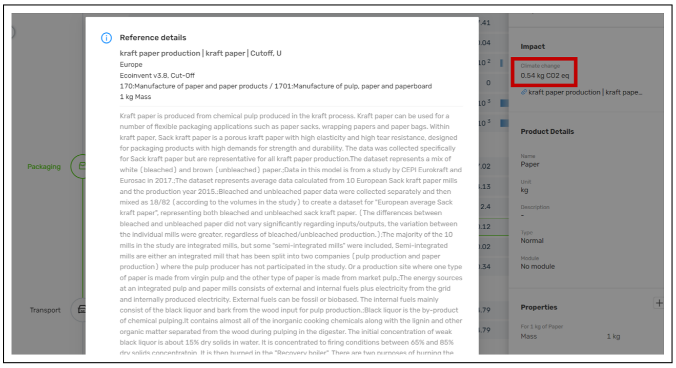


Fig. 26. *Climate change impact category in kg CO_2 equivalent (0.54 kg CO_2 eq) from production of 1 kg of Kraft paper that is used in the parcel locker packaging*

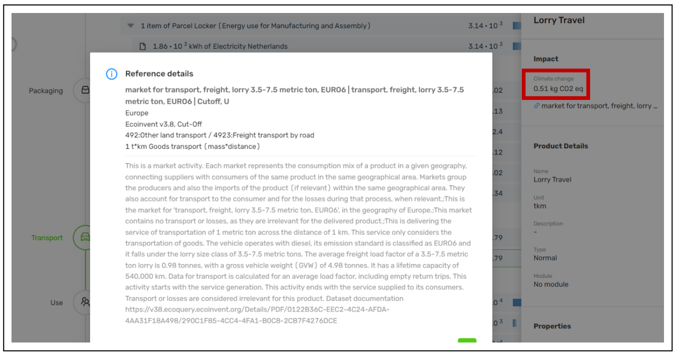


Fig. 27. *Climate change impact category in kg CO_2 equivalent (0.51 kg CO_2 eq) from transport of 1 tkm of PL transport from distributor to installation location*

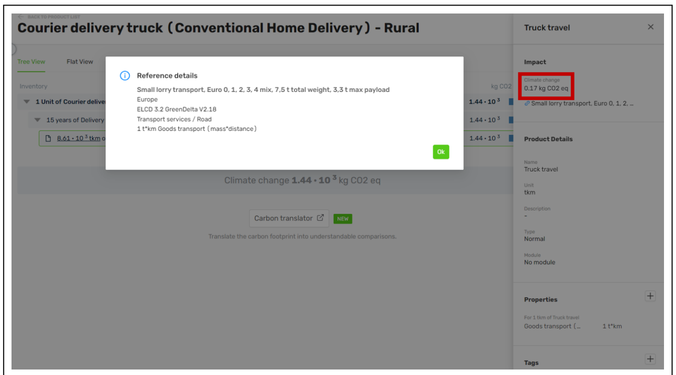


Fig. 28. *Climate change impact category of LSP courier delivery truck travel in kg CO_2 equivalent (0.167 kg CO_2 eq) from transport of 1 tkm of parcels transport*

B

Environment Product Declaration report

This section shows the Environment Product Declaration (EPD) of a company called Steelcase based in Madrid, Spain. This EPD report is used as a reference for the PL considered in this case study [1].

Environmental Product Declaration

EPD®

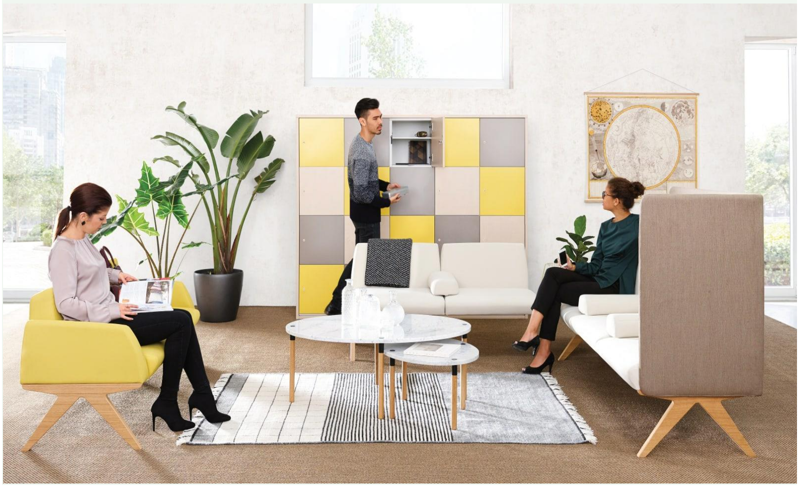
In accordance with ISO 14025 for:

4FH Universal lockers (3 columns)

from

Steelcase

Programme:	The International EPD® System, www.environdec.com
Programme operator:	EPD International AB
EPD registration number:	S-P-02392
Publication date:	2020-11-26
Revision date:	2022-06-03
Valid until:	2025-02-28



Steelcase EPD®

Programme information

Programme:	The International EPD® System EPD International AB Box 210 60 SE-100 31 Stockholm Sweden www.environdec.com info@environdec.com

Product category rules (PCR): *PCR 2012-19, Furniture, except seats and mattresses. Validity until 17-06-2023. Version 2.01, UN CPC 3812 /3813 /3814*
PCR review was conducted by: *Technical committee of the International EPD Gorka Benito Alonso. The review panel may be contacted via info@environdec.com*
Independent third-party verification of the declaration and data, according to ISO 14025:2006: ☒ EPD process certification ☐ EPD verification
Third party verifier: Tecnalia R&I Certificación is an approved certification body accountable for third-party verification *In case of accredited certification bodies:* Accredited by: ENAC, accreditation no. 125/C-PR283 *In case of recognised individual verifiers:* Approved by: The International EPD® System
Procedure for follow-up of data during EPD validity involves third party verifier: ☐ Yes ☒ No

The EPD owner has the sole ownership, liability, and responsibility for the EPD. EPDs within the same product category but from different programmes may not be comparable.

Steelcase EPD®

Company information

Owner of the EPD:
AF Steelcase S.A.
Calle Antonio Lopez,243
28041 - Madrid, Spain
Phone: +34912124700
Email: afinfo@steelcase.com

Description of the organisation:

At its heart, sustainability at Steelcase is about people. It's about creating and supporting the economic, environmental and social conditions that allow people and communities to reach their full potential.

Research and insights direct our path. It's not only about creating goods, it's about creating good. It's not only about creating value, it's about living our values. It's not just about reducing our footprint, it's about expanding our reach. It's about creating lasting and meaningful change to enable the long-term wellbeing of current and future generations.

Innovative products and solutions result. In the development of our products, we work to consider each stage of the life cycle: from materials extraction, production, transport, use and reuse, until the end of its life. We demonstrate performance through third-party verified certifications, such as ISO 9001, ISO 14001, ISO 14006, PEFC, FSC® (FSC-C003932), and voluntary product declarations.

Steelcase's sustainability promises, actions, and results are communicated in an annual Corporate Sustainability Report.

Product information

Product name: 4FH Universal lockers (3 columns)

Product identification: LOC4F1200

Production site: This product is manufactured in Steelcase Madrid (Madrid, Spain).

Product description: Perfectly suited for shared spaces, Universal lockers are great for mobile workers and visitors. With a wide variety of heights and widths,Universal suits any space. Easily create an open meeting space with Universal lockers that cater to collaboration. Whiteboards and pinnable surfaces display and share work to boost team identity and creativity.

Height: 1645mm
Depth: 450mm
Width: 1200mm
Number of columns: 3

UN CPC code: 38121 - Other metal furniture, of a kind used in offices

Geographical scope: Spain

LCA information

Functional Unit	Consists in one 4FH Universal lockers (3 columns) in use for 8 hours a day, 5 days a week, for 15 years.
Source(s) of data	All information about manufacturing processes has been supplied directly by internal data of Steelcase Madrid. The Information about raw materials/components and distances has been supplied directly by our suppliers. All raw materials and components are transported by road.
Reference year for data	2019
LCA Software/ database(s) used	SimaPro v9.1.0.11 multiuser / Ecoinvent 3.6 Database
Exclusions	No exclusions were made
Assignment rules	In this study was considered necessary to perform a phyisical assignment (in fuction of produced units) for water, oil, natural gas, water, and electricity consumptions.
System boundaries	System boundaries include raw materials and components, production (includes processes and facilities maintenance), transport, packaging, distribution, use and end of life, both for the product and for its packaging.
System Scope	System's scope includes the whole life cycle of the product, from obtained raw materials to manufacturing, use and end of life. System is divided in 3 stages: • **UPSTREAM:** Includes components, raw material obtention and their associated manufacturing processes. • **CORE:** Includes transportation of raw materials and components from our suppliers to Steelcase Madrid, product manufacturing processes and waste treatment. • **DOWNSTREAM:** Includes clients shipping, products maintenance, product use and end of life, both for the product and for packaging.

Steelcase EPD®

Upstream

- Components/Raw Materials obtention
- Manufacturing Processes

Core

- Raw materials/components transportation
- Product manufacturing processes
- Waste treatment
- Electricity
- Natural Gas
- Water
- Manteinance

Downstream

- Distribution
- Manteinance
- Product's use
- Product's end of life
- Packaging's end of life

This document has been created contemplating environmental impacts of raw materials and components, their transport and multiple transformation and manufacturing processes, treatment of generated wastes as well as the final product distribution to the customer and the end of life of the product and its packaging.

Steelcase EPD®

Content declaration

Product

Materials	Weight (kg)	% of total weight	% Recycled content
ABS	0,1506	0,13%	15,47%
Steel	108,0823	94,07%	17,37%
Aluminium	0,4410	0,38%	0,00%
Paint	3,2219	2,80%	0,00%
PP	0,0062	0,01%	0,00%
ZAMAK	1,1770	1,02%	50,00%
TOTAL	**113,0789**	**98,42%**	**17,15%**

Packaging

Materials	Weight (kg)	% of total weight	% Recycled content
Cardboard	1,3266	1,15%	100,00%
LDPE	0,3610	0,31%	4,27%
Paper	0,0705	0,06%	0,00%
PE	0,0032	0,00%	45,00%
PP	0,0515	0,04%	0,00%
TOTAL	**1,8128**	**1,58%**	**74,11%**

Steelcase strives to be more environmentally friendly, therefore neither the product nor the packaging contains any substance on the REACH candidate list, nor any mixture classified in Regulation (EC) 1272/2008. In addition, within our organization a scrupulous protocol is carried out to check that all substances and materials comply with the standards of our organization.

Recycled material

Item	Recycled content	Pre-consumer	Post-consumer
Packaging	74,11%	0,88%	73,23%
Product	17,15%	13,39%	3,76%
TOTAL (Packaged product)	**18,04%**	**13,19%**	**4,85%**

Steelcase EPD®

Environmental performance

Potential environmental impact

PARAMETER		UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Global warming potencial (GWP)	Fosil	KgCO2 eq.	5,08E+02	1,10E+02	2,65E+01	6,44E+02
	Biogenic	KgCO2 eq.	7,35E+00	1,40E-01	1,54E-03	7,49E+00
	Land use and land transformation	KgCO2 eq.	3,65E-01	5,85E-02	2,74E-04	4,24E-01
	TOTAL	KgCO2 eq.	5,15E+02	1,10E+02	2,65E+01	6,52E+02
Acidification potential (AP)		KgSO2 eq.	2,27E+00	1,73E+00	1,13E-01	4,11E+00
Eutrophication potencial (EP)		KgPO43- eq.	1,36E+00	9,97E-02	1,82E-02	1,47E+00
Formation potencial of tropospheric ozone (POCP)		kg NMVOC eq.	2,08E+00	2,04E-01	1,59E-01	2,44E+00
Abiotic depletion potential - elements		KgSb eq.	9,68E-02	1,03E-04	1,90E-06	9,69E-02
Abiotic depletion potential - fosil fuels		MJ, net calorific value	5,42E+03	1,52E+03	3,75E+02	7,32E+03
Water scarcity potential		m3 eq.	1,16E+02	2,03E+01	1,97E+00	1,38E+02

Use of resources

PARAMETER		UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Primary energy resources – Renewable	Use as energy carrier	MJ, net calorific value	6,28E+02	1,49E+02	6,53E-01	7,78E+02
	Used as raw materials	MJ, net calorific value	5,980E+01	0,00E+00	0,00E+00	5,98E+01
	TOTAL		6,88E+02	1,49E+02	6,53E-01	8,37E+02
Primary energy resources – Non-renewable	Use as energy carrier	MJ, net calorific value	6,32E+03	1,88E+03	3,76E+02	8,58E+03
	Used as raw materials	MJ, net calorific value	5,98E+01	0,00E+00	0,00E+00	5,98E+01
	TOTAL		6,38E+03	1,88E+03	3,76E+02	8,64E+03
Secondary material		kg	2,48E+01	NA	NA	2,48E+01
Renewable secondary fuels		MJ, net calorific value	NA	NA	NA	0,00E+00
Non-renewable secondary fuels		MJ, net calorific value	NA	NA	NA	0,00E+00
Net use of fresh water		m^3	NA	1,06E-02	1,00E-01	1,11E-01

Steelcase EPD®

Waste production and output flows

Waste production

PARAMETER	UNIT	UPSTREAM	CORE	DOWNSTREAM	*TOTAL*
Hazardous waste disposed	kg	3,89E-02	1,98E-03	1,15E-03	4,20E-02
Non-hazardous waste disposed	kg	1,56E+02	2,42E+00	4,57E+00	1,63E+02
Radioactive waste disposed	kg	2,17E-02	6,64E-03	2,73E-03	3,11E-02

Output flows

PARAMETER	UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Components for reuse	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Material for recycling	kg	0,00E+00	2,35E+01	1,12E+02	1,35E+02
Materials for energy recovery	kg	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Exported energy, electricity	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Exported energy, thermal	MJ	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Other environmental indicators

PARAMETER	UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Human toxicity, cancer impacts	Cases	2,16E-04	4,93E-06	5,66E-08	2,21E-04
Human toxicity, non-cancer impacts	Cases	2,29E-04	8,78E-06	8,09E-07	2,39E-04
Fresh water ecotoxicity	PAF m^3 day	3,05E+07	2,35E+05	9,36E+03	3,07E+07
Land use	Species.yr	7,47E-08	3,10E-08	1,13E-10	1,06E-07

C

Life Cycle Assessment methodology

As shown in Figure C.1, the LCA begins by defining the goal of this study which sets the context of this study followed by scope definition in which the assessment is framed in accordance of goal. This is followed by scoping of the system, selecting assessment parameters and defining systems boundaries of the PL system. The following step of inventory analysis means collecting all the data relevant to this study. For this specific reason a system boundary is defined as shown in Figure 2.2 to make it clear which processes are included in this study. Impact Assessment translates the physical flows and interventions of the product system into impacts on the environment using knowledge and models from environmental science. The final step of LCA entails interpretation of both results of the inventory analysis and the impact assessment elements characterisation and, possibly, normalisation and weighting in order to answer the goal of the study.

The LCA can also be related to the concept of circularity and help organizations take measures towards it. Circular initiatives reduce material, energy use, and emissions in the system. This indicator is attained by means of Life Cycle Assessment(LCA) methodology which assesses the environmental performance of a product or system throughout its life-cycle[3] and a consequent a LCIA (Life Cycle Impact Assessment) will be done. Impact Assessment translates the physical flows and interventions of the product system into impacts on the environment using knowledge and models from environmental science. The final step of LCA entails interpretation of both results of the inventory analysis and the impact assessment elements characterisation and, possibly, normalisation and weighting in order to answer the goal of the study.

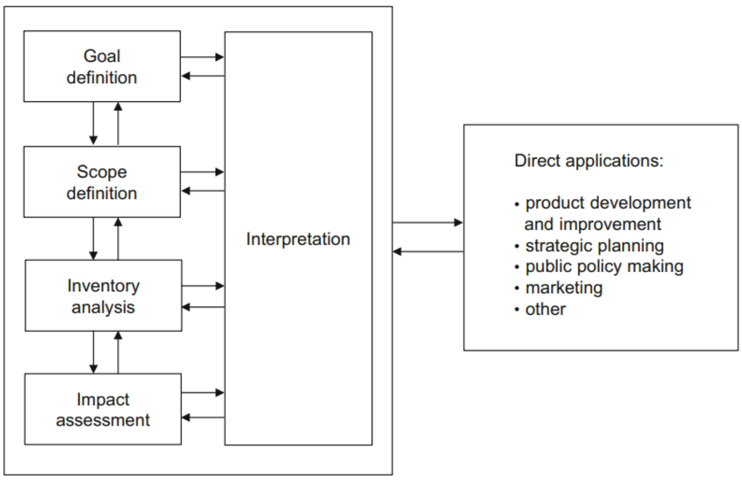


Figure C.1: *LCA Framework*

C.1. Data Acquisition

Life-cycle phases in terms of parcel journey ranging from their presence at 'PL locations' to 'customer home' along with different sub-phases are defined for parcel lockers[3]. Literature research on all the remaining aspects that are not included in EPD will be conducted to know more about the different parameters of the "production" until "end of life" of parcel lockers. Consequently this will be followed be a customer travel analysis, by reviewing already existing literature on mode choice, emissions and preference.

C.2. Data Processing:

1. Processing of data begins with the actual collection of all the data related to the "production" of PL service followed by its evaluation caused from the input data determined in subsection 2.3.3. This process is also known as Life Cycle Inventory(LCI) which is necessary to conduct a life cycle assessment (LCA) of PL service. Data about *"production"* which entails information on the all the materials required for construction. The scope of this study will be from cradle to grave while discussing all the relevant phases of life.

Figure C.2: *Life Cycle phases of the PL system*

2. The characterization of emissions into impact categories can be used to quantify the ability of each of the assigned elementary flows to impact the indicator of the category. Thus for this, characterization of emission data into impact categories takes place which is based on complex scientific models which take into account the emissions to air, water, and soil, and a number of substance properties such as biodegradability, volatility, solubility, toxic mechanisms etc[19]. The resulting characterised impact scores are expressed in a common metric for the impact category. All the necessary and relevant environment effects will be interpreted in the following steps.

Environmental impact Indicators	Description
Climate change - overall	Degree to which objects or sub-objects contribute to climate change
Climate change - fossil	Degree to which objects or sub-objects contribute to climate change due to the use of fossil fuels
Climate change - biogenic	Degree to which objects or sub-objects contribute to climate change due to the use of plant-based materials
Climate change - use of land and changes in use of land	Degree to which objects or sub-objects contribute to climate change due to the use of land and changes in the use of land
Ozone depletion	Degree to which objects or sub-objects contribute to the depletion of the ozone layer
Acidification	Degree to which objects or sub-objects contribute to the acidification of soil or water
Eutrophication - freshwater	Degree to which objects or sub-objects contribute to enriching freshwater with nitrogen and phosphorus
Eutrophication - seawater	Degree to which objects or sub-objects contribute to enriching seawater with nitrogen and phosphorus
Over-fertilization - soil	Degree to which objects or sub-objects contribute to enriching soil with nitrogen and phosphorus
Occurrence of smog	Degree to which objects or sub-objects contribute to the formation of tropospheric ozone (part of smog)
Depletion of abiotic raw materials - minerals and metals	Degree to which objects or sub-objects contribute to the depletion of abiotic raw materials, excluding fossil energy carriers
Depletion of abiotic raw materials - fossil energy carriers	Degree to which objects or sub-objects contribute to the depletion of fossil energy carriers
Use of water	Degree to which objects or sub-objects contribute to the depletion of the sources of water
Emission of particulate matter	Degree to which objects or sub-objects contribute to diseases related to particulate matter
Ionizing radiation	Degree to which objects or sub-objects contribute to humans being exposed to ionizing radiation
Ecotoxicity (freshwater)	Degree to which objects or sub-objects contribute to adverse toxicological effects for freshwater organisms

Figure C.3: *Environmental impact categories[3]*

3. This is followed by Impact Assessment in which all the relevant impacts are evaluated for the differing PL system setups.

Impact category	Unit
Depletion of abiotic raw materials (excluding fossil energy carriers) ADP	kg sb eq.
Depletion of fossil energy carriers ADP	kg sb eq eq.
Global Warming Potential (GWP)	kg CO2 eq.
Ozone layer depletion (ODP)	kg CFC-11 eq.
Photochemical oxidant formation POCP	kg C2H4 eq.
Acidification (AP)	kg SO2 eq.
Fertilization (EP)	kg PO4 eq.
Human Toxicity (HTP)	kg 1,4-DCB eq.
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DCB eq.
Marine Aquatic Ecotoxicity (MAETP)	kg 1,4-DCB eq.
Terrestrial Ecotoxicity (TETP)	kg 1,4-DCB eq.

Figure C.4: *Environmental impact categories[3]*

4. The final step is the interpretation of the impact assessment where most reliable conclusions and recommendations are made as shown in Figure C.5.

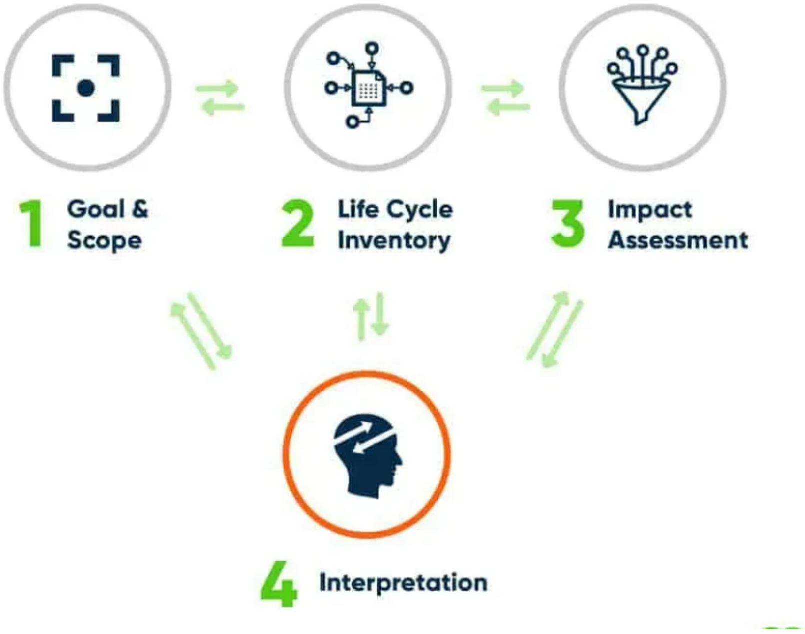


Figure C.5: *Overview for conducting LCA[17]*

D

Calculations & reference data for Case Study

About 75 % of parcels weigh less than 2 kg:

Hence 0.75 * 2 kg (assumed) = 1.5 kgs

About 25 % more than 2 kg (also keeping in mind medium and large cells in the PL):

Hence 0.25 * 5.5 kg (assumed) = 1.37 kgs

Hence, average parcel weight:

1.5 + 1.37 = 2.87 ~ ***2.9 kgs***

Figure D.1: *Average parcel weight calculation based on literature review and self assumption*

Locker type	*Specifications*	*Surface Area = 2(L*W + L*H + W*H)*
Reference Locker (SteelCase)	Height: 1645mm Depth: 450mm Width: 1200mm; 3 columns	Surface Area = 6508500.000 mm^2
Locker considered in this case study	Height: 2006.6mm Depth: 609.6mm Width: 3657.6mm; 4 columns	Surface Area = 21584472.960 mm^2
		Ratio = 3.3

Figure D.2: *Surface Area calculation and their ratio in order to obtain the multiplication factor for materials required*

Locker type	Specifications	Total number of hours in use
Reference Locker (SteelCase)	8 hours use per day for 5 days a week for 15 years	(8 hours * 5 days * 52 weeks * 15 years) = 31200 hours
Locker considered in this case study	24 hours per day for 7 days a week for 15 years	(24 hours * 365 days * 15 years) = 131400 hours
		Ratio = 4.2

Figure D.3: *Number of hours of operation calculation and their ratio in order to obtain the multiplication factor for electricity required*

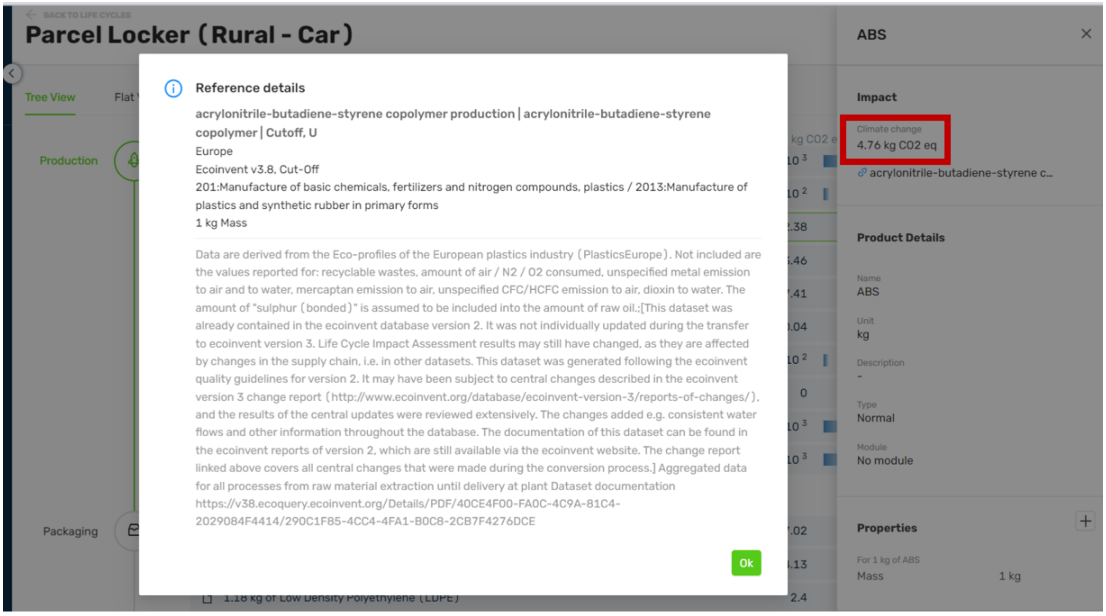


Figure D.4: *Climate change impact category in kg CO_2 equivalent (4.76 kg CO_2 eq) from production of 1 kg of acrylonitrile-butadiene-styrene (ABS) copolymer that is used in the parcel locker production*

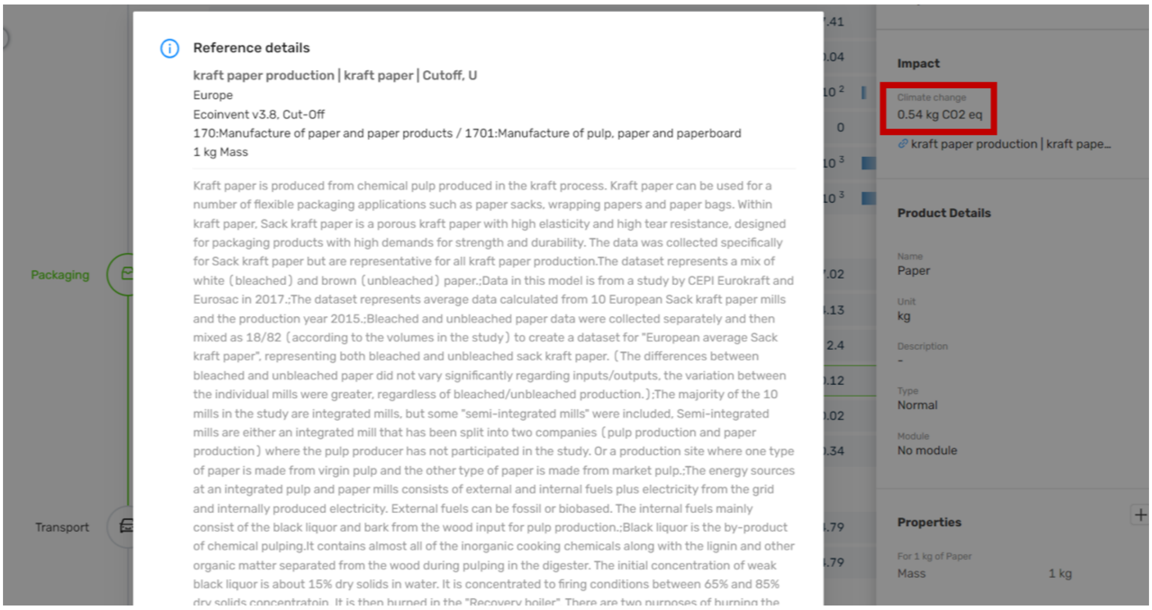


Figure D.5: *Climate change impact category in kg CO_2 equivalent (0.54 kg CO_2 eq) from production of 1 kg of Kraft paper that is used in the parcel locker packaging*

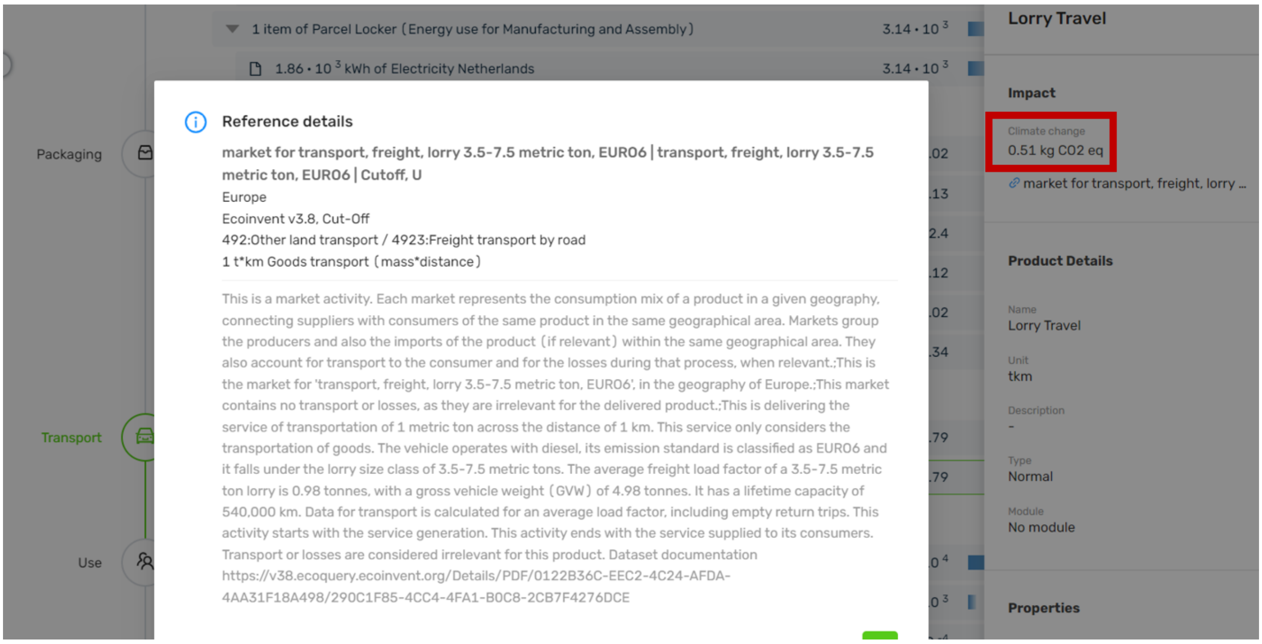


Figure D.6: *Climate change impact category in kg CO_2 equivalent (0.51 kg CO_2 eq) from transport of 1 tkm of PL transport from distributor to installation location*

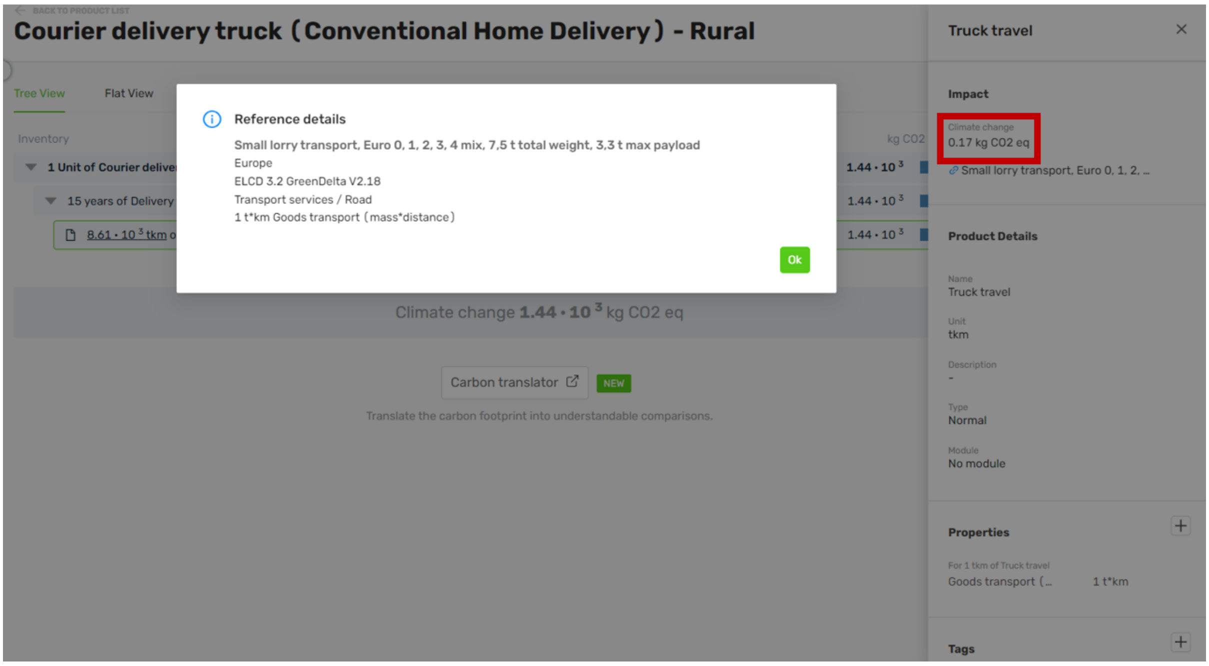


Figure D.7: *Climate change impact category of LSP courier delivery truck travel in kg CO_2 equivalent (0.167 kg CO_2 eq) from transport of 1 tkm of parcels transport*

E

Results

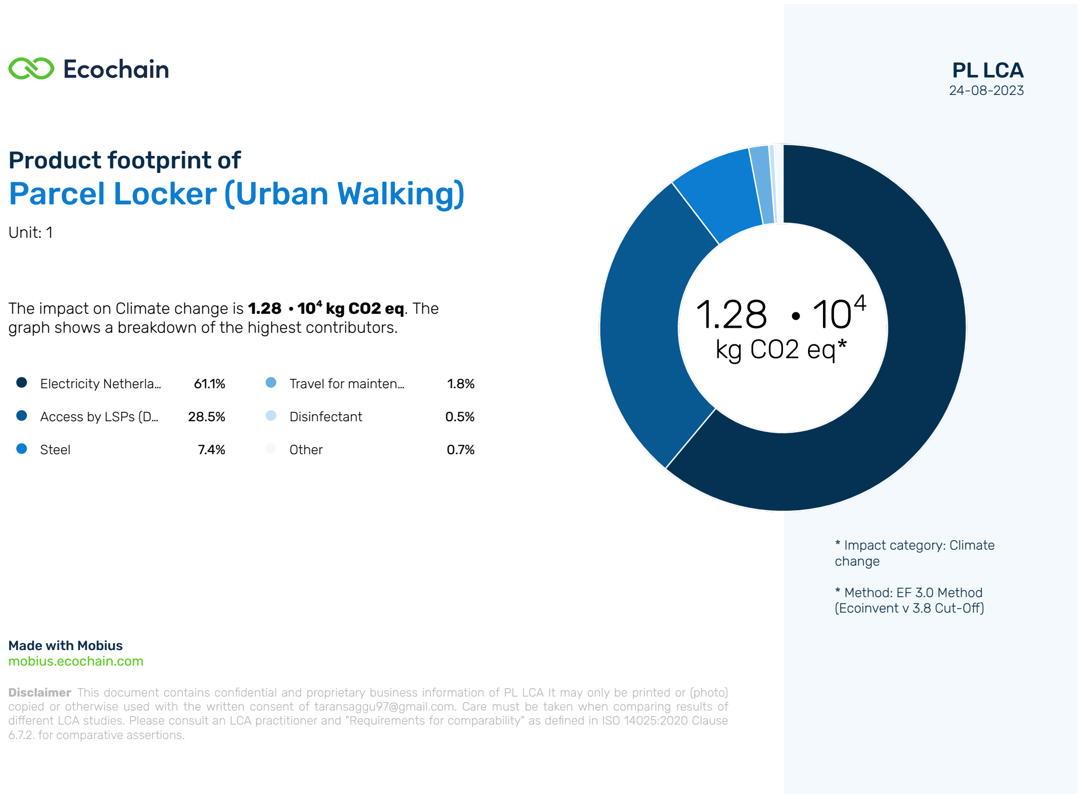


Figure E.1: *Report generated by Ecochain Mobius software highlighting the climate change impacts for urban PL system scenario when customers walk to PL locations*

Name	Amount		Impact in kg CO2 eq	Percentage %
Electricity Netherlands	$1.33 \cdot 10^{4}$	kWh	$7.81 \cdot 10^{3}$	61.1 %
Access by LSPs (Delivery truck from Westzaan to De Pijp)	$2.18 \cdot 10^{4}$	tkm	$3.65 \cdot 10^{3}$	28.5 %
Steel	$4.19 \cdot 10^{2}$	kg	$9.45 \cdot 10^{2}$	7.4 %
Travel for maintenance from Gorinchem to De Pijp	$4.42 \cdot 10^{2}$	tkm	$2.26 \cdot 10^{2}$	1.8 %
Disinfectant	30	kg	59.95	0.5 %
Paint	10.56	kg	57.41	0.4 %
Lorry Travel	27.9	tkm	14.25	0.1 %
Aluminium	1.45	kg	13.46	0.1 %
Cardboard	8.7	kg	8.27	0.1 %
ABS	0.58	kg	2.76	0 %
Low Density Polyethylene (LDPE)	1.23	kg	2.5	0 %
Polypropylene (PP)	0.19	kg	0.38	$2.94 \cdot 10^{-3}$ %
Paper	0.23	kg	0.12	$9.68 \cdot 10^{-4}$ %
Polyethylene (PE)	0.01	kg	0.03	$2.34 \cdot 10^{-4}$ %
ZAMAK	5.79	kg	-	-
Access by customer (Walk)	$2.41 \cdot 10^{5}$	km	-	-

Figure E.2: *Flat view of the PL system life cycle in an urban setup where customers access the PL locations by walking*

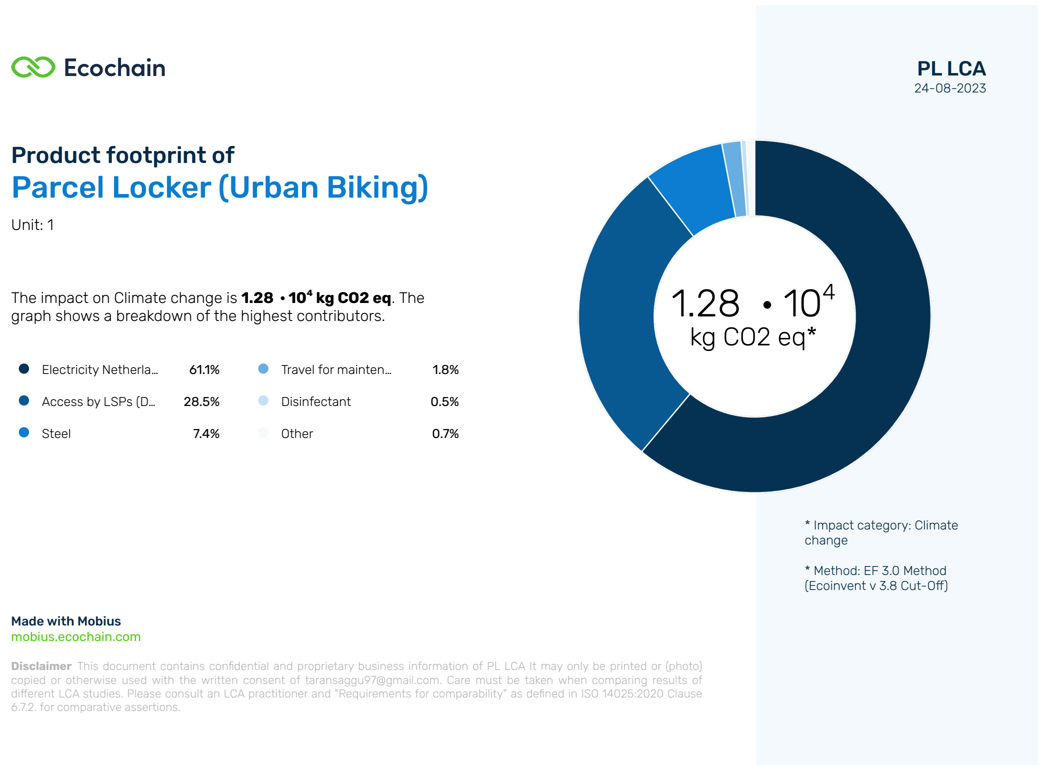


Figure E.3: *Report generated by Ecochain Mobius software highlighting the climate change impacts for urban PL system scenario when customers bike to PL locations*

Name	Amount		Impact in kg CO2 eq	Percentage %
Electricity Netherlands	$1.33 \cdot 10^{4}$	kWh	$7.81 \cdot 10^{3}$	61.1 %
Access by LSPs (Delivery truck from Westzaan to De Pijp)	$2.18 \cdot 10^{4}$	tkm	$3.65 \cdot 10^{3}$	28.5 %
Steel	$4.19 \cdot 10^{2}$	kg	$9.45 \cdot 10^{2}$	7.4 %
Travel for maintenance from Gorinchem to De Pijp	$4.42 \cdot 10^{2}$	tkm	$2.26 \cdot 10^{2}$	1.8 %
Disinfectant	30	kg	59.95	0.5 %
Paint	10.56	kg	57.41	0.4 %
Lorry Travel	27.9	tkm	14.25	0.1 %
Aluminium	1.45	kg	13.46	0.1 %
Cardboard	8.7	kg	8.27	0.1 %
ABS	0.58	kg	2.76	0 %
Low Density Polyethylene (LDPE)	1.23	kg	2.5	0 %
Polypropylene (PP)	0.19	kg	0.38	$2.94 \cdot 10^{-3}$ %
Paper	0.23	kg	0.12	$9.68 \cdot 10^{-4}$ %
Access by customer (Bike)	$6.02 \cdot 10^{5}$	km	0.1	$8.1 \cdot 10^{-4}$ %
Polyethylene (PE)	0.01	kg	0.03	$2.34 \cdot 10^{-4}$ %
ZAMAK	5.79	kg	-	-

Figure E.4: *Flat view view of the PL system life cycle in an urban setup where customers access the PL locations by biking*

Ecochain

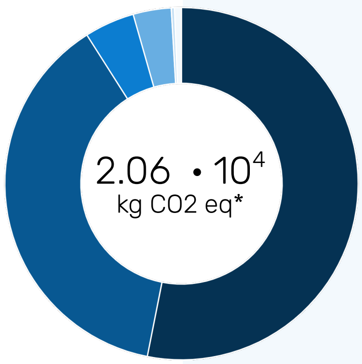
PL LCA
24-08-2023

Product footprint of
Parcel Locker (Rural Biking)

Unit: 1

The impact on Climate change is **$2.06 \cdot 10^{4}$ kg CO2 eq**. The graph shows a breakdown of the highest contributors.

Access by LSPs (D...	53.1%	Travel for mainten...	3.5%
Electricity Netherla...	37.9%	Disinfectant	0.3%
Steel	4.6%	Other	0.6%



* Impact category: Climate change

* Method: EF 3.0 Method (Ecoinvent v 3.8 Cut-Off)

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Figure E.5: *Report generated by Ecochain Mobius software highlighting the climate change impacts for rural PL system scenario when customers bike to PL locations*

Name	Amount		Impact in kg CO2 eq	Percentage %
Access by LSPs (Delivery truck from Hoogeveen to Ten Boer)	$6.55 \cdot 10^{4}$	tkm	$1.09 \cdot 10^{4}$	53.1 %
Electricity Netherlands	$1.33 \cdot 10^{4}$	kWh	$7.81 \cdot 10^{3}$	37.9 %
Steel	$4.19 \cdot 10^{2}$	kg	$9.45 \cdot 10^{2}$	4.6 %
Travel for maintenance from Gorinchem to Ten Boer	$1.41 \cdot 10^{3}$	tkm	$7.2 \cdot 10^{2}$	3.5 %
Disinfectant	30	kg	59.95	0.3 %
Paint	10.56	kg	57.41	0.3 %
Lorry Travel	89.1	tkm	45.5	0.2 %
Aluminium	1.45	kg	13.46	0.1 %
Cardboard	8.7	kg	8.27	0 %
ABS	0.58	kg	2.76	0 %
Low Density Polyethylene (LDPE)	1.23	kg	2.5	0 %
Polypropylene (PP)	0.19	kg	0.38	$1.83 \cdot 10^{-3}$ %
Access by customer (Bike)	$8.43 \cdot 10^{5}$	km	0.15	$7.04 \cdot 10^{-4}$ %
Paper	0.23	kg	0.12	$6.01 \cdot 10^{-4}$ %
Polyethylene (PE)	0.01	kg	0.03	$1.45 \cdot 10^{-4}$ %
ZAMAK	5.79	kg	-	-

Figure E.6: *Flat view view of the PL system life cycle in an rural setup where customers access the PL locations by biking*

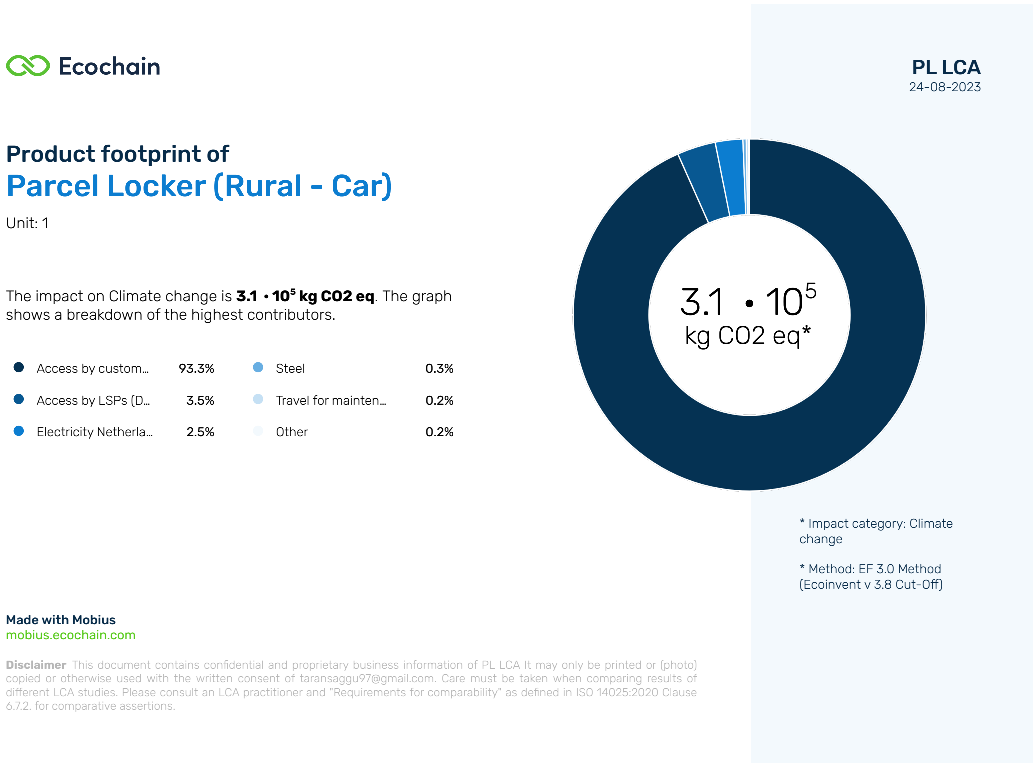


Figure E.7: *Report generated by Ecochain Mobius software highlighting the climate change impacts for rural PL system scenario when customers use car to access PL locations*

Name	Amount		Impact in kg CO2 eq	Percentage %
Access by customer (Car)	$2.89 \cdot 10^{5}$	km	$2.89 \cdot 10^{5}$	93.3 %
Access by LSPs (Delivery truck from Hoogeveen to Ten Boer)	$6.55 \cdot 10^{4}$	tkm	$1.09 \cdot 10^{4}$	3.5 %
Electricity Netherlands	$1.33 \cdot 10^{4}$	kWh	$7.81 \cdot 10^{3}$	2.5 %
Steel	$4.19 \cdot 10^{2}$	kg	$9.45 \cdot 10^{2}$	0.3 %
Travel for maintenance from Gorinchem to Ten Boer	$1.41 \cdot 10^{3}$	tkm	$7.2 \cdot 10^{2}$	0.2 %
Disinfectant	30	kg	59.95	0 %
Paint	10.56	kg	57.41	0 %
Lorry Travel	89.1	tkm	45.5	0 %
Aluminium	1.45	kg	13.46	$4.34 \cdot 10^{-3}$ %
Cardboard	8.7	kg	8.27	$2.67 \cdot 10^{-3}$ %
ABS	0.58	kg	2.76	$8.92 \cdot 10^{-4}$ %
Low Density Polyethylene (LDPE)	1.23	kg	2.5	$8.09 \cdot 10^{-4}$ %
Polypropylene (PP)	0.19	kg	0.38	$1.22 \cdot 10^{-4}$ %
Paper	0.23	kg	0.12	$4 \cdot 10^{-5}$ %
Polyethylene (PE)	0.01	kg	0.03	$9.66 \cdot 10^{-6}$ %
ZAMAK	5.79	kg	-	-

Figure E.8: *Flat view view of the PL system life cycle in an rural setup where customers access the PL locations by car*

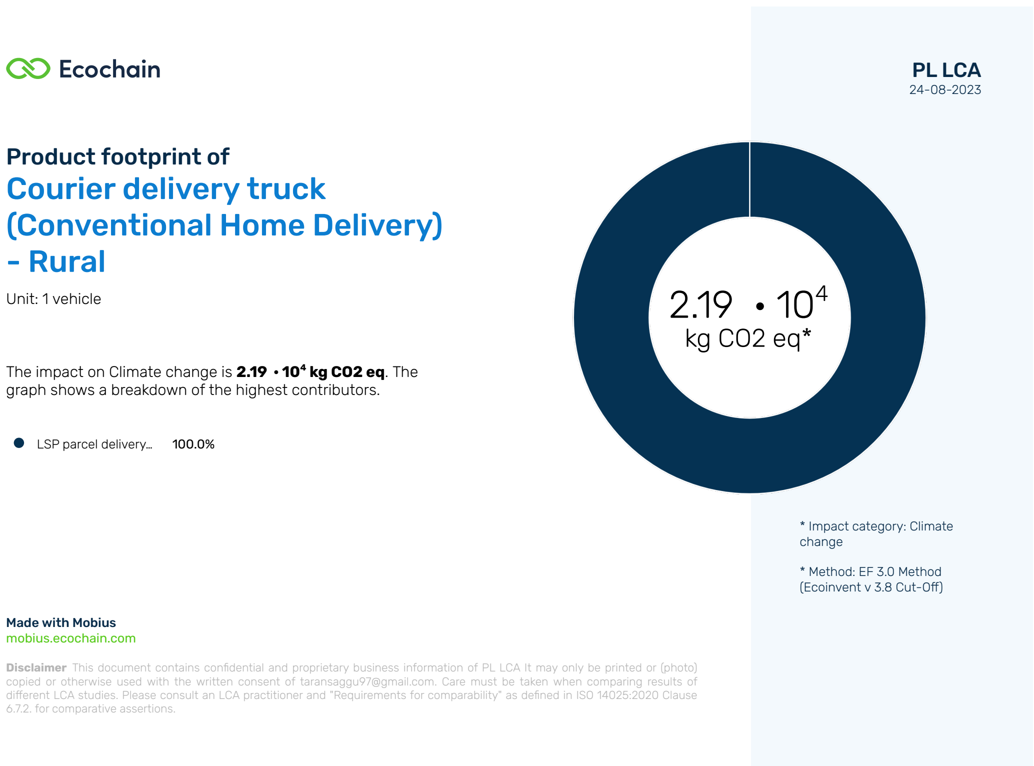
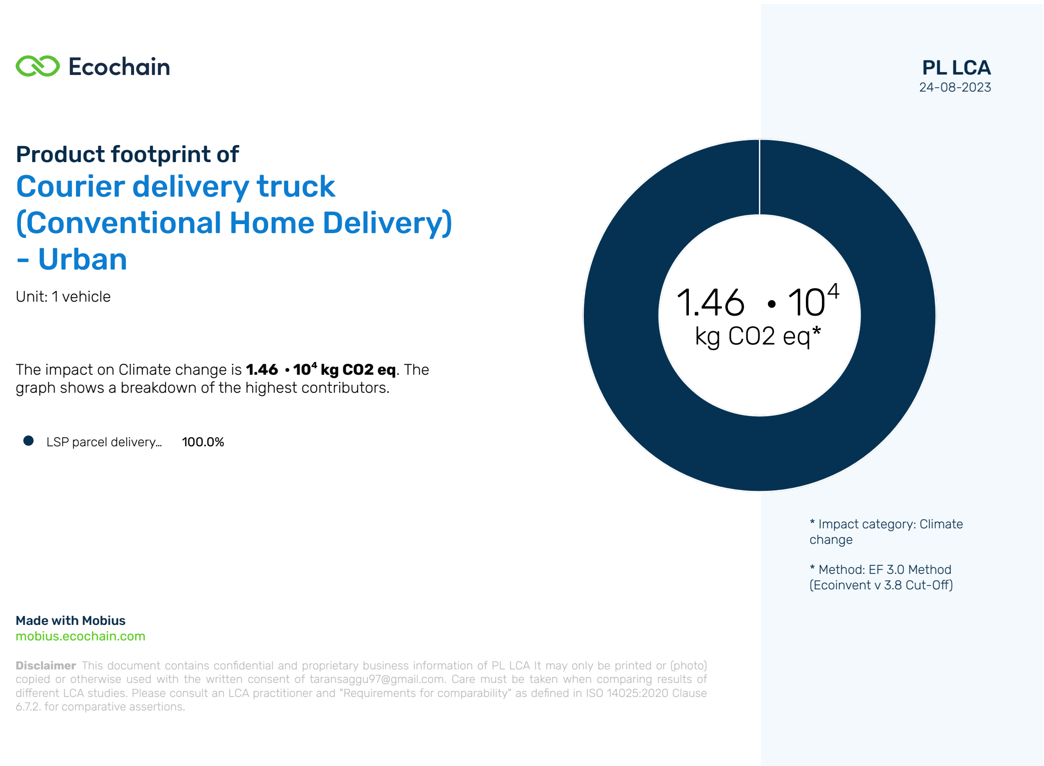


Figure E.9: *Report generated by Ecochain Mobius software highlighting the climate change impacts of the conventional HD system in rural setting where courier trucks deliver and collect parcels to the customers at their residence*



Ecochain

PL LCA
24-08-2023

Product footprint of
Courier delivery truck (Conventional Home Delivery) - Urban

Unit: 1 vehicle

The impact on Climate change is **1.46 • 10^4 kg CO2 eq**. The graph shows a breakdown of the highest contributors.

- LSP parcel delivery... 100.0%

* Impact category: Climate change

* Method: EF 3.0 Method (Ecoinvent v 3.8 Cut-Off)

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Figure E.10: *Report generated by Ecochain Mobius software highlighting the climate change impacts of the conventional HD system in urban setting where courier trucks deliver and collect parcels to the customers at their residence*