Optimizing the Life Cycle of Last-mile Packaging

by
Omar Fabian Pineda Carrillo
Bachelor's in Electronic Engineering, Pontificia Universidad Javeriana

and

Cristina Aguirre Algara
Bachelor's in International Business, Instituto Tecnológico y de Estudios Superiores de Monterrey

SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2024

Signature of Author: ______________________________
Omar Pineda Carrillo
Department of Supply Chain Management
May 10, 2024

Signature of Author: ______________________________
Cristina Aguirre Algara
Department of Supply Chain Management
May 10, 2024

Certified by: ______________________________
Dr. Selene Silvestri
Research Scientist, MIT Megacity Logistics Lab
Capstone Advisor

Certified by: ______________________________
Dr. Juan Carlos Piña Pardo
Postdoctoral Associate, MIT Megacity Logistics Lab
Capstone Co-advisor

Certified by: ______________________________
Dr. Matthias Winkenbach
Director, MIT Megacity Logistics Lab
Director of Research, MIT Center for Transportation and Logistics
Capstone Advisor

Accepted by: ______________________________
Dr. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

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ABSTRACT

More than 85 million tons of cardboard waste are created annually, with most ending up in landfills. E-commerce sales have significantly increased over the last decade and are expected to continue in the current trend. Due to increased cardboard waste and climate pledge commitments, companies are looking for ways to reduce their environmental footprint. This capstone project aims to develop a mathematical optimization model to help last-mile delivery companies reduce their carbon dioxide (CO_2) footprint by collecting and reusing cardboard cartons. Our model incorporates box pick-ups into delivery routes, suggesting which boxes should be collected, considering practical constraints such as limited vehicles' capacity and maximum driving time. Emissions savings come from two independent sources: cardboard decomposition and manufacturing emissions, but we also consider emission contributions from logistics implementation using a fleet of fuel-igniting cars. Our results illustrate the trade-off between the environmental factor, which prioritizes logistics emissions or box collection, maximum driving time, and CO_2 emission savings. We observe that CO_2 savings exhibit a logistic growth pattern when evaluated against the environmental factor and the maximum driving time. Further, our results indicate that collecting all potential cardboard boxes is not imperative to achieve the highest possible reduction in CO_2 emissions and presents an opportunity to reduce CO_2 emissions without investing significant additional truck travel time.

Capstone Advisor: Dr. Selene Silvestri
Research Scientist, MIT Center for Transportation & Logistics, Megacity Logistics Lab

Capstone Advisor: Dr. Juan Carlos Piña Pardo
Postdoctoral Associate, MIT Center for Transportation & Logistics, Megacity Logistics Lab

Capstone Advisor: Dr. Matthias Winkenbach
Principal Research Scientist, MIT Center for Transportation & Logistics
Director of Research, MIT Center for Transportation & Logistics
Director, MIT Megacity Logistics Lab
Director, Computational Analytics, Visualization & Education Lab

ACKNOWLEDGMENTS

Cristina:

I would like to express my deepest gratitude to my husband, Felipe, and my parents, Arnulfo, and Maria, for their constant support and encouragement throughout this journey. Their love and understanding have been my pillars of strength. I am deeply grateful to my capstone partner, Omar, for his collaboration and friendship, which made this research work a rewarding and enjoyable experience. I am grateful to my distinguished advisors, Selene, Juan, and Matthias, for their invaluable guidance, insightful feedback, and unwavering belief in our capabilities. Your mentorship has been important in shaping this project.

Omar:

I would like to express my heartfelt gratitude to my parents, Rodrigo and Amanda, my brother Ruben, and my friend Laura for encouraging me to continue my studies at MIT. Their unwavering support and belief in my abilities influenced my decision to follow this path. Their encouragement inspires me to succeed, and I am grateful for having them in my life.
Special thanks to my dog Milo, who provided comfort and companionship during the long hours of research and writing; to my teammate Cristi for her dedication and the smooth process that we enjoyed together; and to Selene, Juan, and Matthias for their guidance, patience, and valuable time on this project.

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1. Introduction

E-commerce has grown considerably over the last decade. Online sales have increased from $1.3 billion in 2014 to $6.3 billion in 2023 (Chevalier, 2022), which represents an expansion of almost 500%. According to Forbes*,* 20.8% of retail purchases are expected to be placed online during 2023, meaning that almost one-quarter of all retail purchases worldwide will be online by 2027 (Baluch, 2023).

Leading companies in the e-commerce sector, with extensive expertise in the last-mile delivery business, aim to deliver packages from a distribution center to final customers efficiently. They broadly agree that the last-mile phase is the most challenging and expensive part of the delivery journey (Jencap, 2023), emphasizing the critical role of packaging.

Experts in the packaging sector affirm that similar e-commerce companies ship more than 608 million packages each year, equivalent to shipping 1.6 million packages daily (Mr. Box Online, 2016), and most of them represent the need to manufacture or purchase a brand-new cardboard shipping carton. An average market cost of $0.50 for a transportation box (Kwick Packaging, 2023) implies that $800,000 is spent daily on packaging. These already substantial numbers, coupled with the expectation that e-commerce will continue to grow, highlight the need to reduce money spent on packaging.

However, cost is not the only concern for last-mile logistics companies, the environmental effects caused by e-commerce expansion are overwhelming. Considering that 93% of paper comes from trees (Inkbot Design, 2023), manufacturing 1.6 million cardboard boxes daily severely impacts deforestation and global warming. Additionally, some statistics reveal poor disposal practices related to paper and cardboard: more than 85 million tons of paper waste are created annually (Xodo Sign, 2018), with most ending up in landfills. Thus, paper accounts for around 26% of total waste at landfills worldwide (Paper Waste Facts, n.d.) and around 40% considering only United States landfills (Xodo Sign, 2018).

Encouraging the protection of the planet has also become a key development factor for recognized companies that prioritize sustainability and see benefits such as increased brand recognition, customer loyalty, revenue increase, and customer attractiveness (Inkbot Design, 2023). A recent survey indicates that 81% of consumers believe brands should actively work to protect the environment, and more than 60% of customers are willing to pay more for sustainable brands (Inkbot Design, 2023).

Recognition is also significant, as winning sustainability awards or being listed in “green brand” rankings helps raise awareness of sustainable leadership and success cases. Leading companies within the last-mile industry have established a clear and public objective of “net-zero” carbon emissions by 2040 (Amazon, 2023). These companies are also working toward reducing extra packaging to achieve their net-zero targets. However, to the best of our knowledge, none is considering reusing cardboard shipping cartons.

In this context, this capstone project aims to develop a solution that helps logistics companies reduce the amount of cardboard waste. We particularly focus on the last-mile delivery segment, as packaging is primarily designed to protect and deliver goods during their final transit to customers. Our goal is to provide companies with a structured way to reuse packaging for future purchases. This enables them to save money on shipping cartons while moving toward the objective of net-zero carbon emissions.

1.1 Problem Statement and Research Questions

More and more e-commerce companies seek different means to achieve a zero-waste future. In this project, we evaluate the alternative of reusing cardboard shipping cartons from products that have been previously dispatched. The goal is to develop an optimization model that allows companies to collect and re-incorporate used packaging into the supply chain. Currently, last-mile logistics companies have their delivery networks in place with established routes and capacity constraints. The idea is to incorporate box pick-ups into delivery routes, requiring drivers to stop at various locations for either delivery or empty box collection. The ultimate goal of this project is to define an optimal strategy that allows last-mile companies to decide in which cases boxes should be picked up. For this study, we use data provided by the 2021 Amazon Last Mile Routing Research Challenge (Merchán et al., 2022), which provides real delivery routes from Amazon to its customers in five cities in the United States. However, although our mathematical model can be applied to any of these cities, we only focus on one city for this project.

Incorporating empty box pick-ups into daily delivery routes may incur extra logistics costs. Nevertheless, the reuse of cardboard shipping cartons contributes to reducing the ecological footprint of last-mile logistics companies and helps them achieve the desired objective of net-zero carbon emissions. Thus, in our study, we consider key metrics such as the number of cartons collected, savings on purchasing brand-new cartons, weight and volume of waste reduction, and total CO_2 emissions avoided, with the intent to estimate the benefits of reusing cardboard cartons.

In this context, the questions to be answered include:

1. What methodology should be implemented to define optimal policies for picking up cardboard shipping cartons?
2. How much extra logistics time is required to implement the suggested policies?
3. What are the estimated benefits of the suggested policies?

1.2 Project Goals and Expected Outcomes

With data provided by Amazon and considering only the last-mile delivery segment, the main objective is to create an optimization model to optimally define in which cases cardboard cartons should be picked up or not within the distribution route. Additionally, we intend to provide last-mile logistics companies with managerial insights to understand the benefits and drawbacks of collecting and reusing cardboard cartons. Even though the model evaluates only a single city, it can be later extrapolated to other cities if required.

We gather additional information, such as CO_2 emissions and details about the cardboard manufacturing process and combine it with the data provided by the 2021 Amazon Last Mile Routing Research Challenge to ensure we consider all the factors that could impact the decisions.

The model considers all these input parameters when evaluating various scenarios over a range of budget values. Each scenario balances time constraints and environmental benefits based on different priorities. Some prioritize environmental benefits over time and allocate a larger budget. Others are cost-conscious, with the smallest budget possible. Meanwhile, others combine both approaches to create a new policy that allows for a gradual transition to a zero-waste supply chain while maintaining the initial cost low.

The deliverables of this capstone project include:

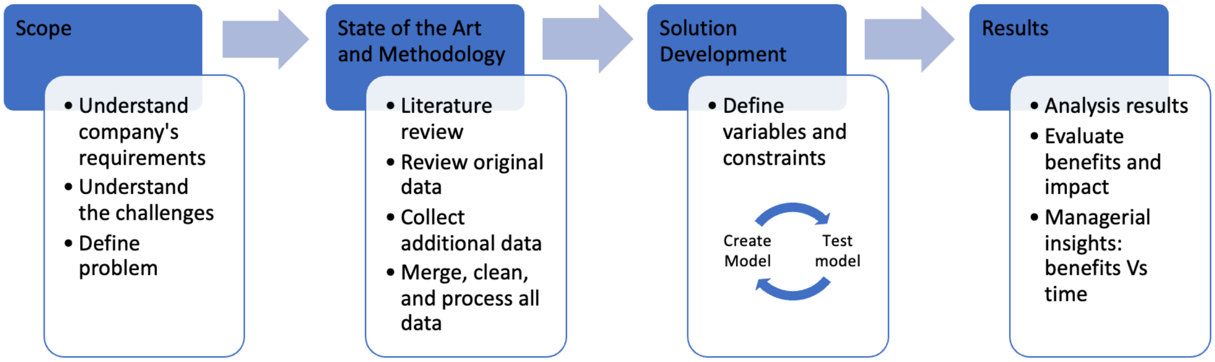
1) Quantitative model that provides outcomes for the scenarios mentioned above.
2) Time estimation of suggested pick-up policies.
3) Benefit analysis of suggested pick-up policies.

1.3 Plan of Work

Figure 1 shows a flowchart of the project steps for conducting the capstone project. The first phase aims at understanding the problem and identifying the questions to be answered. During the second phase, we investigate similar e-commerce companies to learn about sustainability policies. All the data gathered is merged, cleaned, and processed to be able to define the main variables and constraints. The solution development phase is intended to develop and test a mathematical optimization model using an iterative approach. The last phase is dedicated to analyzing the results for the scenarios previously described. We evaluate the benefits and the impacts to provide managerial insights to help last-mile logistics companies understand the costs and benefits of collecting and potentially reusing cardboard shipping cartons.

Figure 1

High-level Project Phases



2. State of the Practice

In this section, we review the relevant literature about packaging and reverse logistics studies. We begin by reviewing the literature on returnable transport items. We then focus on sustainable packaging, environmental impact, and vehicle routing problems in the last-mile delivery segment. Finally, we highlight our findings and how to leverage existing approaches to build our mathematical formulation.

2.1 Returnable Transport Items

Reusing cardboard shipping cartons is known in supply chain literature as returnable transportation packaging (RTP) (Hariga et al., 2016) or returnable transport items (RTI) (Yahaya et al., 2017). Both terms are considered equivalent, and we refer to them as RTI throughout this paper. Yahaya et al. (2017) describe RTI as a combination of two approaches: first, as the way to transport, store, and handle products, with the benefit of cost reduction and profit maximization; and second, as a change in attitude to achieve environmental sustainability through countering negative environmental impact.

Although cost is the main barrier to implementing and using RTI (Kroon et al., 1995), several industries have used it due to its benefits over traditional single-use packaging (Hellström et al., 2010), such as in the brewery and soft drink industries. Monsreal (2014) and Privé et al. (2006) consider the vehicle routing problem with picking up RTI. Monsreal (2014) studies the brewery industry in Mexico, where a reverse logistics network is structured, and then develops two algorithms to pick up packaging optimally. The first algorithm considers visiting all customers, and the other one includes a profitability analysis that determines whether it is worth it or not to visit a customer (Monsreal, 2014). Privé et al. (2006) focus on the distribution of soft drinks in Quebec, Canada. The authors propose a mixed-integer linear program (MILP) to minimize transportation costs while considering the revenue generated for the collection of RTI. Using real-world data, Privé et al. (2006) show that a distance reduction of up to 23% can be achieved by allowing delivery vehicles to deliver goods and pick up recyclable material at customer locations.

The implementation of RTI within the last-mile segment is still under development; the benefits have already been evaluated but only achieved in a few cases. Food delivery services, for example, are expected to exhibit a yearly growth rate of 12% worldwide. In China, this industry emitted 13.35 million tons of CO_2 in 2019 and is projected to reach 19.2 million by 2024 (Statista, 2023), with reusable packaging expected to reduce CO_2 emissions by 54% compared to traditional single-use methods (Camps-Posino et al., 2021).

Bortolini et al. (2018) develop an optimization model for delivering fresh food in the Emilia-Romagna region of Italy. Their objective function aims to minimize both the cost and environmental emissions, considering a finite lifespan for an RTI as well as the advantages and disadvantages of reusable and disposable packaging. Optimal solutions consider the coexistence of both types of packaging, resulting in savings of 45% in CO_2 emissions with only a 35% increase in logistics costs.

2.2 Sustainable Packaging and Environmental Impact of Last-mile Delivery

Our project focuses on minimizing environmental impact through the reuse of cardboard boxes in last-mile delivery. To quantify this impact, we review some literature that helps us estimate CO_2 emissions and evaluate future initiatives that can contribute toward footprint reduction.

There are many parameters for measuring the environmental impact of last-mile delivery, such as distances, population density, packaging, return rates, product waste, mode of transportation, CO_2 emissions, and fuel consumption; see, e.g., Fichter (2008) and Pålsson et al. (2017). An optimization model aiming to reduce environmental impact through RTI and reverse logistics should consider negative impacts on transportation, such as CO_2 emissions, which are caused by the type of vehicle, road, density, and distance traveled (Alvarado & Liu, 2019), as well as the future use of collected packaging, which can be recycled, reused, or thrown out, considering their goal of cost versus environmental benefit (Zhang et al., 2023).

One of the factors this capstone considers is the amount of corrugated paper used for the packaging. The environmental benefits will depend on the package's origin: reused, recycled, or new box. Most of the packages used in e-commerce come from single-use packaging materials, like corrugated paper, plastic, and Bubble Wrap (Lai et al., 2022). Some companies are becoming more innovative by not only using recycled materials but also changing their packaging. Examples include *PUMA*, which reduces its environmental footprint in packaging by using die-cut cardboard and reusable, polypropylene bags (Cheng, 2019). In the wine industry, *Garçons Wines* has redesigned its wine bottles to be made flat with 100% recycled polyethylene terephthalate (Escursell et al., 2021).

2.3 Returnable Transport Item Optimization

RTI models found in the last-mile delivery segment are based on the vehicle routing problem (VRP). VRP is an optimization problem aiming to optimize routes with a set of trucks to deliver customer orders (Alvarado & Liu, 2019). One of the variants of VRP is the vehicle routing problem with simultaneous pick-up and delivery services (VRPPD), in which some customers expect to receive goods while others expect to return them (Serdar et al., 2012). Dethloff (2021) presents VRPPD as a genetic algorithm-based approach problem that takes into consideration vehicles' capacities, distances, delivery amounts, pickup amounts, and a binary variable indicating when a vehicle should travel from one node to another, and the load of the vehicle after serving a customer node. However, those models only focus on distance and cost minimization, while other problems gain prominence among the industry, such as CO_2 emissions. Tajik et al. (2012) develop a further and more robust optimization approach for minimizing pollution in a routing problem with pick-up and delivery, in which emissions and fuel consumption are also part of the objective function in conjunction with the distance minimization from a regular VRP, known as the time window pickup-delivery pollution routing problem. This considers factors such as CO_2 emissions, fuel consumption cost, travel, and service time, and even considers environmental factors such as air friction and road slopes.

A simpler but effective optimization model to minimize CO_2 emissions is also created by Figliozzi et al. (2020). This does not focus on designing a route to visit customers, such as in the VRP problem, but on minimizing emissions based on an established VRP distance, a fixed number of customers, and vehicles, taking into consideration several types of emissions.

2.4 Summary of Findings

Our literature review shows that RTI logistics is implemented and optimized in some industries through different mathematical models. However, to the best of our knowledge, none of them focuses on maximizing emissions savings through the reuse of cardboard boxes within the last-mile delivery segment.

Different optimization methods to handle RTI are analyzed, with different objective functions: revenue maximization, distance minimization such as VRP or VRPP, CO_2 emissions reduction, and emissions with routing distance reduction simultaneously. Due to the nature of the goal of this project and our focus on environmental impact rather than on designing delivery routes, our mathematical model focuses mainly on CO_2 emissions minimization. It is similar to the model presented by Figliozzi et al. (2020), in which the objective function for the total vehicular emissions incorporates based on their different lifecycle stages, the vehicular production, disposal, and utilization phases. However, as our problem is related to cardboard-generated emissions within a delivery and pick-up routing problem, we use the method developed by Tajik et al. (2012) as guidance. The study presents a MILP with a set of customers to pick up and deliver, a set of vehicles and depots, and decision variables suggesting when a client should be visited, also considering extra pollution factors.

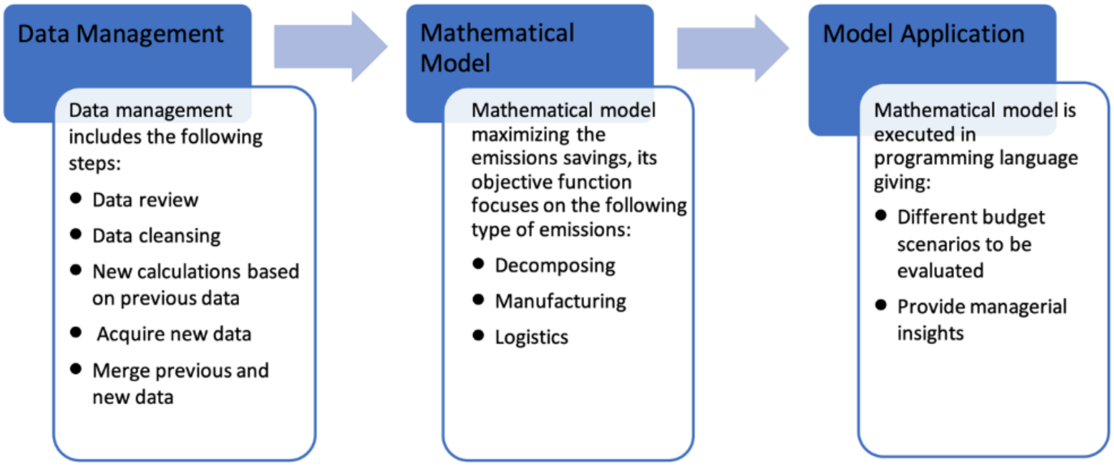
With the help of both studies from Tajik et al., Figliozzi et al. (2014), and the suggested way of calculating the carbon footprint in transportation based on distance, vehicle type, fuel consumption, driving environment, and cargo load presented by Velazquez et al. (2013), we structure a mixed integer linear problem that maximizes emissions savings within distribution network in the last-mile delivery segment.

3. Methodology

In this section, we review the methodology implemented during this capstone project. Figure 2 summarizes the main steps of our methodology.

Figure 2

High-level Methodology Description



Data Management

Data management includes the following steps:

- Data review
- Data cleansing
- New calculations based on previous data
- Acquire new data
- Merge previous and new data

Mathematical Model

Mathematical model maximizing the emissions savings, its objective function focuses on the following type of emissions:

- Decomposing
- Manufacturing
- Logistics

Model Application

Mathematical model is executed in programming language giving:

- Different budget scenarios to be evaluated
- Provide managerial insights

Data management is our first challenge; even though our main source of information is the data set provided by Amazon (Merchán et al., 2022), we review, clean, and prepare the data in accordance with the requirements of this project. To estimate emissions from cardboard boxes, new calculations are required. These calculations include determining distances using two Global Positioning System (GPS) coordinates and considering external emission factors.

After reviewing the data, we create a mathematical model that enables us to optimize emissions reduction. This model considers the emissions saved from methane release due to cardboard decomposition, the emissions saved from not manufacturing a new cardboard box, and the emissions generated from customer visits for box collection.

The analysis of the mathematical results allows us to provide last-mile delivery companies with managerial insights. These insights aim to help them understand the best approach to identify which cardboard box pickup locations to prefer to maximize CO_2 emissions savings. To implement and solve the model we use the high-level programming language Python and the Optimization Solver Gurobi.

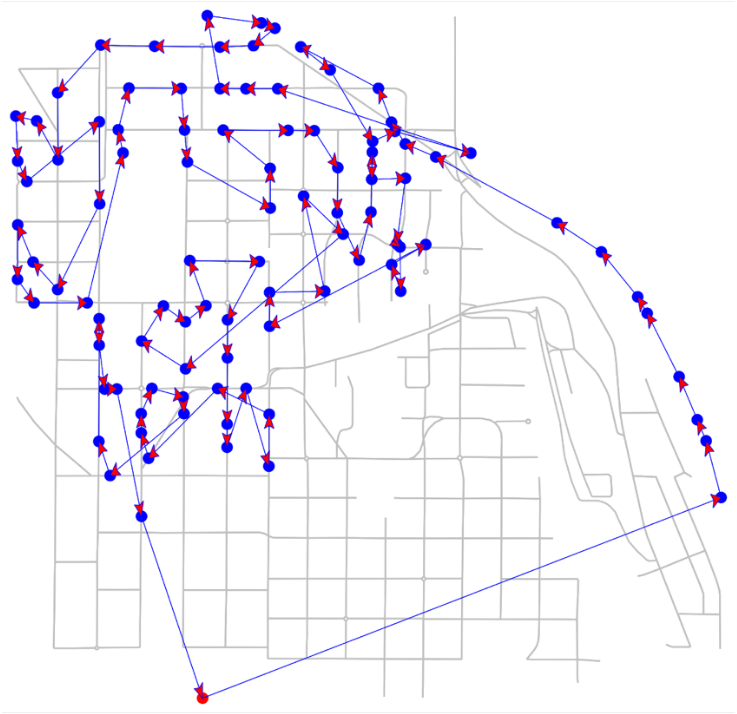
3.1 Data Management

This section describes the data format and data processing for this project. As mentioned above, most of the data we use comes from the 2021 Amazon Last Mile Routing Research Challenge (Merchán et al., 2022). This data provides 6,112 real delivery routes from Amazon to its customers in five cities. The data is categorized into three sections: route level, stop level, and package level, and must be cleaned and shaped accordingly to be used in this model. At the route level, the following are the data fields relevant to this project: the route identifier, the volumetric capacity of the vehicle, the sequence in which customers are visited, and each stop on the route. At the stop level, the relevant fields are: the stop identifier, GPS coordinates for stops, geographical planning area, and packages belonging to the stop. Finally, at the package level, the relevant fields are: the package identifier, dimensions, and package delivery service time. For further information regarding the data set, please refer to Merchán et al. (2022).

Figure 3 shows an example of a real route where customers are presented in blue circles, the Amazon warehouse is displayed as a red circle, the blue line represents the route, and the red arrows indicate the direction of movement.

Figure 3

Example of One Route in the Amazon Data Set



The model focuses on environmental impact and is measured based on CO_2 emissions reduction; therefore, we estimate the weight of a cardboard box based on dimensions, among others some conversion factors required to measure all the impacts over the same scale, such as emissions released when cardboard decomposes. According to Brogaard et al. (2014), the mean of corrugated cardboard is 1.14 kg of carbon emissions per kilogram. Estimated emissions when a new cardboard box is manufactured are also required as a model data input. Additionally, some fuel consumption constants are calculated based on vehicle type and delivery area, as mentioned by Velazquez et al. (2013).

3.2 Model Formulation

The project aims to develop an optimization model for last-mile companies to reuse cardboard shipping cartons by integrating collection into existing delivery routes. This section presents the mathematical model by describing the sets, parameters, decision variables, objective function and its constraints.

Our problem setting considers two set of customers: customers requesting delivery services and others who request pickup services. Each customer is assigned to a specific, pre-defined route. A customer requesting delivery must be served, while the company must decide whether to pick up or not the boxes of those requesting pickup service. Our model aims to maximize emission savings by deciding which boxes should be picked up, subject to a total logistics time budget and vehicle capacity constraints. Savings come from two independent sources: cardboard decomposition and manufacturing emissions, but we also consider emission contributions from logistics implementation using a fleet of fuel-igniting cars. The objective function is the total CO_2 savings, which corresponds to the sum of the savings and the emissions generated. We define the time budget as the extra time allocated to cover logistics for picking up used cardboard boxes. Specifically, the time budget is a constraint in our model and one of the primary barriers to RTI implementation in the supply chain (Hellstrom et al., 2019).

Tables 1 to 3 show the notation used in our model formulation.

Table 1

Sets

Sets	
R_r	Set of complete routes already established to visit customers; $r \in R$
I_r	Set of customers stops to deliver or pick up within a delivery route; $i \in I_r$

Table 2

Parameters

Parameters	
δ_{ir}	Type of customer i within route r: 1 for delivery, 0 for pick-up; $r \in R, i \in I_r$
C_r	Initial capacity of vehicle dedicated to pick-up boxes in route r; $r \in R$
d_{ir}	Extra distance traveled to pick-up a box at customer i, within the delivery route r; $r \in R, i \in I_r$
w_{ir}	Cardboard box weight to be picked up or delivered to customer i, within the route r; $r \in R, i \in I_r$
D	Decomposing emission factor
M	Manufacturing emission factor
L	Logistics factor associated with type of vehicle, loading, type of delivery area, and fuel consumption
B	Time budget limit: a percentage of time route reserved exclusively for pick-up transport boxes
α	Environmental prioritization factor, $\alpha \in [0,1]$
T_{ir}	Driving time to visit customer i in route r, $r \in R, i \in I_r$
S_{ir}	Time that is serving the package is expected to require for customer i in route r, $r \in R, i \in I_r$

Table 3

Variable

Variable	
x_{ir}	1, if vehicle performing route $r \in R$ visit customer $i \in I_r$; 0 otherwise

Model formulation. The model formulation is presented below.

$$\text{maximize} \sum_{r\in R}\sum_{i\in I_r} \alpha \cdot w_{jr} \cdot x_{ir} \cdot D \; + \sum_{r\in R}\sum_{i\in I_r} \alpha \cdot w_{jr} \cdot x_{ir} \cdot M - \sum_{r\in R}\sum_{i\in I_r} (1-\alpha) \cdot d_{ir} \cdot x_{ir} \cdot L \tag{4}$$

Subject to:

$$w_{ir} \cdot \; x_{ir} \leq \; C_r + \sum_{\substack{j\,\in\, I_r \\ j<i}} w_{jr} \cdot \delta_{ir} - \sum_{\substack{j\,\in\, I_r \\ j<i}} w \cdot x_{jr} \qquad r \in R,\;\; i \in I_r \tag{5}$$

$$\sum_{i\in I_r} x_{ir} \cdot (T_{ir} + \; S_{ir}) \leq B \qquad r \in R \tag{6}$$

$$x_{ir} \leq 1 - \delta_{ir} \qquad r \in R,\; i \in I_r \tag{7}$$

$$x_{ir} \in \{0{,}1\} \qquad r \in R,\; i \in I_r \tag{8}$$

The objective function (4) maximizes a convex combination between the emissions saved and the emissions generated. The first term of the equation denotes the emissions avoided for methane release caused by cardboard decomposition. The second term is associated with CO_2 emissions savings from not having to manufacture a new cardboard box. Finally, the third term is the extra pollution generated by visiting a customer to pick up a box. Constraints (5) guarantee that no vehicle exceeds its load capacity at any point on its delivery routes. The budget time is limited in Constraints (6). Constraints (7) specify the non-coexistence of pickup and delivery. Finally, the domain of the decision variables is defined in Constraints (8).

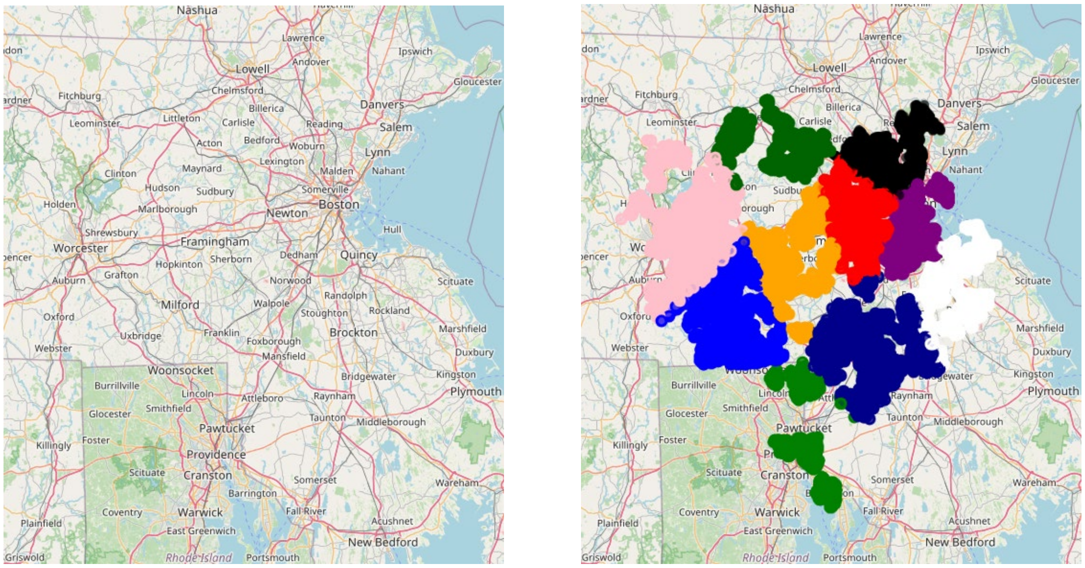
4. Results

In this section, we begin by discussing the results of narrowing Amazon's data set to only include the Boston metropolitan area as the selected location, along with the associated routes, customers, and packages. We then present all the assumptions and parameters for the various model scenarios, concluding with computational results on emissions savings and the number of boxes collected to determine the best trade-off between emissions savings and cost/time. The mathematical model is implemented in Python and solved using Gurobi 11.0.1.

4.1 Case Study

We focus on the metropolitan area of Boston, which considers 414 routes and 59,711 stops. We use a k-means algorithm to cluster the customers and evaluate route density and the number of packages, as shown in Figure 4. The metropolitan area of Boston is chosen because it represents a good sample in terms of the number of routes and stops.

Figure 4



Metropolitan Boston Area Map:

Map with 10 Clusters:

Table 4 displays the number of packages and routes per cluster in the Boston metropolitan area. This table shows the different concentrations of routes and packages based on geographical region. Cluster 3, highlighted in purple on the right-hand map in Figure 4, has the highest number of routes and packages. In contrast, Cluster 7, shown in dark green, has the lowest concentration of both, even though the geographical areas are comparable.

Table 4

Clusters Description

Cluster	No. Packages	Routes
0	19,054	75
1	4,937	22
2	5,433	24
3	24,862	109
4	6,124	27
5	13,482	55
6	6,342	31
7	1,865	10
8	3,871	17
9	9,564	44

Packages dimensions are also evaluated per cluster. However, we notice that all of them are normally distributed with similar mean and standard deviation across all clusters. Table 5 describes statistically the dimension of the boxes in the studied service area.

Table 5

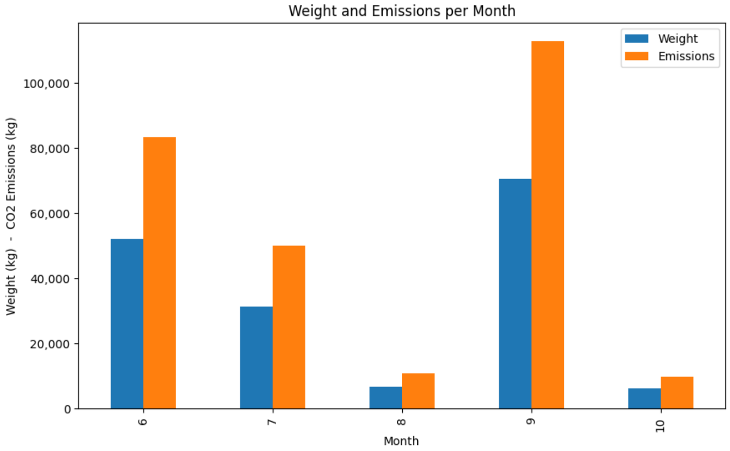
Package Dimensions: Statistical Description

	Depth (cm)	Height (cm)	Width (cm)
Mean	34.42	10.78	25.01
Standard deviation	9.32	7.43	7.33
25% (First Quartile)	26.80	5.30	18.20
50% (Median)	33.00	8.40	24.60
75% (Third Quartile)	39.40	12.70	29.70

Figure 5 depicts the estimated CO_2 emissions from the disposal of cardboard boxes from June 2021 to October 2021, using Amazon's data set and assuming no cardboard reutilization in the metropolitan area of Boston. These emissions are visually represented by the orange bars, while the blue bars represent the total weight of cardboard waste.

Figure 5

Emissions and Weight of Cardboard Waste



4.3 Parameter Choices

In this section, we provide a detailed description of the parameters' values we consider. The first parameter to consider is β, i.e., the probability used to randomly classify a location in the data set as pick-up or delivery. A higher value of β increases the likelihood of assigning the location as a delivery point.

Logistics time budget, B, and environmental prioritization factor, α, are the next key parameters. Since they play a key role, we solve several instances with different values of these parameters. First, with a restrictive budget to evaluate the environmental impact of the policy with negligible impact on companies' profit. Second, with a flexible budget to capture most of the emission savings of picking up the cardboard boxes. Third, to find a balance point between benefits and investment. Several simulations are required to establish a clear relationship between investment and environmental benefits. B is defined as the percentage over our baseline benchmark reference, which is the scenario in which no cardboard boxes are reused. For a given route $r \in R$, the time for this scenario is calculated as follows: $\Sigma_{i \in I_r} \delta_{ir} \cdot (T_{ir} + S_{ir})$.

Table 6 lists the parameters used and the corresponding values evaluated during the multiple simulations:

Table 6

Parameters Description

Parameter	Evaluated Values
β	{20%, 40%, 50%, 60%, 80%}
α	{0, 0.01, 0.02, 0.03, 0.04, 0.05, 0.07, 0.10, 0.20, 0.40, 0.60, 0.80, 1}
B	{1%, 3%, 5%, 10%, 15%, 20%, 25%, 30%, 40%}
D	0.65
M	0.95
L	0.3512*
T_{ir}	Time calculated based on constant speed of 30km/h
δ_i	{0,1}

* The logistics emissions factor is 0.3512, which corresponds to the emissions of a fully loaded type 1 vehicle with a capacity of less than 7.5 tons (Velazquez et al., 2013).

4.4 Computational Results

We solve the optimization model for 350 instances (one instance per unique parameter combination) to determine a trade-off between CO_2 emissions savings, time budget B, β, and α. This section illustrates those trade-offs.

Figure 6 and Figure 7 show the maximum CO_2 emissions savings in kilograms achieved and the optimal number of boxes to be collected versus the time budget B, considering an environmental factor of $\alpha = 1$ and $\alpha = 0.03$, respectively. The three β values 60%, 70%, and 80% are plotted simultaneously. We observe that CO_2 savings exhibit a logistic growth pattern, where an increase in B significantly impacts CO_2 savings. However, as B continues to rise, the growth rate of CO_2 savings gradually slows and eventually plateaus. This behavior is characteristic of a system approaching its saturation point or carrying capacity, which in this case is limited by the capacity of the vehicle or by logistics emissions generated to collect the box. Based on the model iterations, it is evident that any value of B exceeding 25% will not result in substantial savings. This is because when B is set at 25%, we are already capturing at least 95% of the maximum potential savings.

Figure 6

CO_2 Savings Achieved by Different Values of β, Considering α = 1.00

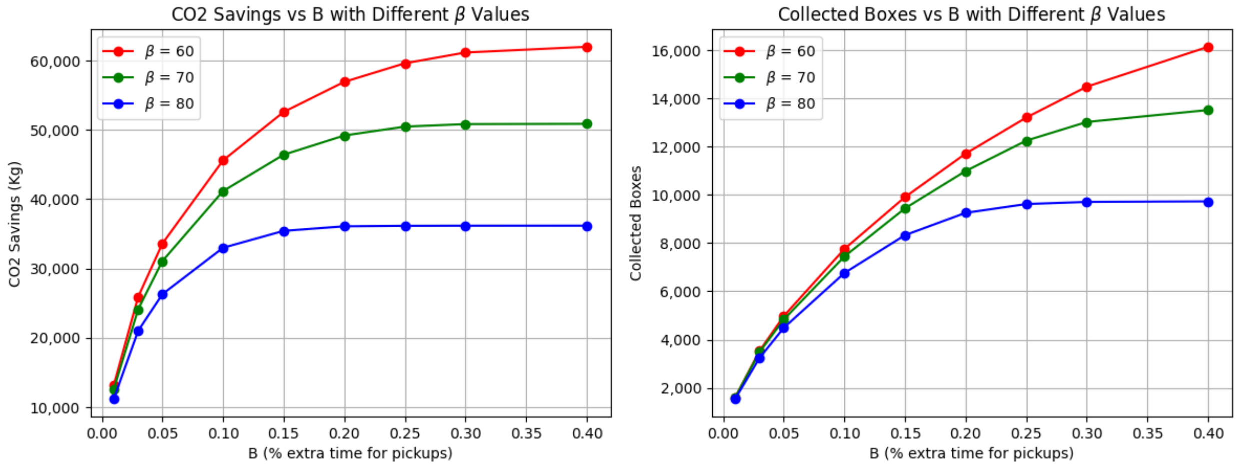
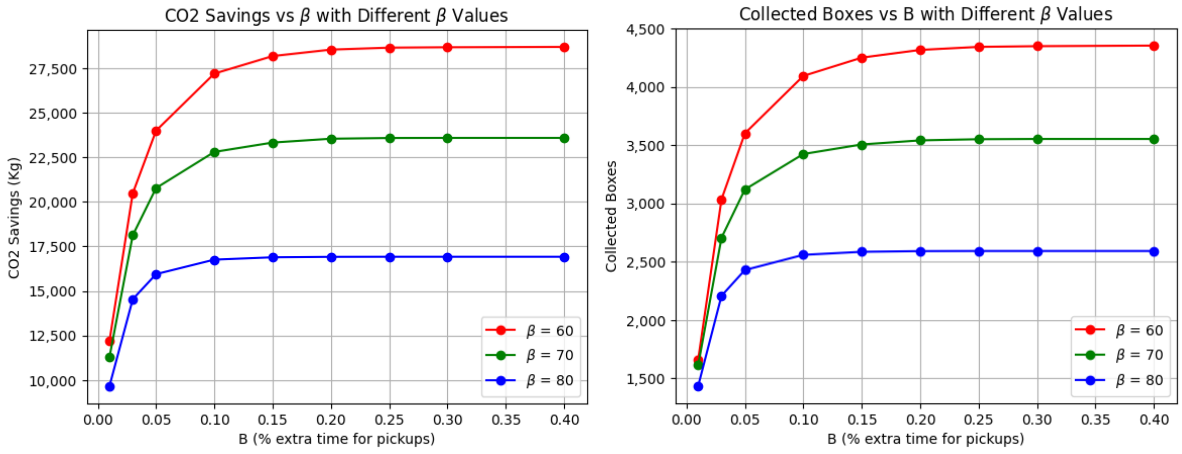


Figure 7

CO_2 Savings Achieved by Different Values of β, Considering α = 0.03



We now focus on evaluating the impact of the prioritization factor α on the CO_2 savings. For this reason, we keep constant the values of β and B, while changing α values. Table 7 presents the savings and the number of boxes collected for $\beta = 60$ and maximum time budget B = 0.40. We observe that increasing the value of α increases the savings. However, similar CO_2

emissions savings can be obtained by using any α value greater than 0.40, as shown in the highlighted section of Table 7.

Table 7

CO_2 Savings Achieved by Different Values of α, Considering B *=0.4 and* β *= 60*

CO_2 Savings	α	Collected Boxes
0	0.00	0
16,168	0.01	2,321
23,375	0.02	3,435
28,684	0.03	4,354
32,732	0.04	5,090
36,235	0.05	5,793
41,813	0.07	6,984
47,700	0.10	8,457
57,234	0.20	11,537
62,445	0.40	14,555
62,627	0.60	15,808
62,095	0.80	16,120
62,008	1.00	16,138

After evaluating the impact of the environmental factor α with a constant time budget B, we turn our attention to evaluating its impact with different values of B. Figures 8 and 9 show the relationship between CO_2 emission savings and time budget B, for various α values. The plots exhibit the optimization result for β values of 60% and 70%, respectively.

A low α value gives higher priority to emissions generated from logistics activities, while a high value gives higher priority to the savings achieved through collecting and reusing boxes. A value of zero eliminates the savings, therefore in that case it is better not to pick up any box to avoid more emissions. As expected, increasing the value of α increases the savings. However, it is noticeable that savings stabilizes with a α value of 0.40. Any higher value does not provide significant changes in the output model, suggesting that the useful range of this parameter is between 0.01 and 0.40.

Figure 8

CO_2 Savings Achieved by β = 60

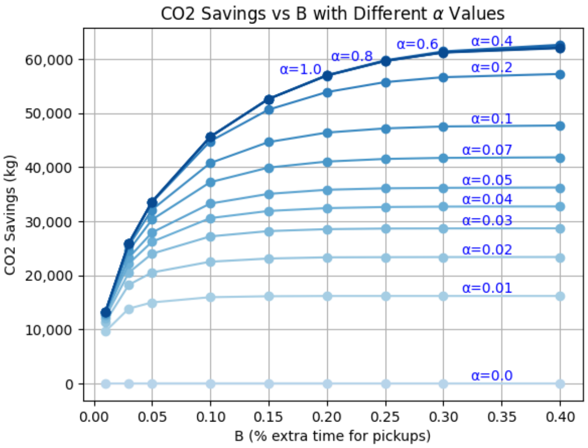
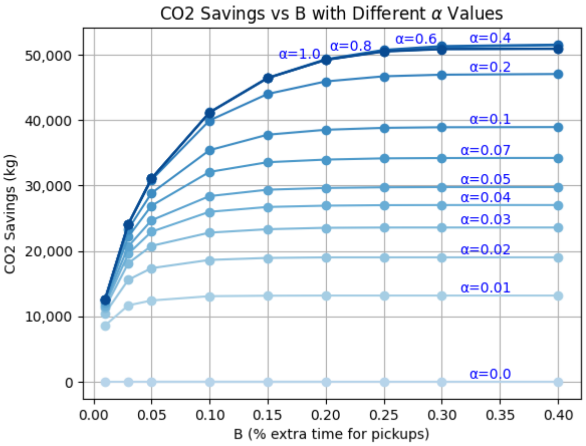


Figure 9

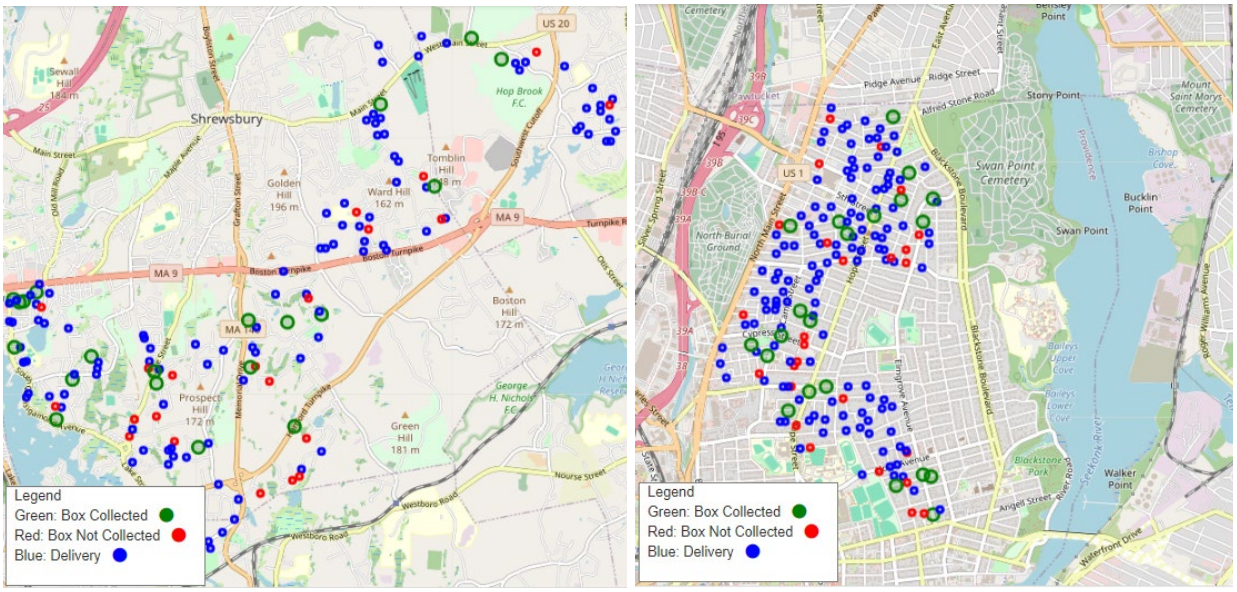
CO_2 Savings Achieved by β = 70



Next, we provide visual and statistical results from the optimization model to understand the impact of cardboard weight and pick-up distance on the decision variable x, which determines whether to collect a box. Figure 10 illustrates two routes on a map with a limited time budget of 10%, an α value of 0.40, and β value of 60. The blue points represent the delivery points, the red points represent the locations that are not visited for pick-ups, and the green points represent the customers that need to be visited to pick up boxes. These results indicate that locations that are far from the initial route are disregarded, while the closest ones are visited. This may indicate that it is not worthwhile to pick up a box beyond a certain distance.

Figure 10

Boston Metropolitan Area Map with Two Different Routes



Route 1:

Route 2:

The statistical findings below provide insights regarding weight, distance, and the decision to collect a box. Figure 11 shows a histogram that indicates the model prioritizes collection from customers who are closer to a delivery site, as the distance difference is smaller. Figure 12 shows that the model suggests collecting boxes from places with the highest cumulated cardboard weight available to pick. These results are based on all routes within the metropolitan area of Boston.

Figure 11

Distance Histogram Considering B =0.1, α =0.4, and β = 60

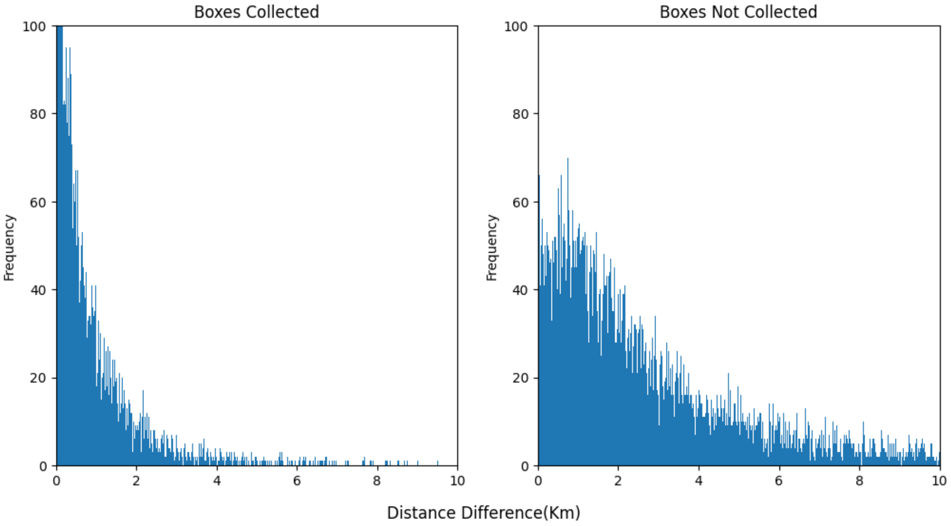
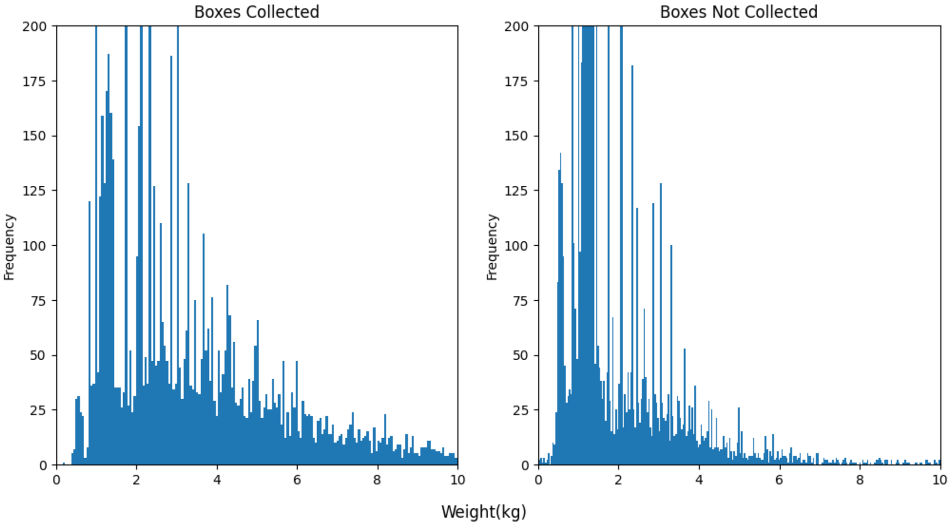


Figure 12

Weight Histogram Considering B =0.1, α =0.4, and β = 60



To offer a better understanding of the model's outcomes in terms of weight and distance fluctuations, we include the ratio of available cardboard weight to the distance required to collect it. This weigh-distance ratio is presented in Figure 13, which depicts a box plot with a constant β and different α values to assess their impact on the model. Figure 14 shows a similar structure, but with a fixed value of α and different β values to assess its impact. The plots differentiate between boxes recommended for collection and those that are not.

The results indicate that a box is unlikely to be collected if the weight-distance ratio is less than 7.5 for most of the combinations of α and β. However, it is more likely to be collected in the opposite case. The weight-distance factor varies for collected boxes based on parameters α and β, with α having the greatest influence; lower values of α cause the model to prioritize boxes with a higher weight-distance ratio. The relationship between β and the weight-distance factor is the same, but its impact is less significant. The model prioritizes weight and distance factors simultaneously to maximize CO_2 emissions.

Figure 13

Weight / Distance Boxplot for Collected and Non-Collected Boxes: Constant β *and Different* α

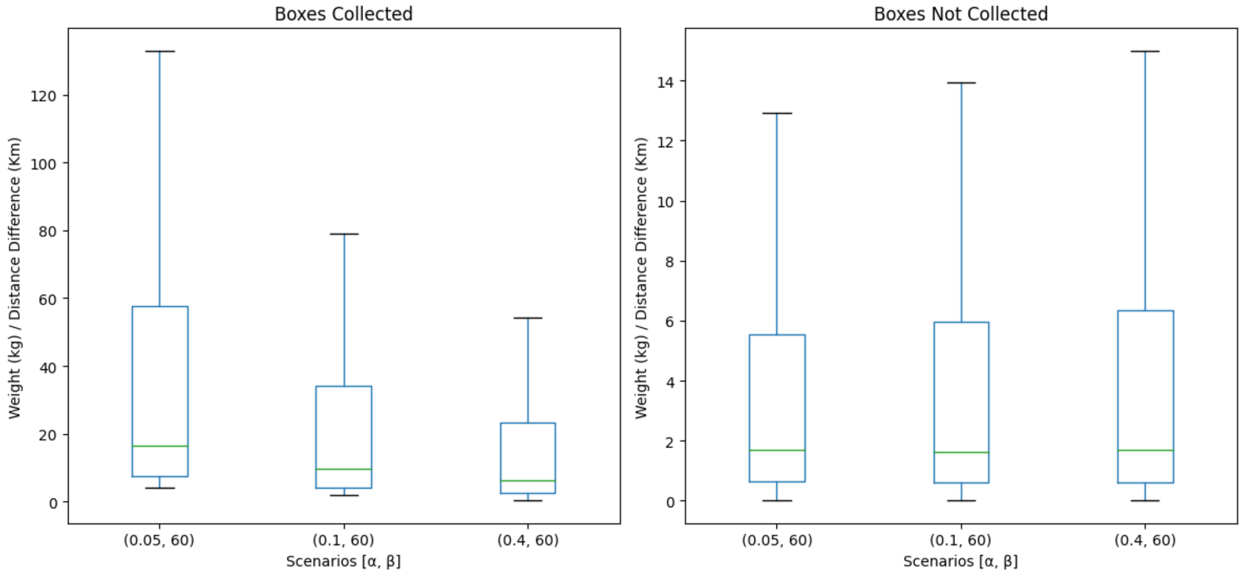
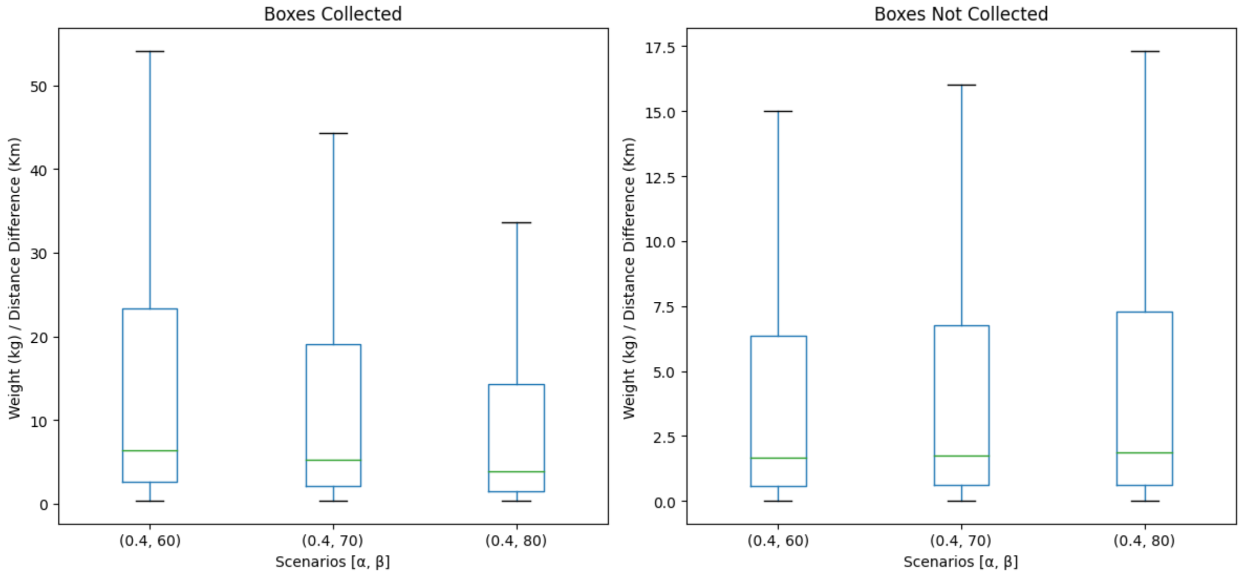


Figure 14

Weight / Distance Boxplot for Collected and Non-Collected Boxes: Constant α and Different β



5. Discussions and Managerial Insights

The presented results and analysis illustrate the relationship between CO_2 emission savings and the decisions to collect or not empty boxes for various combinations of parameters, such as environmental factor, budget, and the probability of being a delivery location. Section 4 yields several relevant insights for the model. We summarize these in the following.

Investing significant additional time not necessarily reduces CO_2 emissions. Our results show that extra additional time for pick-ups leads to higher emissions savings. However, CO_2 emissions eventually reach their maximum potential savings without requiring additional time investments.

The collection of all boxes is not imperative to achieve the highest possible reduction in CO_2 emissions. Our results clearly show that once the environmental prioritization factor reaches a certain value, the reduction in emissions begins to decrease, regardless of the increase in the number of collected boxes. E-commerce companies must optimize their delivery and pick-up routes according to the locations of the stops. If the locations are not close to each other, there is a high likelihood that only a small number of boxes would be eligible for pick-up.

The investment in electric vehicles will decrease emissions resulting from logistics and will incentivize a box collection policy. As stated in Section 4.3, the emissions factor for logistics is calculated based on a type 1 vehicle that is fully loaded and has a capacity of less than 7.5 tons. However, there is now a growing trend of companies investing in electric vehicles. Transitioning to such vehicles will decrease emissions, although it will not completely eradicate all carbon dioxide.

6. Conclusion

As most last-mile logistics companies continue to use cardboard boxes as single-use packaging, this optimization initiative provides a long-term competitive advantage in achieving the zero-waste climate pledge goals. If a last-mile delivery company decides to implement it, the following insights should be considered. First, the additional logistics required for picking up cardboard boxes and CO_2 emission savings follow a logistic growth pattern, and the budget should not exceed the value that will not result in significant changes in emissions.

Second, if a company decides to prioritize emissions savings over emissions generated by logistics activities, it can adjust the environmental prioritization parameter. Any value outside of a determined range will not cause a significant change to the output. A lower value reduces emission savings, while a higher value allows more boxes to be collected and increases savings. The effective range is associated with the locations of the customers and the cardboard weight available to collect.

Our results show that collecting more boxes does not always result in higher emissions savings. The trade-off between box collection and emissions reductions is determined by two factors: cardboard weight and extra driving distance. Customers with a higher cumulative cardboard weight and locations near delivery points are more likely to be visited. Whereas those in outlying areas and with the smallest cardboard box sizes are more likely to be ignored, demonstrating that the number of boxes is not a deciding factor, but distance and weight are. The pick-up decisions prioritize the weight-distance ratio when deciding which customers should be visited.

It is worth noting that any change to a greener logistics mode of transportation, such as new truck models, electric vehicles, and drones, will result in greater fuel-related carbon savings. Furthermore, the landscape of each city, population density, and traffic may influence the route optimization for determining which boxes should be collected.

While this study focuses on last-mile delivery for business-to-consumer e-commerce companies, the findings can apply to other businesses. Business-to-business, especially retailers, accumulate many boxes from their suppliers. When suppliers deliver new products, they could collect the cardboard boxes for reuse instead of recycling them. Future studies can investigate this approach. Another avenue for future research is the implementation of established pick-up locations in key areas of the city. As an alternative to collecting the boxes from each customer, the truck would collect, at one single stop, a larger group of boxes. It is critical to investigate the optimal location and number of centers for the greatest reductions in emissions and costs.

Leading companies in the e-commerce industry have already set climate pledge objectives for 2040, identifying two potential approaches to meet the targets: one focuses on supply chain decisions, while the other invests in innovative technology that delivers carbon savings. Our initiative focuses on optimizing supply chain decisions in the last-mile delivery segment, allowing businesses to achieve short-term emissions savings with substantially less expenditure than greener technology development.

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