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Provider-Side Cost and Climate Feasibility of Reusable Packaging in Parcel-Locker Last-Mile Delivery: Evidence from Milan

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Abstract

This thesis evaluates the provider-side cost and climate-change feasibility of reusable packaging in a parcel-locker last-mile delivery system in Milan. It compares three scenarios for one delivered parcel: S1, single-use cardboard packaging; S2, a centralized reusable loop represented by a HeyCircle M-informed polypropylene-rich package proxy; and S3, a local-circulation loop represented by a ReZip-style reusable cardboard package proxy. ArcGIS routing outputs are integrated with packaging life-cycle climate-impact accounting and provider-side cost modelling for route operation, package acquisition, maintenance or cleaning, capacity-based empty-package redistribution and end-of-life handling. A 50 km one-way rigid-truck redistribution leg from the central facility or depot to a representative fulfilment/packing point applies to all centrally processed S2 packages and to the 50% depot-return fraction in S3. Because neither reusable configuration operates in Milan, the deterministic assessment relies on transparent assumptions and proxy data and lacks an independent operational dataset for external validation. In the Milan base network, S1 costs 0.770 EUR/parcel and generates 0.319 kg CO₂e/parcel. S2 lowers the impact to 0.102 kg CO₂e/parcel but raises cost to 1.029 EUR/parcel, mainly because of package acquisition and central maintenance; S3 reaches 0.615 EUR/parcel and 0.047 kg CO₂e/parcel under the local-circulation proxy assumptions. Cost parity with S1 requires about 169 effective uses for S2 and 9.27 for S3. Sensitivity tests of attributed redistribution vehicle distance (25–100 km, with the high case including a 50 km empty return) and capacity-based allocation quantity produce small changes and retain the scenario ordering. Reusable packaging is therefore not automatically provider-side feasible: performance depends on realized reuse, loop governance and the allocation of return, maintenance, redistribution and stock-control burdens.

Keywords: parcel lockers; reusable packaging; provider-side break-even.

Abstract in lingua italiana

Questa tesi valuta la fattibilità economica lato provider e l'impatto climatico degli imballaggi riutilizzabili in un sistema di consegna dell'ultimo miglio basato su parcel locker a Milano. Confronta tre scenari per un pacco consegnato: S1, imballaggio monouso in cartone; S2, ciclo riutilizzabile centralizzato rappresentato da un imballaggio proxy ricco di polipropilene basato su HeyCircle M; S3, ciclo a circolazione locale rappresentato da un imballaggio proxy in cartone in stile ReZip. I risultati di routing ottenuti con ArcGIS sono integrati con la contabilizzazione dell'impatto climatico del ciclo di vita e con un modello di costo lato provider per operazioni di consegna, acquisizione, manutenzione o pulizia, redistribuzione degli imballaggi vuoti allocata in base alla capacità e fine vita. Una tratta unidirezionale di 50 km con autocarro rigido dal centro o deposito a un punto rappresentativo di preparazione/confezionamento degli ordini si applica a tutti gli imballaggi S2 trattati centralmente e alla quota S3 del 50% che rientra al deposito. Poiché nessuna delle due configurazioni riutilizzabili è operativa a Milano, la valutazione deterministica utilizza ipotesi trasparenti e dati proxy e non dispone di dati operativi indipendenti per la validazione esterna. Nella rete base di Milano, S1 costa 0.770 EUR/pacco e genera 0.319 kg CO₂e/pacco. S2 riduce l'impatto a 0.102 kg CO₂e/pacco, ma aumenta il costo a 1.029 EUR/pacco, principalmente per acquisizione e manutenzione centralizzata; S3 raggiunge 0.615 EUR/pacco e 0.047 kg CO₂e/pacco nelle ipotesi proxy di circolazione locale. La parità di costo con S1 richiede circa 169 usi effettivi per S2 e 9.27 per S3. Le prove di sensibilità sulla distanza di veicolo attribuita alla redistribuzione (25–100 km, con il caso alto che include un ritorno a vuoto di 50 km) e sulla quantità di allocazione basata sulla capacità producono variazioni contenute e mantengono invariato l'ordinamento degli scenari. Gli imballaggi riutilizzabili non sono quindi automaticamente fattibili lato provider: i risultati dipendono dagli usi effettivi, dalla governance del ciclo e dalla distribuzione dei carichi di ritorno, manutenzione, redistribuzione e gestione dello stock.

Parole chiave: parcel locker; imballaggi riutilizzabili; break-even lato provider.

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1 | Introduction

1.1. Background

E-commerce has become an important part of European retail, and its growth impacts product flows, parcels, packaging, and resources related to logistics moving through the city environment. According to Eurostat, in 2024 77% of Internet users living in the EU bought or ordered goods or services online in the past 12 months, compared to 59% in 2014 [27]. This trend is important for the last-mile delivery, as online orders are fragmented into parcel flows and require connections to household and workplace addresses, as well as to out-of-home collection points. Moreover, the trend has implications for packaging as e-commerce deliveries often require transport packaging to protect the products being fulfilled and moved around.

The last-mile delivery of those parcels is one of the components of the sustainability challenge. Last-mile delivery depends on customer availability, urban density, restrictions on routing, service time, vehicle capacity, and location of delivery facilities. Boysen et al. see the last-mile delivery problem as an expanding operational problem, driven by e-commerce and urbanization and involving infrastructure design, fleet and personnel planning, routing and scheduling as decision-making domains [4]. In that regard, parcel lockers are not just another address but the delivery node used to consolidate couriers' efforts and make it possible for customers to pick up parcels outside of their homes. Market data show a trend towards out-of-home delivery: according to DHL, 35% of European customers choose direct out-of-home delivery, and 10% and 25% of Italian customers prefer lockers and parcel shops respectively [14]. These numbers must not be considered as the proportion of parcels delivered via lockers; instead, they indicate that out-of-home delivery nodes have become an important delivery interface in the face of e-commerce demand.

Figure 1.1 summarizes the motivation cascade linking e-commerce growth, parcel-locker delivery interfaces, packaging pressure and the research opportunity addressed in this thesis.

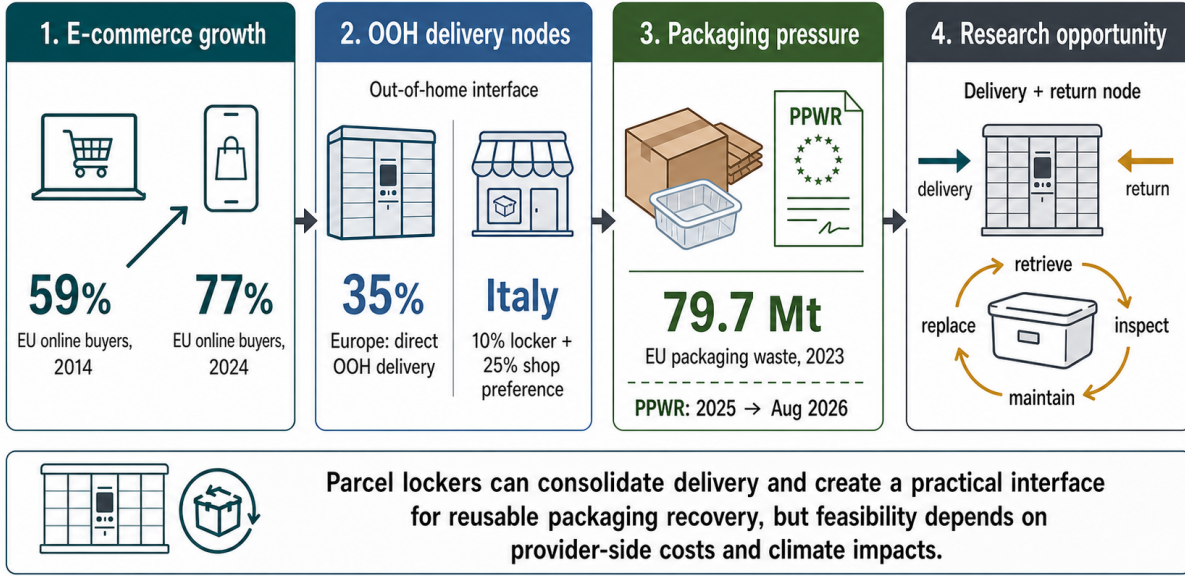


Figure 1.1: Motivation cascade linking e-commerce growth, out-of-home delivery nodes, packaging pressure and the research opportunity for reusable packaging in parcel-locker systems. The online shopping and packaging-waste figures are reported by Eurostat, while the out-of-home delivery preference figures are reported by DHL [14, 27, 28].

Packaging is an important problem as well. In 2023 the EU generated 79.7 million tonnes of packaging waste, amounting to 177.8 kg per capita [28]. At the same time, the packaging policy in Europe is becoming more circular. The European Commission sees high quantity of packaging with low reuse, collection, and recycling rates as obstacles to a low-carbon circular economy. The Regulation (EU) 2025/40 on packaging and packaging waste entered into force on 11 February 2025 and will generally apply from 12 August 2026 [24, 26]. These policy statements and statistics do not necessarily mean that reusable packaging is always better but help understand why packaging became the logistics and operations problem, not just materials management problem.

Parcel lockers become relevant to this question because they could serve as a link between delivery flows and reverse flows. The home-delivered parcel is distributed among private addresses after the delivery, whereas the parcel locker delivery finishes at the node repeatedly visited by logistics providers and their customers. Hence, the locker serves as the node where the return of the parcels and reusable packaging can be arranged. However, the return function is not automatic. Lockers may act as a return interface only when they are configured for returns and related handling operations. Therefore, reusable packaging in a parcel-locker system needs to be assessed rather than assumed to be feasible.

Reusable packaging changes the nature of the packaging in this respect. The package in a single-use system is mostly an input material for one parcel and ends up in recycling or disposal. In a reusable system, the package becomes an asset that needs to be retrieved, inspected, maintained or cleaned, stored, replenished, and finally recycled or replaced. The reviews on reusable packaging show that the environmental performance of the packaging system depends on the reuse rate, number of reuse cycles, material choice, cleaning, reverse logistics, and system design [5, 10, 55]. Similarly, operations management literature treats the reusable packaging and the returnable transport items as the asset used in the closed-loop supply chain and requires decisions to be made about the ownership, dispatch and return planning, maintenance, repairs, replacements, and inventory levels [34, 51]. As for e-commerce packaging specifically, the research shows that the climate break-even can be achieved by reusable packaging if there are enough reuse cycles and not too burdensome return logistics [7, 73].

This thesis sits at the intersection of these two strands. While parcel-locker studies have modelled delivery consolidation, route costs, locker location, service time, and environmental performance [54, 58, 64], and reusable-packaging studies have examined reuse cycles, return rates, cleaning, reverse logistics, and system design, less attention has been paid to what happens when reusable packaging is introduced into parcel-locker operations as a circulating asset. This creates a feasibility question at the level of the locker-based delivery system: how reusable packaging performs when retrieval, inspection, maintenance or cleaning, return handling, and eventual replacement are considered after delivery.

1.2. Problem Statement

The key issue investigated in this thesis is reusable packaging, which is commonly discussed as a circular alternative to single-use packaging, while parcel lockers are commonly viewed as a last-mile delivery innovation. Separation of the two leads to the exclusion of the characteristic feature of the system. While the parcel lockers can make reusable packaging more plausible through the repeated interface for return flows, the reusable packaging can complicate the parcel locker operations through the introduction of return handling, inspection, maintenance, and replacement tasks not involved in the single-use packaging baseline.

The previous parcel locker studies provide the evidence on route design, delivery consolidation, location choice, service time, costs, and emissions [54, 58, 64], while the reusable packaging studies focus on the reuse cycles, return rates, cleaning, reverse logistics, and packaging ownership [5, 10, 55]. The contribution of this thesis lies in the investigation

of the combined provider-side viability of reusable packaging in a parcel locker last-mile delivery system.

Figure 1.2 positions this research gap at the intersection of parcel-locker delivery and reusable-packaging research.

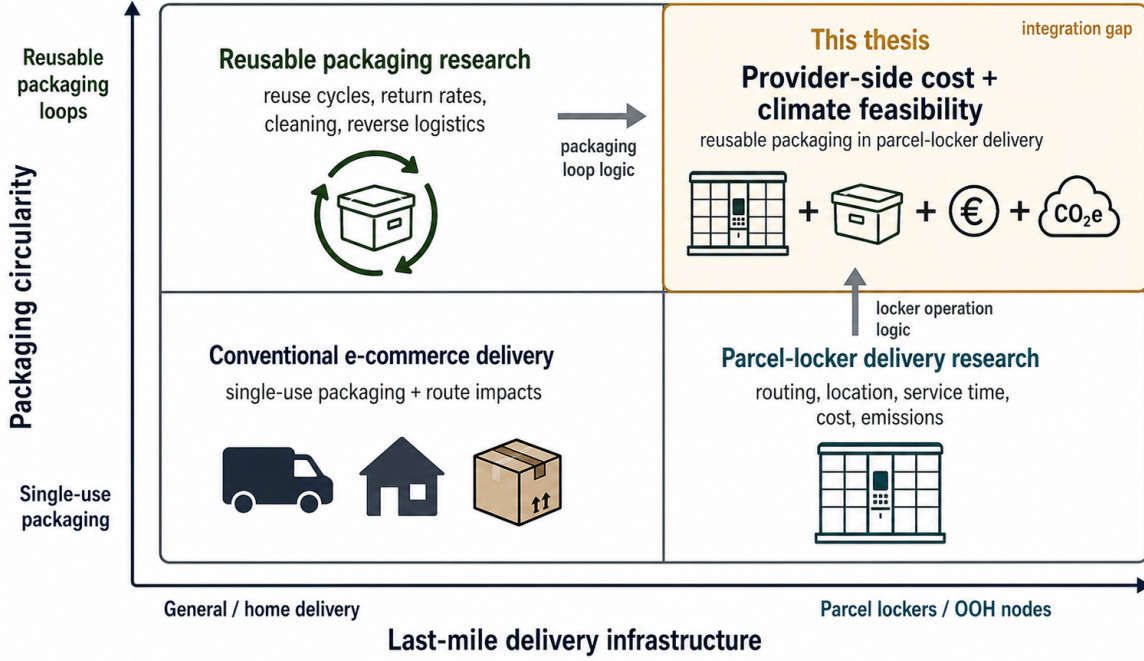


Figure 1.2: Research gap matrix positioning this thesis at the intersection of parcel-locker last-mile delivery research and reusable-packaging research. The thesis integrates these streams through a provider-side cost and climate-change feasibility assessment.

The analysis adopts a provider-side boundary. It covers vehicle routing, delivery operations, packaging acquisition, maintenance or cleaning labour, capacity-based allocation of empty-package redistribution from the central facility or depot to a representative fulfilment/packing point, and provider-controlled end-of-life handling of packaging. Product manufacturing and use, customer trips to lockers, customer incentives or deposits, and IT platform development costs are outside the quantitative model. Recovery from lockers to the central facility is represented as integrated into locker-based flows. The additional empty-package redistribution leg applies to all centrally processed S2 packages and to the S3 depot-return fraction, set at 50% in the base case. Within this scope, the thesis evaluates the cost and climate-change consequences of integrating reusable packaging into the parcel-locker delivery system in Milan.

In terms of the context, the case study involves the situation in Milan where parcel lockers

already exist as the element of the urban e-commerce delivery system. The empirical part includes a Milan base-network case, route operational modeling together with life-cycle climate-impact accounting and provider-side cost calculations. There are three scenarios under investigation. Scenario S1 is based on single-use cardboard packaging. Scenario S2 uses a centralized reusable loop with a HeyCircle M-type flexible polypropylene-rich package as a proxy for a durable reusable design. Scenario S3 assumes a local-circulation loop with a ReZip-type package as a proxy for a lighter reusable design. The comparison evaluates how differences in packaging type and reuse-loop design affect provider-side cost and climate-change feasibility in the parcel-locker system.

1.3. Research Aim and Questions

The aim of this thesis is to evaluate the provider-side cost and climate-change feasibility of reusable packaging in a parcel-locker-based last-mile delivery system in Milan. The functional unit of the analysis is one parcel delivered in the last-mile delivery system based on the parcel lockers from the provider's perspective. The analysis involves integration of the route planning, packaging life-cycle climate-impact accounting, and cost modeling for the route operation, packaging loop and redistribution transport.

Guiding questions:

1. What is the provider-side cost of delivering one parcel in the parcel locker last-mile delivery system in Milan with the single-use cardboard packaging and with two different designs of the reusable packaging loop?
2. What is the climate-change impact, expressed as kg CO₂e per parcel, of delivering one parcel in the same scenarios taking into account route emissions, packaging production, maintenance or cleaning, redistribution and end-of-life handling?
3. Under what selected reuse-loop conditions can the reusable packaging scenarios become competitive with the single-use cardboard baseline in both provider-side cost and climate-change impact?

1.4. Research Contribution

The thesis contributes to the literature through the integration of two sustainability strategies that are typically studied separately. It examines parcel lockers and reusable packaging as an integrated logistics setting in which the locker may support both delivery and reusable-packaging return flows.

The methodological contribution involves the combination of route planning output, packaging life-cycle inventory data, and provider-side cost components within the single consistent scenario framework. This allows examining the trade-offs that can not be captured in isolated packaging or route level assessments. For example, the reusable package could help decrease the impacts of packaging production per parcel while the provider could increase the labor or acquisition costs if the loop needed to be maintained centrally. Conversely, decentralized or local-circulation loops may lower the provider-side costs but would need assumptions about return rates, effective reuse cycles, and packaging losses.

The managerial contribution is to provide the insights for the providers of parcel-locker delivery and, specifically, the reusable-packaging service designers. The findings could contribute to the decisions on the design of the reusable-packaging loop in parcel-locker delivery. The thesis is focused on the provider-side cost and climate-change feasibility, and the scoped perspective is considered valuable as the provider is responsible for operating the loop, allocating the labor, coordinating return and maintenance activities, and bearing the extra costs.

1.5. Thesis Structure

Figure 1.3 summarizes the thesis logic from the motivation and research gap to the scenario model, break-even analysis and provider-side feasibility interpretation.

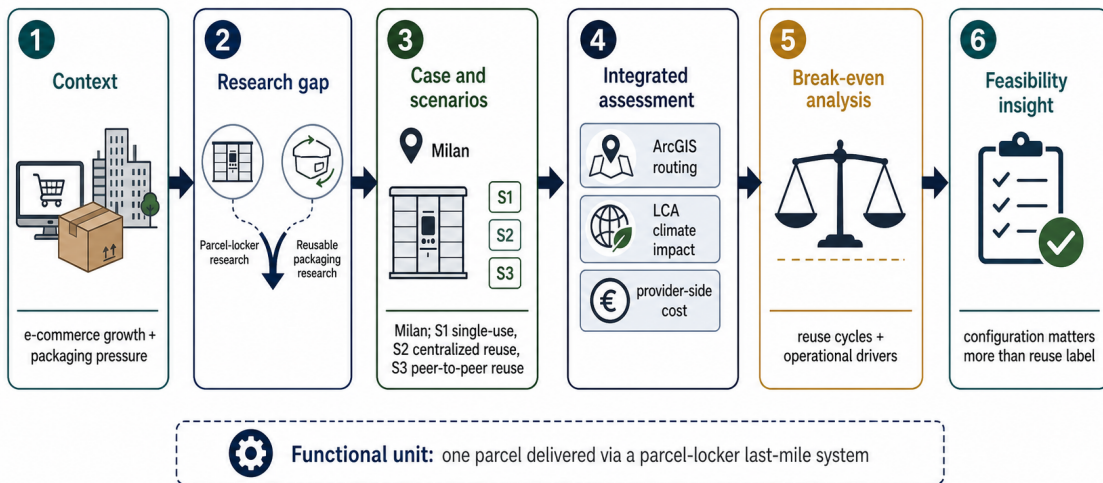


Figure 1.3: Thesis logic roadmap. The study moves from the e-commerce and packaging context to the research gap, Milan case scenarios, integrated route, life-cycle climate-impact and cost assessment, break-even analysis and provider-side feasibility interpretation.

The rest of the thesis is organized as follows. Chapter 2 provides the literature review on the topic of parcel locker last-mile delivery, reusable packaging, life-cycle assessment, and provider-side cost modeling. Chapter 3 describes the methodology involving the case study setting, scenario definition, vehicle routing assumptions, life-cycle climate-impact model, provider-side cost model, and threshold and sensitivity analysis. Chapter 4 contains the results of the base case, threshold checks and the sensitivity analysis. Chapter 5 discusses the findings, operational and climate-change implications, and the limitations of the study. Chapter 6 provides conclusions and suggestions for future research.

2 | Literature Review and Theoretical Background

2.1. Parcel-Locker Last-Mile Delivery

Parcel lockers are part of out-of-home delivery (OOHD), which also includes attended parcel shops and other collection points used as alternatives to direct home delivery. In this literature, lockers are not treated simply as additional delivery addresses. They are handover nodes that separate the carrier's delivery operation from the recipient's collection activity. Survey-based research on last-mile delivery links such solutions to the wider growth of e-commerce and urban logistics pressures [4]. Recent OOHD reviews emphasize that these nodes can consolidate deliveries, improve route-planning flexibility and reduce failed home deliveries, but only when dedicated infrastructure and recipient participation are in place [45]. This perspective is important for the present thesis because the parcel locker is the delivery interface around which the Milan case-study system is built, and it is the node through which reusable packaging could be connected to return flows.

The first research stream considers parcel lockers from the point of view of network design and location choice. Deutsch and Golany consider the design of a parcel-locker network as the optimization of quantity, locations, and size of locker facilities that should maximize the provider's profit taking into account costs of facilities and discounts for customers' travel [13]. With this study, parcel lockers were defined as the infrastructure design problem, but not only a customer service feature. Further studies expand this concept by considering the location choice in the context of demand, recipient choice, cost and sustainability. Seghezzi et al. compare the cost advantages of parcel lockers and home delivery in urban and rural settings of Italy and show that the cost advantage is driven primarily by delivery density and decrease in failed deliveries [64]. Peppel and Spinler introduce the location choice problem by combining the multinomial logit choice model and the location choice model. They demonstrate that optimal locations of lockers can reduce costs, but the environmental outcomes depend on regional context and recipient's

behavior [58]. This does not mean that a denser locker network is always better: optimal location and network extension involve a balance between recipient accessibility, facility costs, parcel volume per locker and the risk of fragmented deliveries across too many nodes [58, 59]. Therefore, these studies suggest that the feasibility of the locker solution implies not only its installation, but also its location, ability to attract demand and interactions with existing delivery routes.

The second stream examines whether lockers really make the operations more efficient. Field study by Ranjbari et al. demonstrates that common carrier parcel lockers in residential buildings can reduce the time spent by couriers in buildings by about 50-60%, while reducing vehicle dwell time in loading zones is not statistically significant [61]. This fact is significant because saving time at one stage of delivery process does not necessarily mean proportionate saving in the whole process. The evidence provided by Singapore Locker Alliance studies is consistent with this finding, but it is examined from network perspective. Lyu and Teo demonstrate that the choice of locker, walking distance and coverage are important factors for network utilization [49]. Wang et al. demonstrate that the use of the locker network under the pilot and two-trip operating mode increases total delivery distance by 41.92% on average, and the benefits of optimized mixed-trip routing can be insignificant under low locker adoption [70]. Thus, the studies from the operational literature confirm the potential of lockers, but at the same time recognize its conditionality on adoption, network design and integration with home deliveries in courier routes.

The third discussion concerns the environmental performance of lockers and pick-up points. Some modeling studies show that the use of lockers allows decreasing the provider-side distance, fuel consumption and delivery costs. However, some papers warn that the results could be different when recipient's trips to receive parcels are taken into account. Peppel and Spinler note positive CO₂e saving from the viewpoint of the logistics service provider in regional case studies, but the overall emissions could be higher in less populated areas because of longer distances to visit lockers [58]. The same conclusion was made by Niemeijer and Buijs using the combination of the route efficiency model and the trip chaining model that takes into account customer's transport mode; in addition, they claim that pick-up points are not always environmentally friendly, but the potential for carbon saving is high in urban context [54]. Pinchasik et al. separate the effects of the logistics service provider from recipient's pick-up trips and show robust CO₂ reduction under real-life behavior scenarios, while the constructed scenario with dedicated pick-up car trips leads to the reverse outcome [59]. This line of research is especially important for the present thesis since it demonstrates why the perspective of the assessment should

be explicitly stated.

These operational and environmental trade-offs are summarized in Table 2.1.

Dimension	Core trade-off	Potential benefit	Condition or risk
Network and location design	Feasibility depends on demand density, location and recipient choice.	Consolidation can reduce provider-side cost and improve route use.	Outcomes vary by urban/rural context, locker density, walking distance, recipient behavior and delivery fragmentation.
Operational efficiency	Handover-time savings require sufficient adoption and route integration.	Common-carrier lockers can reduce in-building delivery time by about 50–60%.	Low adoption or poorly integrated two-trip operation can increase distance; Wang et al. report +41.92% in the Singapore pilot two-trip mode.
Environmental assessment boundary	Provider-side route savings may be offset by recipient pick-up travel.	Urban locker or pick-up networks can have carbon-saving potential.	Dedicated car pick-up trips, sparse areas or long customer travel distances can weaken or reverse the benefit.

Table 2.1: Operational and environmental trade-offs in parcel-locker last-mile delivery literature.

Source: Author’s synthesis based on [54, 58, 59, 61, 64, 70].

Finally, parcel lockers could be considered as parts of the urban logistics ecosystem. In this regard, the OOH review distinguishes between logistics service providers that own and operate the own infrastructure, delivery service providers that use the third-party facilities, and facility providers that offer and maintain the locker or pick-up networks [45]. Ma et al. make a similar distinction between the independent self-collection facilities available for different last-mile operators and the facilities owned by each operator or platform, claiming that the design of self-collection systems involves joint consideration of operator planning and consumer participation [50]. Moreover, the Singapore Locker Alliance case demonstrates the possibility of the open-access or carrier-neutral locker network designed to complement the proprietary locker systems [49]. Thus, this literature suggests that the parcel locker should be considered not only as a physical device, but also as the infrastructure interface between couriers, facility providers, retailers and consumers.

This ecosystem interpretation is summarized in Figure 2.1.

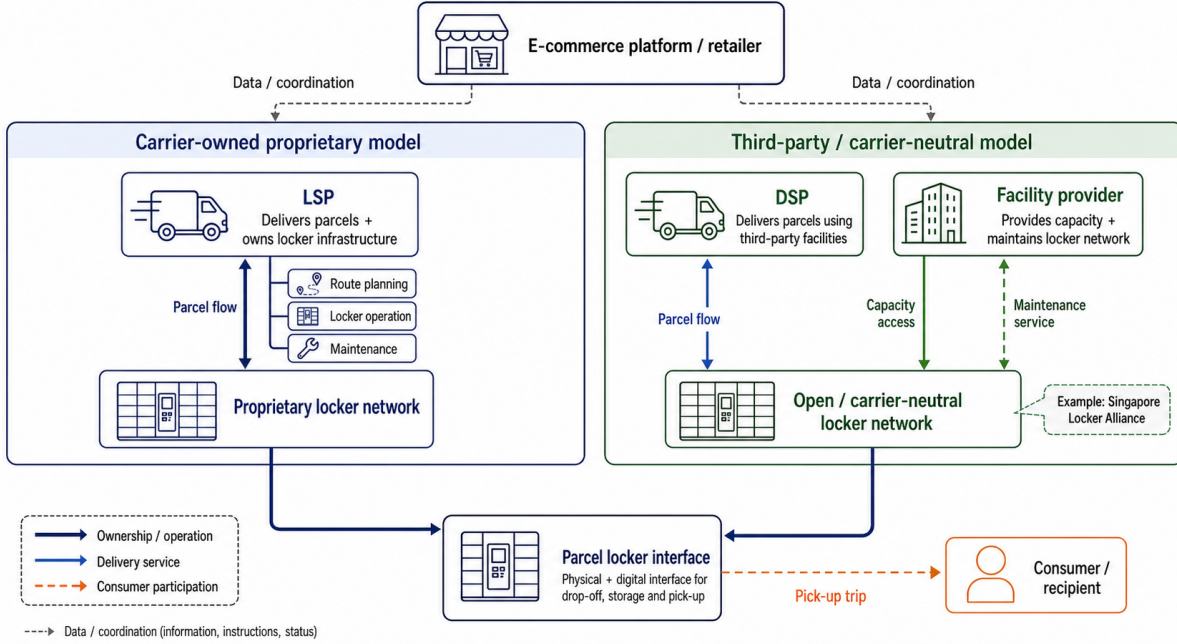


Figure 2.1: Parcel lockers as infrastructure interfaces in proprietary and carrier-neutral last-mile delivery ecosystems. Source: author’s synthesis based on [45, 49, 50].

For the purposes of the present thesis, the main implication is that there already exists a good basis in the parcel locker literature in terms of delivery consolidation, location choice, routing, service time, adoption, cost and emissions. However, this literature usually discusses parcel lockers as handover and storage nodes for parcels and generally ignores how the system changes when packaging becomes the circulating element within this system. In this situation, the provider might need to retrieve, inspect, maintain or clean, store, redistribute and finally replace or recycle the packaging. These actions go beyond the typical parcel locker problem and connect the last-mile infrastructure to the literature on reusable packaging and circular packaging systems, which will be discussed in the next section.

2.2. Reusable Packaging and Circular Packaging Systems

The discussion of parcel lockers readily spills over to a second body of literature about reusable packaging and circular packaging systems. In this domain, reusable packaging is not seen as just another type of material; instead, it is viewed as a system in need of

repetitive movement between consumers, logistics providers, and recovery points. Unlike single-use packaging, reusable packaging makes packaging serve a function of something that needs to be returned, stored, checked, washed, repaired, traced, and eventually replaced. Thus, the performance of reusable packaging is not only a property of packaging but also a property of the reuse system as a whole [5, 10, 51].

This closed-loop interpretation is summarized in Figure 2.2.

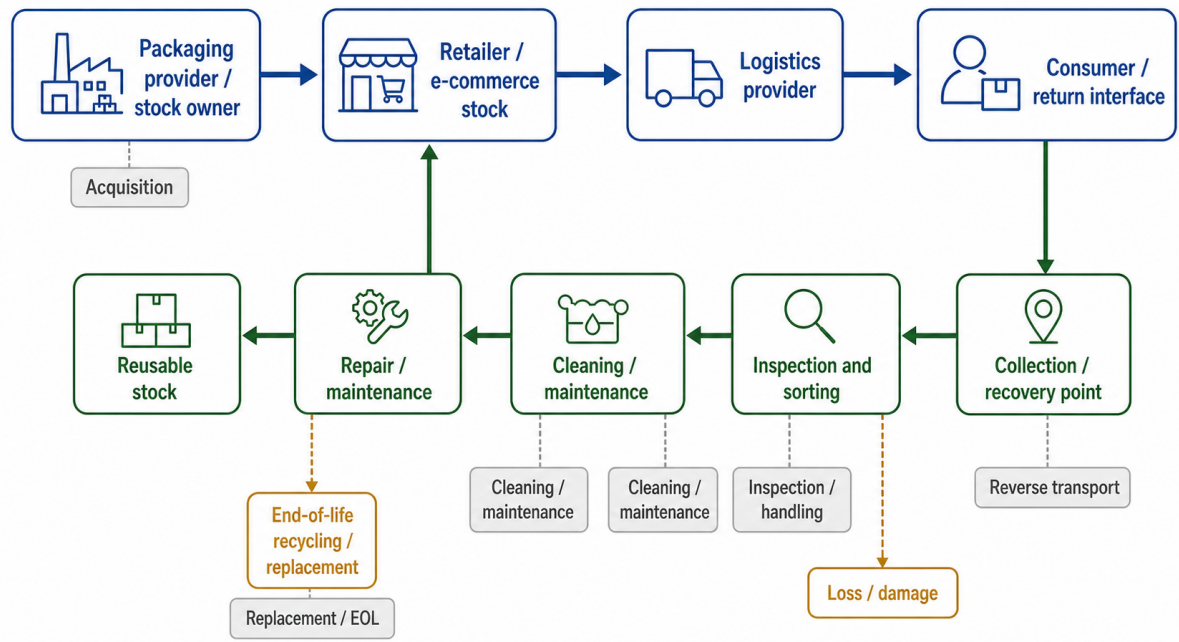


Figure 2.2: Closed-loop operational cycle of reusable packaging systems. Source: author's synthesis based on [3, 5, 34, 51].

In the existing literature, reusable packaging is usually differentiated based on its place in packaging hierarchy and dynamics of reuse. Coelho et al. [10] distinguish several types of reusable packaging: refillable packaging, returnable packaging, and reusable transit packaging. Similarly, Bradley and Corsini [5] make a distinction between primary refillable packaging, primary returnable packaging, and secondary or tertiary returnable packaging. This classification is important because reusable packaging systems for B2B logistics (like pallets, crates, and returnable transport items) are simpler than e-commerce packaging. It is easier to organize because there are fewer actors and flows involved, and it is easier to allocate responsibility for return in B2B scenarios. In contrast, e-commerce packaging often relies on customer participation, easy channels for return, and cooperation between retailers, logistics providers, and packaging companies [5, 10].

These classification dimensions are summarized in Figure 2.3.

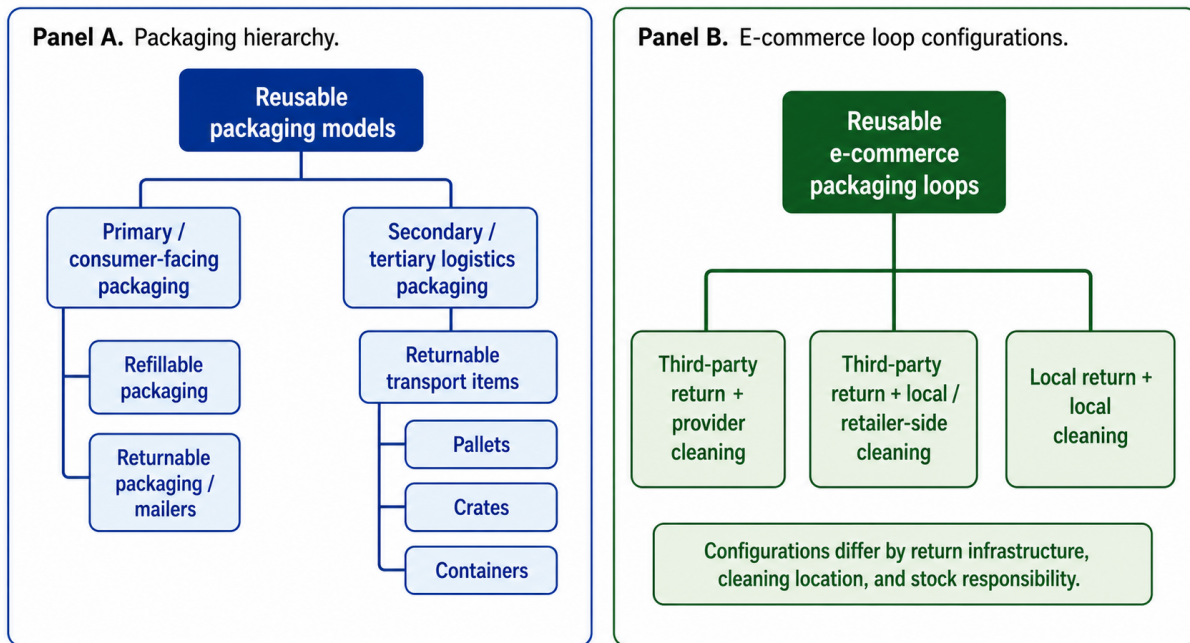


Figure 2.3: Taxonomy of reusable packaging models and e-commerce loop configurations. Source: author's synthesis based on [5, 10, 35].

One of the common conclusions made in the literature is that reusable packaging cannot be assumed environmentally superior to disposable packaging. In several literature reviews, it is emphasized that the comparison between reusable and disposable packaging is heavily dependent on the context. Bradley and Corsini [5] show that the sustainability of reusable packaging depends on several factors: customer acceptance, return rate, loss rate, supply chain length, standardization, and management of the system. Pålsson and Olsson [55] come to a similar conclusion: the existing evidence is inconsistent, and reusable packaging can be more sustainable than disposable packaging only in certain circumstances, depending on reuse cycles, transport distances, material of the packaging, recycling considerations, and supply chain configuration. Thus, the question is not whether reusable packaging is better but when it is better.

The dependence on particular logistics conditions is especially evident in e-commerce packaging. Park and Waqar [56] show that environmental performance of returnable mailers depends greatly on the total distance traveled per cycle and the number of reuse cycles. The authors suggest that reusable mailers can perform better in shorter or localized supply chains, but in long-distance and low number of reuse cycles, this performance is lower. Park et al. [57] also compare different models of returnable packaging and show that centralized and decentralized designs result in different environmental impacts. These papers contribute to the discourse by moving the debate from simple reusable vs.

disposable dichotomy to particular logistics conditions where reuse is preferable.

An additional strand of literature considers reusable packaging as returnable transport item or logistics assets that circulate. Glock [34] defines returnable transport items as reusable packaging assets (pallets, boxes, crates, and containers) moving in closed-loop systems. In such a system, the package has to be dispatched, returned, washed, repaired, replaced or stored to be used again. Mahmoudi and Parviziomran [51] further clarify that the management of reusable packaging includes decisions about asset ownership, inventory management, return forecasting, collection frequency, repair quality, safety stocks, and tracking. This strand of literature is especially relevant to the present thesis as it shows special features of reusable packaging not present in single-use systems.

The complexity of operations associated with reusable packaging is closely related to cost considerations. The literature identifies several cost drivers: acquisition cost, washing and maintenance, handling labor, reverse logistics, storage costs, tracking systems, losses, damages, and replacement. Betts et al. [3] suggest a number of metrics for evaluation of reusable packaging in circular supply chains and emphasize that package recovery and package loss are crucial aspects of environmental performance and logistics cost. Bradley and Corsini [5] note that reusable systems can have higher infrastructure and labor costs, especially if washing and maintenance is needed. Thus, while reusable packaging reduces demand for manufacturing of new packaging, it can also incur additional process costs.

The recent research on reusable packaging in e-commerce also sheds light on this topic. González Romero et al. [35] explore several cases of reusable packaging in European e-commerce and show three major factors impacting performance: material, return rate and reuse rate, and supply chain design. They show that the use of centralized systems increases reverse logistics distance, while decentralized systems lower transport burden if the packaging can be returned, washed and reused closer to the destination. Clement and Spinler [7] also analyze reusable packaging in e-commerce logistics and show that inventory balance, reuse rate, and network configuration can greatly impact both cost and emissions. While the focus of this study is on industrial packaging in e-commerce logistics rather than on consumer parcel packaging, it is still relevant as it demonstrates how reusable packaging changes logistics from a one-way process to a system with stock balance and circulation of assets.

For the purposes of the present thesis, it is especially important to notice that reusable packaging has to be considered as a system rather than an independent package. Several factors affecting performance of reusable packaging are already identified in the literature: number of reuse cycles, return rate, loss rate, material production, reverse logistics,

maintenance, storage, replacement and end-of-life treatment. However, these factors are usually studied in generic reusable packaging systems, B2B returnable transport item systems, or e-commerce packaging systems without explicit parcel-locker infrastructure. Such disconnect creates a gap between reusable packaging research and parcel-locker last-mile delivery research.

This gap is significant because parcel lockers can influence conditions of reusable packaging. A parcel locker network can not only serve as delivery channel for packages but also as return and local storage channel for reusable packaging. But this does not automatically make reusable packaging feasible because the providers will still need to collect returned packaging from lockers, wash or maintain it, redistribute reusable packaging stock, and replace the damaged or lost packaging. Thus, the combination of reusable packaging and parcel lockers requires an assessment that combines packaging life-cycle impact with last-mile routing and provider-side costs. This connection underpins the following sections dedicated to LCA and cost modeling.

2.3. LCA of Reusable Packaging in E-Commerce

After discussing reusable packaging as a circular system, this section turns to its environmental assessment.

LCA is an established and standardized methodology for comparing environmental burdens of product systems. In compliance with ISO 14040 and ISO 14044, LCA consists of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [41, 42]. For the packaging studies, the stage of goal and scope is especially important as it specifies the functional unit, system boundary, life cycle stages involved in the assessment, assumptions and data required. The functional unit is responsible for providing comparability among various packaging alternatives with the help of defining the service they deliver, whereas the system boundary defines the processes that are covered by the assessment. Otherwise, various studies may look like comparison of the same packaging alternatives while considering different systems.

The ISO-based LCA stages are summarized in Figure 2.4.

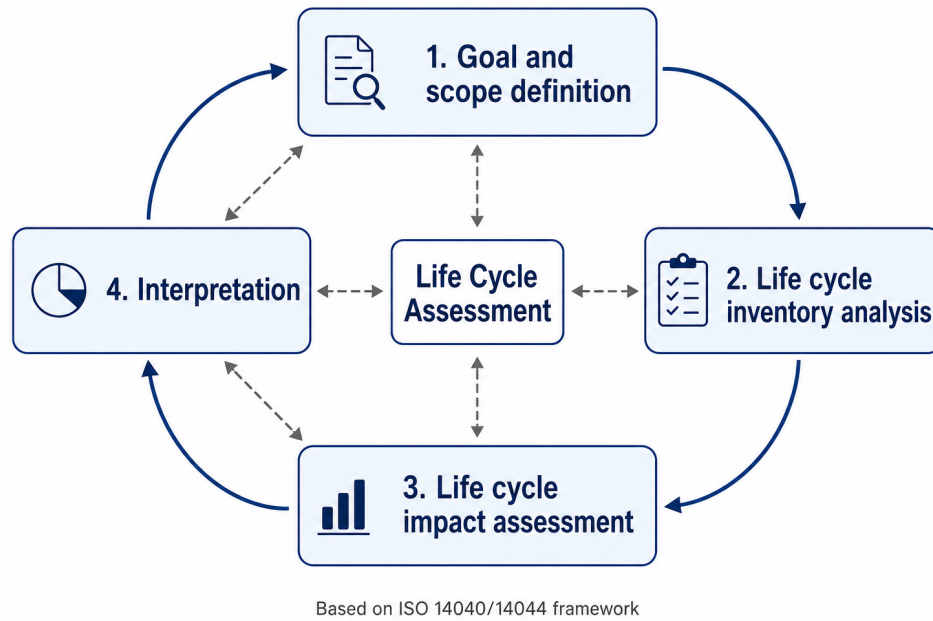


Figure 2.4: ISO 14040/14044 life cycle assessment framework. Source: author's schematic based on [41, 42].

The life cycle of packaging in e-commerce becomes even more complex owing to the multifunctionality of packaging: it protects the products, ensures its transportation and handling, and adds up to the customer experience. E-commerce often involves additional packaging compared to traditional retail and the impact of this packaging depends not only on the production of materials but also on the packaging size, transport distance, delivery mode, waste treatment, and return flows [19]. Frommeyer et al. present this idea clearly with the example of the online apparel sector. In their study, they combine interviews of retailers, data of consumers' surveys, and LCA results and reveal that consumers' preferences might not be consistent with the ranking produced by the LCA results. It shows the necessity of transparent environmental assessment instead of intuitive perception of packaging material [33].

Comparison of single-use and reusable packaging requires special attention in terms of methodology. Cottafava et al. argue that LCA results are extremely sensitive to assumptions about the functional unit, system boundary, and modeling and this sensitivity is especially high in case of reusable and single-use systems [12]. Key assumptions in case of reusable packaging include the number of reuses, package weight, sanitization/cleaning method, transport logistics, return rate, breakage rate, and end-of-life treatment. Therefore, Cottafava et al. recommend including multiple scenarios into the study and applying sensitivity analysis, scenario analysis, and break-even analysis. It is relevant for the cur-

rent thesis, as in this case, reusable packaging is considered not separately but as part of the logistics loop of the parcel-locker system.

The resulting difference in system boundaries is illustrated in Figure 2.5.

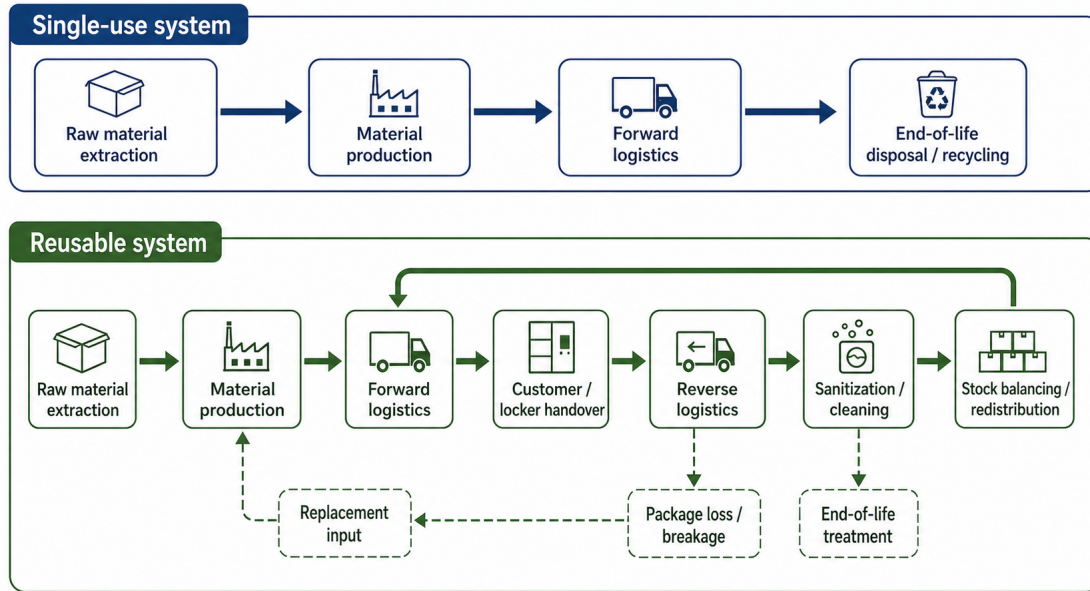


Figure 2.5: Comparison of LCA system boundaries between single-use and reusable packaging systems. Source: author’s synthesis based on [3, 12, 41, 42, 56, 57].

The empirical studies of LCA of returnable packaging in e-commerce confirm the above-mentioned approach. Park and Waqar compare a returnable polypropylene mailer with two alternative single-use packaging options in Canadian apparel e-commerce. They conduct a cradle-to-grave LCA using TRACI 2.1 impact categories [56]. According to their findings, the returnable mailer can outperform some single-use packages under favorable conditions, but the advantage in terms of environmental performance gets lost in case of change in consumer location or the number of reuse cycles. Specifically, the returnable option performs worse when there are few reuse cycles and long transport distance. In other words, the benefits from reuse depend on sufficient reuse cycles and efficient return routes.

This issue is developed further in Park et al.’s study where they assess various returnable packaging systems in terms of different e-commerce business models and packaging management [57]. As a result, it appears that a centralized returnable mailer system can involve higher environmental impact than a single-use mailer in most impact categories due to the increased transport distance. On the contrary, the decentralized returnable box system connected to a rental business model outperforms a single-use corrugated box in

several impact categories. Overall, the environmental performance of reusable packaging depends much on total trip distance, reuse frequency, loss rate, and return and maintenance systems organization. Such results are relevant for the current thesis, as S2 and S3 involve different configurations of the reuse loop rather than the same reusable packaging.

The similar conclusions were made based on the carbon-footprint analysis. Zimmermann and Bliklen conduct a comparison of single-use and reusable shipping packaging in e-commerce and use break-even analysis to identify the number of reuse cycles needed for reusable packaging to have a lower carbon footprint [73]. Zimmermann and Hauschke recently expand this research area and explore how transport allocation influences the carbon footprint of reusable shipping packaging in parcel deliveries [74]. They show that different allocation approaches can significantly affect the absolute carbon footprint of the packaging while the break-even points in their cases stay almost unchanged. The key point is that emissions from transport in parcel delivery are not neutral background information but need to be analyzed, especially in case when the results are presented per parcel or per use cycle.

Figure 2.6 summarizes the climate-impact and provider-side cost break-even conditions. The two thresholds may occur at different numbers of effective uses because they arise from different impact and cost structures.

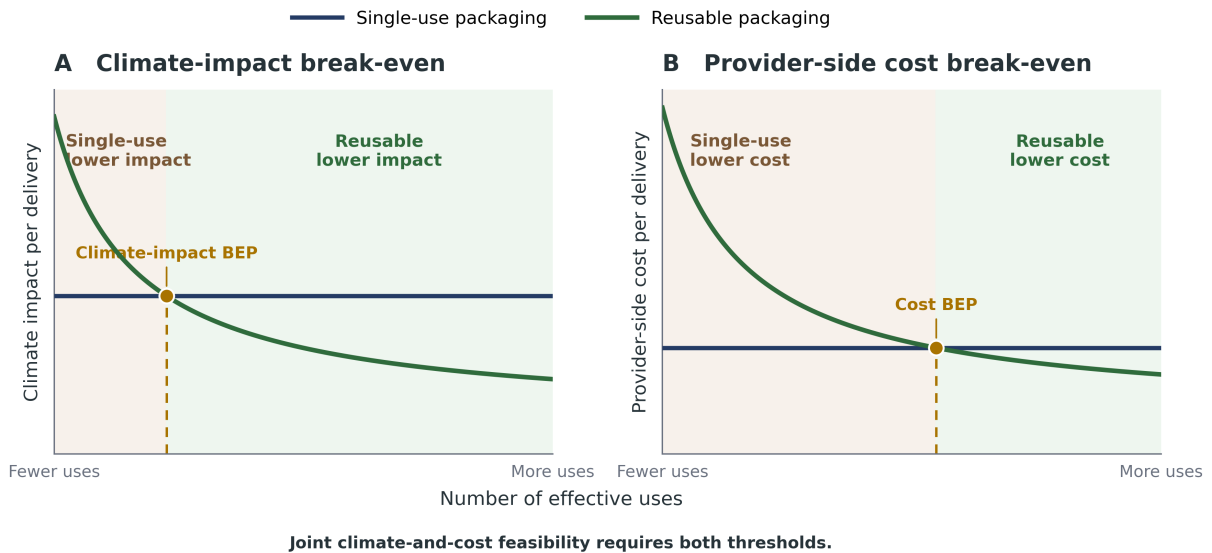


Figure 2.6: Conceptual illustration of climate-impact and provider-side cost break-even conditions for reusable packaging. Threshold positions are schematic, and their relative ordering depends on system conditions. Source: author's synthesis based on [3, 12, 53, 73, 74].

The evidence from non-European delivery systems confirms the above-mentioned ideas but it should not be immediately translated to the current situation in Milan. Tan et al. compare single-use plastic delivery bags and reusable plastic delivery boxes in China and find out that reusable boxes have better environmental performance in case of intra-city delivery but they can be worse in case of inter-city delivery due to additional transport impacts [66]. The study also reveals that the increase in the number of reuse cycles decreases the average impact per delivery cycle. It shows the general conclusion drawn from the literature review: the reusable packaging has better environmental performance in case of the short reuse loop and sufficient reuse.

There are three major implications for the current thesis from the above-mentioned literature. First, the perspective of assessment should be explicitly identified. In case of parcel lockers, it could be both the reduction of provider-side delivery effort and an additional customer-side delivery effort. Thus, it is required to identify whether the study evaluates the provider side, recipient side, or the whole urban mobility system. The thesis focuses on the provider side and considers the delivery and packaging loops organized/financed by the provider. Second, the functional unit should be connected to the logistics service analyzed. In this case, the functional unit is defined as one parcel delivered through the parcel-locker delivery system. Third, the reusable packaging should be evaluated through both static comparisons and break-even logic. Static results show the climate and cost impacts of reusable packaging under given assumptions, whereas the break-even analysis identifies the reuse-cycle and operating-condition thresholds needed for reusable scenarios to reach parity with single-use cardboard.

Overall, the literature on LCA suggests that the environmental viability of reusable e-commerce packaging is conditional but not universal. Besides material substitution, the key factors determining the environmental performance include the number of reuse cycles, return rate, replacement rate, sanitizing/cleaning/maintenance, transport distance, end-of-life assumption, and logistics impacts allocation. Thus, this thesis considers climate-change feasibility as the output of the entire parcel-locker reuse system but not as the inherent characteristic of the reusable packaging.

2.4. Provider-Side Cost Modelling

Moving from the environmental evaluation of reusable packaging to its economical side is essential. Indeed, a reusable packaging system not only affects the material use and emissions but also the cost structure faced by the parties who run the system. On the side of providers, the main issue is not only whether the use of reusable packaging results

in reduced impact per use but whether the additional operations required by the reuse loop can be accommodated in the parcel-locker last-mile delivery scenario.

Within the field of the literature about parcel lockers, costs are viewed as a part of the last-mile delivery cost structure and network design. Deutsch and Golany consider parcel locker network as a facility location and profit maximization problem where the costs include facility opening, operating costs, discount given to customers and the demand loss that occurs if the locker is located too far from the user [13]. The analysis done by Seghezzi et al. gives an explicit comparison between home delivery and parcel-locker delivery taking into account van costs, driver costs, failed delivery costs, locker operating costs, and investment payback. The researchers conclude that the parcel locker may reduce the costs of delivery mainly through higher density of delivery and lower number of failed deliveries depending on fill rate, annual cost of the locker, and context [64]. In turn, Peppel and Spinler incorporate the costs into a parcel-locker location model through a combination of the customer choice and mixed-integer optimization including costs of opening, operating, shipping, and CO₂e effects [58]. Altogether, it becomes evident that parcel locker is sufficiently analyzed as a cost-relevant last-mile infrastructure; however, the cost object is mainly the delivery operation and not the packaging circulation.

By comparison, the literature on reusable packaging and returnable transport items takes a completely different look on the matter of costs. Specifically, Mollenkopf et al. develop the model of relative costs of expendable and reusable container systems which includes such cost components as container purchase cost, transportation cost, labor cost, disposal cost, and recycling revenues [53]. The research concludes that decision outcomes are influenced by such factors as ratio of reusable to expendable cost, average daily volume, delivery distance, cycle time, pack quantity, and variability in peak volume [53]. Importantly, it makes clear that the use of reusable packaging should not be judged by division of purchase cost by the number of uses as a more complex systems-based approach should be used. In turn, Glock's review of returnable transport item models reaches the same conclusion stating that the management of reusable packaging includes purchasing, forecasting of returns, inventory control, repairs and replacements, routing, and management of lost or damaged items [34]. Furthermore, Mahmoudi and Parviziomran organize the literature into such themes as economic and environmental feasibility, logistics system design, and operations management emphasizing that such factors as ownership, reverse logistics, cleaning, maintenance, storage, and return rates influence the cost of reusable packaging system [51].

In recent years, some research moves the conversation closer to the topics of e-commerce and circular supply chains. Specifically, Betts et al. argue that total logistics cost is an

appropriate systems metric for reusable packaging taking into account such cost components as sorting cost, inspection cost, cleaning cost, storage cost, transportation cost, handling cost, fixed cost of the system, and cost of replacement for lost or damaged packages [3]. In turn, Clement and Spinler analyze returnable transport items in the context of the e-commerce distribution network showing that reuse, inventory balancing, and inter-warehouse shipments may decrease both packaging costs and environmental impact; however, the model is focused on the warehouse-level reuse transport items and not on parcel locker last-mile delivery [7]. Also, Sun analyses reusable express packaging in the context of inventory sharing and competition and demonstrates that reusable express packaging generates inventory decisions in stochastic loss rates and that sharing may improve the profits of express delivery companies [65]. Overall, the reusable express packaging may be considered as the shared and managed asset; however, it does not include the modeling of the parcel-locker route and the service of parcel lockers.

The cost parameters covered by these streams and by the present thesis are summarized in Table 2.2.

Study	Route	Time	Locker	Failed	Acquire	Return	Clean	Loss	Stock	EOL
Deutsch and Golany (2018)	P	–	Y	–	–	–	–	–	–	–
Seghezzi et al. (2022)	Y	Y	Y	Y	–	–	–	–	–	–
Peppel and Spinler (2022)	Y	–	Y	P	–	–	–	–	P	–
Mollenkopf et al. (2005)	Y	Y	–	–	Y	Y	–	Y	Y	Y
Glock (2017)	P	–	–	–	Y	Y	Y	Y	Y	P
Mahmoudi and Parviziomran (2020)	P	–	–	–	P	Y	Y	Y	Y	P
Betts et al. (2022)	Y	P	–	–	Y	Y	Y	Y	Y	P
Clement and Spinler (2025)	P	–	–	–	Y	Y	–	P	Y	P
Sun (2024)	P	–	–	–	Y	Y	–	Y	Y	–
This thesis	Y	Y	–	–	Y	P	Y	P	P	Y

Table 2.2: Cost parameters considered in parcel-locker and reusable-packaging cost literature.

Source and notes: Author's synthesis based on [3, 7, 13, 34, 51, 53, 58, 64, 65]. Y = explicitly included; P = partly included or treated indirectly; – = not included or outside the study scope. Acquire = packaging acquisition; Return = return or redistribution transport; Clean = cleaning or maintenance; Stock = inventory or cycle time; EOL = end-of-life treatment.

Overall, the literature reveals two relevant yet mostly separate perspectives. First, the parcel-locker literature reveals how density of delivery, structure of route, facility location, time of service, and failed deliveries affect last-mile costs. Second, the literature on reusable packaging and RTI shows how acquisition, return, loss, cleaning, maintenance, inventory balancing, and replacement affect costs of keeping the packaging in circulation. Still, these perspectives are rarely combined in one provider-side analysis. For the current

study, the important gap is not only lack of cost-focused analyses but the integration between parcel-locker routing/service operations and additional cost elements caused by reusable packaging loops.

3 | Methodology

3.1. Research Design and Analytical Framework

This study uses a scenario-based quantitative case study design. Instead of modeling a specific real-world commercial parcel locker system in its full extent of operations, the aim is to create an analogous setting where alternative packaging loops can be compared under the same urban delivery context. In the chosen case of Milan, parcel-locker locations and route-operation data anchor the route-operational layer, while the packaging-loop assumptions are scenario proxies rather than observed carrier-specific reusable-packaging operations. In this context, the comparison will be made between a single-use cardboard packaging and two types of reusable packaging, and thus concentrate on how the change of the packaging system affects provider side costs and climate change effects associated with delivery of a single parcel.

An integrated modeling framework is needed for this research due to the nature of the problem to be studied. Comparing to single-use packaging, which mainly used for one-way transport, reusable packaging changes the role of packaging more fundamentally. Instead of being a one-way transport input, it becomes an asset that requires return, possible checkup and/or maintenance, and possible redistribution and replacement over time. Therefore, the assessment cannot base itself on the weight of packaging or even its material type. It needs to include the effects of route operation, assumptions about reuse cycles, maintenance, costs incurred on the provider's part. The climate-change impact part follows life-cycle inventory and impact-assessment logic, with goal and scope, inventory, impact category, and interpretation explicitly defined [41, 42].

The proposed modeling framework includes three levels that are interrelated. The first level is the route operation model based on the ArcGIS/VRP route output. It gives the data on the distance of the route, route time, service-time implications, route cost, and emissions from transport operation. The second level is the packaging climate-impact and provider-side cost model, giving estimations on packaging production, acquisition, maintenance or cleaning, replacement, capacity-based allocation of empty-package redis-

tribution and end-of-life impacts per parcel, accounting for the distribution of impacts from reusable packaging according to effective reuse cycles. Finally, the third level is the threshold and sensitivity analysis that investigates whether the results of the model depend on the assumptions concerning effective reuse cycles, maintenance labour, acquisition cost, service time, depot-return fraction, redistribution distance and capacity-based allocation quantity.

Figure 3.1 presents the relationships between scenario construction, the modeling layers, and final feasibility assessment.

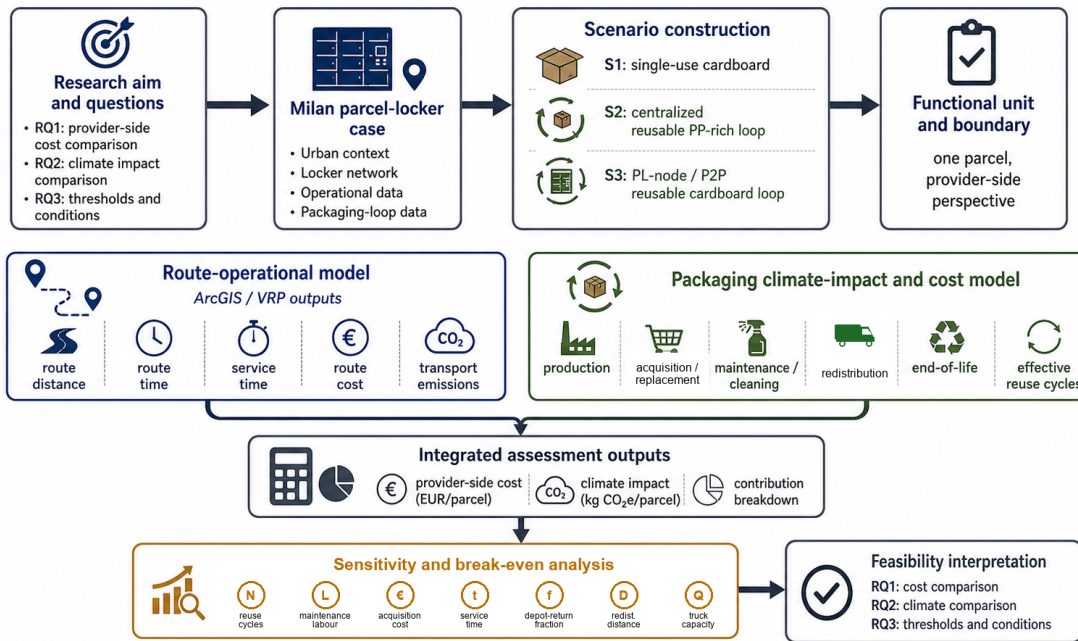


Figure 3.1: Analytical framework linking scenario construction, route-operational modelling, packaging climate-impact and provider-side cost modelling, sensitivity analysis, and research-question-level feasibility interpretation.

It was mentioned above that the analytical framework allows answering three research questions sequentially. RQ1 is answered through the cost calculation that accounts for route operation, packaging acquisition, maintenance, redistribution and end-of-life costs. RQ2 is answered using the climate-impact calculation that takes into account transport emissions, packaging production, maintenance, redistribution and end-of-life impacts. Finally, RQ3 is addressed through the threshold and sensitivity analysis, which identifies how selected reuse-loop conditions affect whether the reusable scenarios become competitive with S1 in provider-side cost and climate-change impact.

3.2. Case Study, Scenario Definition and Assessment Boundary

In this section, the three scenarios, the functional unit, and the boundary of quantitative assessment will be specified. The scenarios are grounded on the parcel-locker delivery scenario in Milan and correspond to three different types of packaging loops, namely: the one-way flow of single-use packaging, the centralized reusable loop, and the local-circulation reusable loop. The packaging proxies used in the respective reusable scenarios serve as proxies for these system setups and are summarized in Table 3.1. The proxies are not exact dimensional matches, but they are selected to represent medium parcel-compatible packaging formats with broadly comparable carrying functions rather than packaging for fundamentally different shipment sizes. They provide an opportunity to turn the scenario design operational while maintaining the focus of the assessment on the cost and climate-change feasibility of the provider side of the system, and not on its overall commercial performance, including the commercial performance of particular packaging companies.

Table 3.1: Packaging proxies used to represent the three model scenarios and their source references.

Scenario	Packaging proxy	Role in the scenario	Source reference
S1	Medium single-use cardboard package	One-way baseline; leaves provider control after customer collection.	Enviropack medium cardboard box page [18].
S2	HeyCircle M-informed PP-rich flexible reusable package proxy	Centralized reusable-loop proxy; based on public product data, not product-specific LCA.	HeyCircle M-box product page [38].
S3	ReZip-style reusable cardboard package	Local reusable-cardboard proxy; depot return only for the non-local-reused fraction.	RAJA RE-ZIP product page and RE-ZIP packaging overview [60, 62].

The comparison is based on a functional unit of one parcel delivered via a parcel-locker-based last mile system. The quantitative boundary intentionally follows the logistics provider perspective. It includes provider-side delivery and packaging processes, namely parcel-locker route operation, package acquisition, reusable-package handling, maintenance or cleaning, redistribution, replacement, and provider-controlled end-of-life handling where applicable. It excludes product manufacturing, customer consumption, cus-

customer travel and time, deposits, incentives, information technology platform development, and wider social externalities. These exclusions do not imply that the excluded processes are unimportant. Rather, they keep the model aligned with the research question of whether the provider-side operating loop can be cost- and climate-feasible.

In the system-boundary figures, the representative fulfilment/packing point is shown as an upstream physical interface, while the modelled last-mile route begins at the urban delivery hub. Product packing and the common packed-parcel movement between these points are not separately parameterised; among the movements shown around this interface, only the scenario-specific empty-package redistribution is added as a separate transport term.

In modelling terms, the provider-side boundary is treated as a consolidated operating boundary. The same provider-side actor is assumed to organize or finance the parcel-locker last-mile operation, reusable-package acquisition, maintenance, stock handling and provider-controlled end-of-life treatment. In real commercial settings, these functions may be split among logistics providers, locker operators, merchants or third-party reusable-packaging service providers. Such contractual allocation is outside the quantitative model and is treated as a governance question.

Scenario S1 is the single-use baseline: a medium-sized cardboard package is used once and leaves provider control after customer collection. The quantitative assessment includes packaging material production and conversion, package acquisition, parcel-locker route operation and the end-of-life climate burden. It includes no reusable-package return, return handling, maintenance or redistribution. Figure 3.2 shows the S1 boundary.

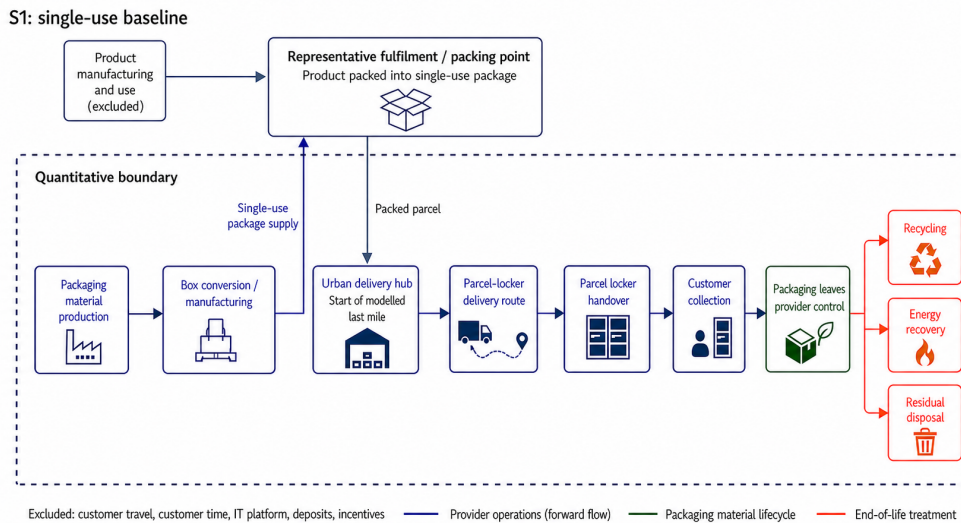


Figure 3.2: System boundary of S1 single-use baseline.

Scenario S2 specifies the centralized reusable packaging loop. The proxy for it is a Hey-Circle M-informed PP-rich flexible reusable package proxy. Public product information on size, weight, reuse potential and material family is used to define the modelling proxy, while no manufacturer-specific bill of materials or product-level LCA is assumed. In this scenario, the package is used as the managed reusable asset, which means that after the use by the customer the package will be collected by the courier, delivered back through the parcel-locker system, inspected, sorted, prepared for reuse and redistributed into the following delivery cycle. The light cleaning step is included as a quality-assurance preparation step for a centrally reconditioned durable package, because customer acceptance of reusable packaging depends partly on receiving packages in a visibly clean and serviceable condition. After central processing, folded empty reusable packages are moved from the central facility to one representative fulfilment/packing point by an 18 t rigid truck, with cost and emissions allocated per package on a capacity basis. Therefore, the boundary of quantitative assessment includes packaging material production and conversion, acquisition, parcel-locker route operation, return handling at locker and at depot, inspection and sorting at the depot, label removal, light cleaning or maintenance, empty-package redistribution, reuse cycle integration into the stock, replacement via effective reuse-cycle distribution and EoL for scrapped or lost units. Figure 3.3 shows the S2 boundary.

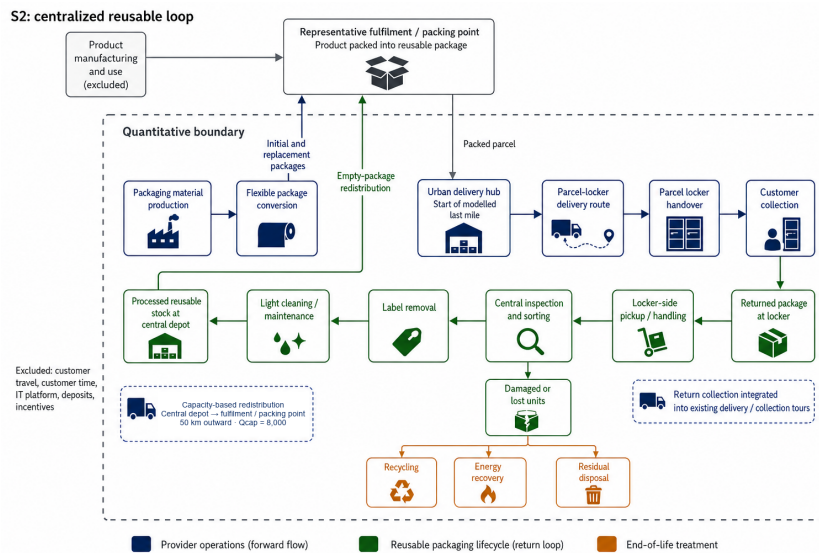


Figure 3.3: System boundary of S2 centralized reusable loop.

Scenario S3 is modelled as a local-circulation reusable packaging loop. The packaging proxy for it is a ReZip-style reusable cardboard package. This scenario represents local circulation with lower dependence on depot maintenance. It is not based on an operating system currently used by ReZip or by Milan parcel lockers. In this modelled setup,

returned packages first pass through a check at the parcel-locker node; those in good enough condition are assumed to be kept in local stock for reuse in a subsequent peer-to-peer (P2P) shipment. A P2P sender collects an available empty package from the locker stock, packs the item, and deposits the outbound parcel at the same node. The deposited parcel then enters the existing carrier collection flow. Because packaging and handover occur locally, this path does not require redistribution to a central fulfilment or packing point; capacity-based allocation of empty-package redistribution is therefore applied only to the depot-returned fraction. Packages that are not appropriate for local reuse, exceed local stock requirements or need further handling are represented by the depot-returned fraction and are sent to the depot for dry maintenance and reuse-cycle reintegration. For this cardboard-based proxy, quality control is represented through local checks and dry maintenance for the depot-returned fraction, since wet cleaning would be inconsistent with the material assumption. The cost advantage of S3 can therefore arise only if local circulation avoids converting every return into a centrally processed depot return. For this reason, depot-side labour, electricity and subsequent empty-package redistribution are assigned only to the depot-returned fraction, while packages retained in local stock avoid the full reconditioning step. The S3 depot-return fraction r_{dep} is set at 50% in the base case. The cardboard proxy also accounts for behavioural factors of an open or semi-open reuse system: customers may keep reusable packages if they find them useful, attractive and valuable for personal use [9]. The ReZip-style reusable cardboard package is used to test a local-circulation configuration that remains close to conventional transport packaging while enabling repeatable use. Figure 3.4 shows the S3 boundary.

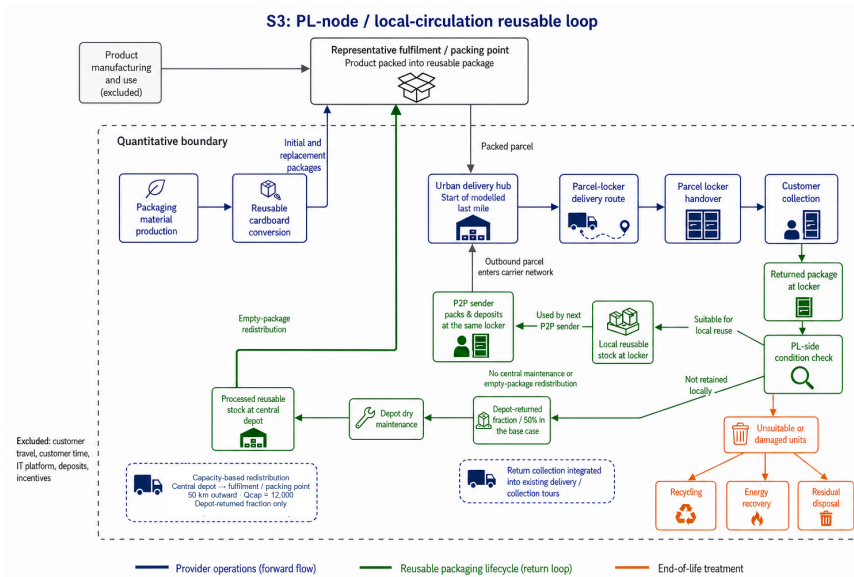


Figure 3.4: System boundary of S3 local-circulation reusable loop.

The approach to return transport is similar in S2 and S3. The base model assumes that reusable package collection is integrated into the already existing delivery and collection visits of parcels. For this reason, no dedicated return route and no additional return-route distance are added in the route model. Because empty returned packages are treated as lightweight marginal loads on routes that already take place, the additional fuel use and route emissions caused by their weight are assumed to be negligible. The operational burden of the return process is represented through locker service time, depot-side handling, maintenance, replacement needs, effective reuse cycles and, in the case of S3, depot-return fraction. After central processing, folded empty reusable packages are transported 50 km one way from the central facility or depot to one representative fulfilment/packing point by an 18 t rigid truck, with cost and emissions allocated per package on a capacity basis. All centrally processed S2 packages enter this redistribution leg, while for S3 it applies only to the depot-return fraction. The details of service-time assumptions and redistribution calculations are given in the following sections.

In total, the three scenarios differ in both packaging material and circulation setup. Scenario S1 involves one-way packaging flow; Scenario S2 corresponds to the centralized reusable loop in which all returns go through central reconditioning and capacity-allocated empty-package redistribution; and Scenario S3 corresponds to a local-circulation reusable loop in which part of the packaging stock can be kept in the parcel-locker node and the depot-return fraction receives maintenance and empty-package redistribution. This setting compares reusable packaging across both material and circulation-system assumptions.

3.3. Route-Operational Modelling

The route-operational model turns the parcel-locker networks into the transport inputs that are needed for cost and climate-change impact calculation. Within this layer, the Milan subset of Provider 1 is used as the base route input for the principal provider-side cost and climate-change calculations. This model does not aim to replicate the commercial operation of each carrier. It provides a common last-mile routing layer where locker locations, depot locations, locker demand, capacity constraints, and service-time assumptions become integrated in the framework of an ArcGIS Vehicle Routing Problem (VRP). ArcGIS Pro Network Analyst was chosen because the VRP framework is made for assigning orders to a vehicle fleet taking into account route, depot, and time constraints [20].

Figure 3.5 demonstrates how the route-operational model transforms spatial and opera-

tional inputs into route outputs that can be then used for calculating costs and climate-change impacts.

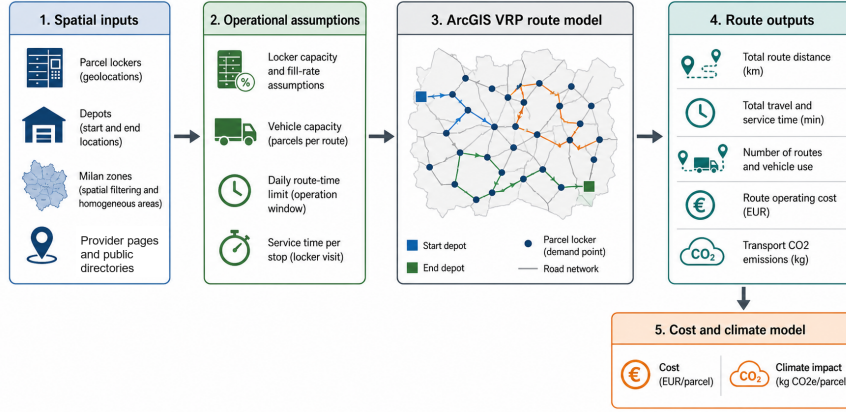


Figure 3.5: Route-operational model inputs and outputs used to connect spatial parcel-locker data, ArcGIS VRP modelling and downstream provider-side cost and climate-impact calculations.

Locker and depot coordinates were compiled independently from publicly available provider location pages and public location directories and processed as spatial inputs for the route model. The four route-input datasets are labelled Provider 1–4 throughout the thesis to distinguish public-data provenance from operator participation in the study. The Milan subset of Provider 1 is used as the base route input, while the other provider networks check the route layer across different network sizes, locker concentrations and depot or hub configurations. The larger Provider 1 locker layer was assigned to Milan homogeneous zones so that zone-level routes could be calculated. The homogeneous-zone grouping provides an additional route-layer check across areas with different urban and suburban locker concentrations, following Seghezzi et al.’s emphasis on delivery density in parcel-locker delivery costs [64]. Spatial input datasets used in the route model are listed in Table 3.2 while their route-input networks are demonstrated in Figure 3.6.

Table 3.2: Spatial input datasets used in the route-operational model.

Network	Raw PL records	Final PL stops in VRP	Depot/hub input	Spatial coverage	Location data source
Provider 1	460	322 total; 137 Milan subset	1 hub, Pieve Emanuele	Milan and seven surrounding homogeneous zones in the Metropolitan City of Milan	Public provider location finder [40].
Provider 2	322	184	6 depot candidates around Milan	Milan urban area after filtering	Public location directory for Milan [47].
Provider 3	20	17	4 depots in the Milan–Segrate area	Milan urban area after filtering	Public provider parcel-shop finder [6].
Provider 4	106	37	6 hubs around Milan	Milan urban area after filtering	Public provider service-point finder [15].

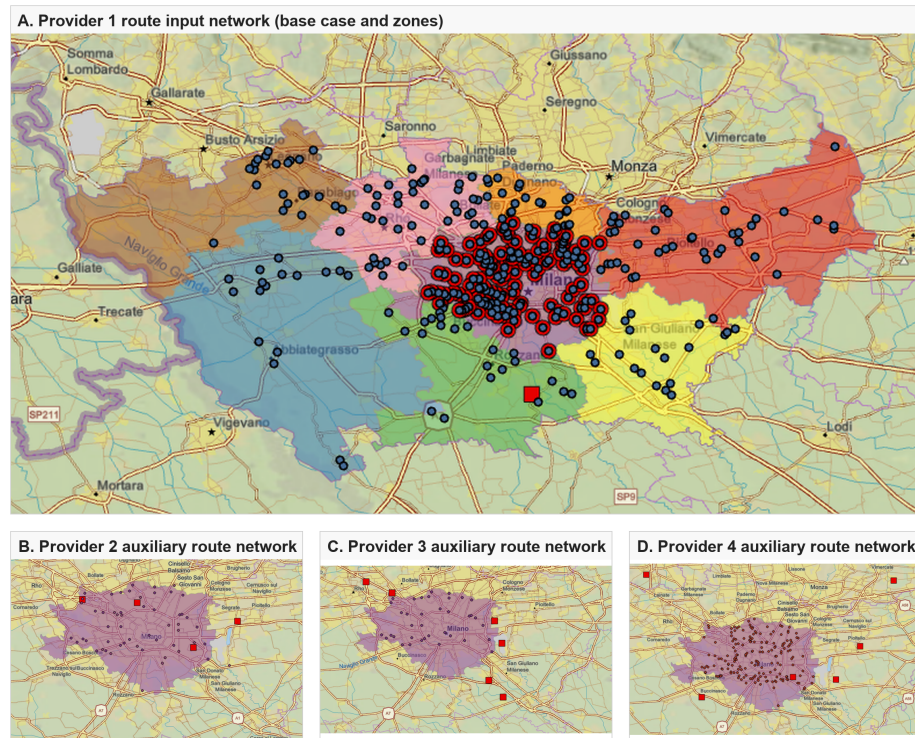


Figure 3.6: Route input networks for the ArcGIS base case and robustness checks.

Table 3.3: Main route-operational assumptions used in the ArcGIS VRP model.

Input	Value	Role in the route model	Source or treatment
Coordinate system	WGS 1984 (EPSG:4326)	XY import of locker and depot coordinates.	ArcGIS project setting.
Locker capacity proxy	52 slots	Basis for estimated locker-level daily demand.	Author's field survey of 20 Milan parcel lockers; observed mean 52.1.
Base fill-rate interval	0.8–0.9	Main demand interval for base route outputs.	Scenario assumption used in the route model.
Lower fill-rate intervals	0.7–0.8; 0.6–0.7	Downward checks on route-demand conditions.	Sensitivity settings.
Vehicle capacity	150 parcels	Maximum parcel quantity assigned to each route.	Based on Seghezzi et al. [64].
Maximum total route time	480 min	Daily route-duration constraint.	Based on an eight-hour route window and Seghezzi et al. [64].
Start depot service time	20 min	Loading and route-preparation time at the depot.	Operational route-model assumption.
End depot service time	10 min	Route-closing time at the depot.	Operational route-model assumption.
ArcGIS route time-cost coefficient	0.278 EUR/min	Rounded coefficient embedded in the imported route costs.	Based on the driver wage assumption in Seghezzi et al. [64]; distinct from the exact hourly-wage conversion used for maintenance labour.
Vehicle distance cost	0.360 EUR/km	Distance-based component of route cost.	Based on Seghezzi et al. [64].
Transport emission factor	154 g CO ₂ /km	Conversion of route distance into tailpipe CO ₂ emissions.	Average new-van emission value reported by Transport & Environment [68].
Scenario service time	S1: 20 s/parcel; S2: 35 s/parcel; S3: 42 s/parcel	Locker stop service time reflecting delivery and reusable-package handling.	Scenario-specific operational assumption embedded in the route outputs.

The locker demand was calculated from a locker capacity proxy and a fill-rate interval. The proxy for the capacity was assumed to be 52 slots per locker as a result of the author's field count of 20 parcel lockers in Milan where the mean value is 52.1 slots. For each route input, parcel demand is represented by Equation 3.1:

$$Q_{r,g} = L_r \times S_{\text{slot}} \times f_g, \quad (3.1)$$

where $Q_{r,g}$ is the parcel quantity for route input r and fill-rate group g , L_r is the number of lockers, $S_{\text{slot}} = 52$ is the locker-capacity proxy, and f_g is the fill-rate realization used for that route-demand group. The route-input table reports the resulting rounded parcel totals. The base route model assumes the fill-rate interval 0.8–0.9 while the fill-rate intervals 0.7–0.8 and 0.6–0.7 were kept for route-demand sensitivity checks. The vehicle

capacity, driver cost, and vehicle operating cost were taken according to the parcel-locker cost modeling assumptions of Seghezzi et al. [64]. The VRP assumptions used in the route layer are presented in Table 3.3, and the compressed route-input and route-output traceability table is reported in Table A.7.

The service-time assumption varies by scenario because reusable packaging changes the operation performed at the parcel-locker stop. The service-time component used in the route model is defined in Equation 3.2:

$$T_{s,r,g}^{\text{service}} = Q_{r,g} \frac{t_s}{60}, \quad (3.2)$$

where $T_{s,r,g}^{\text{service}}$ is measured in minutes and t_s is the scenario-specific service time in seconds per parcel. Service time in S1 means standard drop-off, $t_{S1} = 20$ s/parcel. Service time in S2 corresponds to the extra time spent on returned-package pickup and handling, $t_{S2} = 35$ s/parcel. Service time in S3 is higher because an additional local check or stock decision is represented at the locker side, $t_{S3} = 42$ s/parcel. These assumptions affect route time and route cost directly, while route emissions are calculated from route distance using the transport emission factor.

Within the route-operational layer, the Milan subset of Provider 1 is the primary base route input. For the base fill-rate interval, this subset contains 137 lockers and 6,054 parcels. The remaining route inputs are used as route-layer checks, while the principal feasibility interpretation remains anchored in the Milan base-network route input.

3.4. Packaging Climate-Impact and Provider-Side Cost Modelling

The integrated packaging assessment converts the scenario definitions and route outputs into two comparable indicators per functional unit: climate-change impact, expressed as kg CO₂e per delivered parcel, and provider-side cost per delivered parcel. The route-operational model supplies the route distance, route time, route cost and tailpipe emissions. The packaging-process calculations then add the material, conversion, maintenance, replacement, redistribution and end-of-life terms that differ across the three packaging loops. This separation is important because last-mile route emissions and redistribution transport are part of the system-level comparison, but they are not treated as packaging-material production emissions.

The model uses a mixed evidence structure. Public product information is used where

package size, mass, acquisition cost and reuse-cycle references are available. Literature and previous reusable-packaging studies support the inclusion of processes such as return handling, inspection, sorting, cleaning, maintenance, loss and replacement. Background emission factors are derived from ecoinvent v3.10 cumulative LCIA results, using EF v3.0 climate change without long-term emissions [16]. The selected factors are matched to the inventory role they represent: material supply, conversion service, utility input, transport operation or waste treatment. Where product-specific operational data are not available, the thesis uses transparent scenario and engineering assumptions. Therefore, the numerical model should be read as a scenario-based feasibility model using life-cycle climate-impact accounting rather than as a full manufacturer-specific, multi-impact LCA or audited commercial cost model.

Both the cost and climate-impact calculations apply the same capacity-based allocation to empty-package redistribution. After cleaning or maintenance at the central processing hub or depot, folded reusable packages are transported to a representative fulfilment/packing point for use in the next delivery cycle. The model assumes a 50 km outward distance d for this movement. In the base case, no separate empty-return trip is modelled because the vehicle return is assumed to be combined with existing backhaul or fleet-repositioning activity, so $D_{\text{attr}} = d = 50$ km. The high sensitivity case tests this assumption by additionally allocating a 50 km empty return, resulting in $D_{\text{attr}} = 2d = 100$ km. The capacity-based allocation quantity is:

$$Q_s^{\text{cap}} = \left\lfloor \min \left(\frac{V^{\text{truck}} u}{V_s^{\text{fold}}}, \frac{M^{\text{payload}}}{m_s} \right) \right\rfloor, \quad (3.3)$$

where V^{truck} is nominal cargo volume, u is space utilisation, V_s^{fold} is folded empty-package volume, M^{payload} is usable payload and m_s is package mass. The vehicle proxy combines the VECTO Class 4 18 t rigid-truck specification [72] with a 42 m³ cargo volume representative of a 16–18 Euro-pallet rigid truck [46]. With the engineering assumptions of a 5 t usable payload and $u = 0.75$, Equation 3.3 gives $Q_{S2}^{\text{cap}} = 8,000$ and $Q_{S3}^{\text{cap}} = 12,000$ packages per modelled movement. All centrally processed S2 packages receive this allocation, whereas S3 applies it only to the existing depot-return fraction $r_{\text{dep}} = 0.5$. The complete physical, operational and price inputs are reported in Table A.2.

3.4.1. Climate-Impact Model

The environmental indicator is limited to the climate-change impact category and is reported as kg CO₂e per parcel. It does not cover the full set of environmental impact

categories used in multi-impact LCA. For each scenario s , total climate-change impact per parcel is calculated by Equation 3.4 as the sum of route emissions, packaging production and conversion, maintenance or cleaning processes, redistribution transport, and end-of-life treatment:

$$E_s^{\text{total}} = E_s^{\text{route}} + E_s^{\text{prod}} + E_s^{\text{maint}} + E_s^{\text{redist}} + E_s^{\text{EOL}}. \quad (3.4)$$

Route emissions E_s^{route} come from the route model described in the previous section. They are calculated from route distance and the tailpipe emission factor in Table 3.3. For a reusable package, production and end-of-life burdens are distributed over the effective number of uses N_{eff} . In this model, N_{eff} is used as an allocation parameter for successful reuse cycles and is informed by product-reported and literature-based reuse-cycle evidence. It therefore represents the number of allocated uses over which acquisition, production and end-of-life burdens are spread in each scenario. The production term is calculated in Equation 3.5:

$$E_s^{\text{prod}} = \frac{\sum_i m_{i,s} EF_i + a_s^{\text{conv}} EF^{\text{conv}}}{N_{\text{eff},s}}, \quad (3.5)$$

where $m_{i,s}$ is the mass of material component i in scenario s , EF_i is its material emission factor, a_s^{conv} is the amount of conversion-service activity, and EF^{conv} is the corresponding conversion-process emission factor. The carton-board box conversion activity is applied as 0.80 kg service per kg used cartonboard. The plastic-film extrusion activity for S2 is applied as 1 kg process per 0.976 kg extruded film. These conversion-service multipliers are applied only to the processing activity term, while material inputs are accounted for separately through the material-mass term [16].

Maintenance and cleaning inputs are scenario-specific. S1 has no reusable-package maintenance. S2 represents a centralized reconditioning loop, so every returned S2 package is assumed to pass through inspection, label removal and light surface cleaning before reuse. S3 uses a dry maintenance logic. Wet cleaning is excluded because the package proxy is cardboard-based, and depot maintenance applies only to the depot-returned fraction. The base values used for these maintenance processes are summarized in Table 3.4; the expanded calculation details and maintenance-process outputs are reported in Table A.5. They should be read as transparent process proxies for scenario modelling, not as manufacturer-specific operational measurements.

Table 3.4: Maintenance and cleaning parameter inputs used in the base case.

Parameter	S2 centralized loop	S3 local loop	Source or treatment
Application scope	Every returned package	Depot-returned fraction only; base 50%	Distinguishes the centralized S2 reconditioning loop from the local S3 reuse loop.
Manual handling	45 s/package	30 s/depot-returned package	Engineering estimates for inspection, label removal, cleaning or dry reintegration.
Energy input	0.008333 kWh/package	0.0125 kWh/depot-returned package	Heat-gun electricity is calculated using Tang's 1.5 kW rated-power proxy and the-sis engineering times of 20 s for S2 and 30 s for S3 [67].
Wet-cleaning input	0.1519 L water and 0.0003038 kg detergent per package	Not applied	S2 light-cleaning proxy scaled from reusable-plastic-crate washing; detailed scaling and factors are reported in Table A.5.

The S2 water and detergent quantities are derived from a reusable-plastic-crate washing proxy rather than from manufacturer-measured HeyCircle data. The reference crate has dimensions of 40 x 60 x 12 cm, equivalent to 28.8 L, and uses 0.4 L of water with 0.2% detergent concentration [48]. Scaling this water input by the HeyCircle M outer-volume proxy, 350 x 250 x 125 mm or 10.9375 L [38], gives a ratio of 0.3798 and therefore 0.1519 L of water per package. Detergent is then calculated as 0.2% of the scaled water mass.

Redistribution emissions are zero in S1. For the reusable scenarios, the attributed rigid-truck emissions are incorporated as climate-impact components:

$$E_{S2}^{\text{redist}} = \frac{D_{\text{attr}} EF^{\text{truck}}}{Q_{S2}^{\text{cap}}}, \quad E_{S3}^{\text{redist}} = r_{\text{dep}} \frac{D_{\text{attr}} EF^{\text{truck}}}{Q_{S3}^{\text{cap}}}. \quad (3.6)$$

The factor $EF^{\text{truck}} = 0.628$ kg CO₂/vehicle-km follows the monitored 4-RD heavy-duty vehicle average [23]. At the base attributed distance, the vehicle movement emits 31.40 kg CO₂. Capacity-based allocation gives 0.003925 kg CO₂ per S2 parcel and 0.001308 kg CO₂ per S3 parcel, the latter including $r_{\text{dep}} = 0.5$. The supporting inventory rows are reported in Table A.3.

Table 3.5: Packaging climate-impact inventory inputs by scenario.

Scenario	Package input	Production and conversion treatment	Maintenance / cleaning	End-of-life treatment
S1	180 g medium single-use cardboard package; $N_{\text{eff}} = 1$.	Containerboard material plus carton-board box conversion.	None; package leaves provider control after customer collection.	Paper/cardboard weighted EOL factor.
S2	550 g HeyCircle M-informed PP-rich reusable package proxy; base $N_{\text{eff}} = 50$.	PP-rich material proxy plus plastic-film extrusion; product-specific BOM not assumed.	Centralized inspection, label removal and light cleaning for every returned package.	PP-rich plastic weighted EOL factor.
S3	195 g ReZip-style reusable cardboard BOM proxy; base $N_{\text{eff}} = 30$.	Corrugated, nylon-dot and kraft-label component proxies plus carton-board box conversion.	PL-side first check in the route layer; depot dry maintenance only for the depot-returned fraction.	Cardboard-dominant weighted EOL factor.

Notes: This table is a compact scenario overview. Detailed parameter sources and inventory rows are reported in Tables A.2 and A.3.

End-of-life emissions are calculated in Equation 3.7 by multiplying package mass by a weighted material-group treatment factor and allocating the burden over N_{eff} :

$$E_s^{\text{EOL}} = \frac{m_s^{\text{total}} E F_s^{\text{EOL}}}{N_{\text{eff},s}}. \quad (3.7)$$

The weighted end-of-life factors combine Italy 2023 packaging-waste treatment shares withecoinvent treatment factors [16]. The base factors are 0.111885 kg CO₂e/kg waste for paper/cardboard packaging and 1.329021 kg CO₂e/kg waste for PP-rich plastic packaging. These are weighted scenario factors rather than raw ecoinvent process factors. The treatment shares, weighted factors and scenario-level EOL outputs are reported with the supporting calculations in Table A.6.

3.4.2. Provider-Side Cost Model

Provider-side cost per parcel is calculated by Equation 3.8, which adds the route-cost component from the VRP model to the packaging-loop costs borne by the provider:

$$C_s^{\text{total}} = C_s^{\text{route}} + \frac{C_s^{\text{acq}}}{N_{\text{eff},s}} + C_s^{\text{maint}} + C_s^{\text{redist}} + C_s^{\text{EOL}}. \quad (3.8)$$

The route-cost term C_s^{route} follows the distance and time cost structure embedded in the route-operational model. Per-parcel route cost is represented by Equation 3.9:

$$C_{s,r,g}^{\text{route}} = \frac{d_{s,r,g} c^{\text{km}} + (T_{s,r,g}^{\text{travel}} + T_{s,r,g}^{\text{service}} + T_{s,r,g}^{\text{depot}}) c^{\text{min}}}{Q_{r,g}}, \quad (3.9)$$

where $d_{s,r,g}$ is route distance, c^{km} is the vehicle distance cost, T^{travel} , T^{service} and T^{depot} are the travel, locker-service and depot-service time components, c^{min} is the driver time cost, and $Q_{r,g}$ is the parcel quantity served by that route input. The depot-time component corresponds to the fixed start and end depot service assumptions in Table 3.3. This formulation explains why the packaging-loop scenarios can change provider cost through service time even when the transport emission calculation still depends primarily on route distance.

The redistribution cost component combines distance-dependent rigid-truck operation with driver occupied time:

$$C_{\text{veh}}(D_{\text{attr}}) = D_{\text{attr}} c_{\text{km}}^{\text{truck}} + \left(\frac{60 D_{\text{attr}}}{v_{\text{truck}}} + t^{\text{load}} + t^{\text{unload}} \right) c_{\text{min}}^{\text{driver}}. \quad (3.10)$$

S1 has no redistribution cost. For the reusable scenarios, the vehicle-movement cost is incorporated into provider-side cost as:

$$C_{S2}^{\text{redist}} = \frac{C_{\text{veh}}(D_{\text{attr}})}{Q_{S2}^{\text{cap}}}, \quad C_{S3}^{\text{redist}} = r_{\text{dep}} \frac{C_{\text{veh}}(D_{\text{attr}})}{Q_{S3}^{\text{cap}}}. \quad (3.11)$$

The speed of 58.8 km/h follows the VECTO Class 4 regional-delivery cycle [72]. The running-cost coefficient of 0.7955 EUR/vehicle-km is the midpoint of the Italian Class C component range for 12–26 t vehicles, excluding driver and toll costs [52]. Driver occupied time uses the 16.7 EUR/hour wage proxy [64], while loading and unloading occupy 60 minutes per modelled movement. The base vehicle-movement cost is 70.68 EUR; capacity-based allocation gives 0.00883 EUR per S2 parcel and 0.00294 EUR per S3 parcel. Supporting cost-inventory rows are reported in Table A.4.

Packaging acquisition cost is allocated over the effective number of uses. The adopted acquisition costs are 0.40 EUR per S1 cardboard package, 18.27 EUR per S2 reusable package and 2.03 EUR per S3 reusable package. Maintenance cost includes labour and the monetized utility or consumable inputs represented in the maintenance proxy. In S2, this includes labour, heat-gun electricity, tap water and detergent for every returned package. In S3, depot maintenance includes labour and heat-gun electricity only for the depot-returned fraction, which is the key cost-model difference between centralized reconditioning and local circulation. The adopted price proxies are 0.2597 EUR/kWh

for electricity, 2.43 EUR/m³ for water and 5 EUR/kg for detergent [1, 32, 69]. Facility, equipment, overhead and platform costs remain outside the base model and are treated as limitations rather than zero-cost processes.

The treatment of end-of-life differs between climate accounting and provider-side monetary accounting. Climate impacts include material end-of-life for comparability across scenarios. Monetary EOL handling cost is included only for provider-controlled scrapped reusable packaging in S2 and S3, using 0.234 EUR/kg as a proxy handling cost. S1 is not assigned this provider-controlled monetary cost in the base case because the single-use package is assumed to leave the provider’s operational control with the parcel and enter the household or municipal packaging-waste stream.

Table 3.6: Provider-side cost components included by scenario.

Scenario	Route cost	Acquisition cost	Maintenance / handling cost	Redistribution cost	EOL monetary cost
S1	VRP route output.	0.40 EUR/package; one use.	No reusable-package maintenance.	No reusable-package redistribution.	Excluded after customer collection.
S2	VRP route output plus return-handling service time.	18.27 EUR/package over $N_{\text{eff}} = 50$.	Central labour plus electricity, water and detergent for every return.	50 km outward; $Q_{S2}^{\text{cap}} = 8,000$; all centrally processed packages.	Included at 0.234 EUR/kg for provider-controlled scrap.
S3	VRP route output plus local-stock inspection time.	2.03 EUR/package over $N_{\text{eff}} = 30$.	Depot labour and electricity for the depot-return fraction.	50 km outward; $Q_{S3}^{\text{cap}} = 12,000$; applied to $r_{\text{dep}} = 50\%$.	Included at 0.234 EUR/kg for provider-controlled scrap.

Notes: Detailed cost inventory rows are reported in Table A.4.

This modelling structure keeps the route layer and packaging-process layer analytically separate while reporting their combined cost and climate effects per parcel. It also makes the proxy status of the main assumptions explicit. S2 and S3 are not evaluated as audited commercial systems; they are scenario configurations used to test whether different reusable-packaging loop designs remain feasible when route handling, maintenance, redistribution, acquisition, replacement and end-of-life are considered together.

3.5. Threshold and Sensitivity Analysis

Comparative life-cycle climate-impact and cost results depend on the way the functional unit, system boundary, allocation logic and key assumptions are defined. For this reason,

interpretation of comparative LCA-informed results requires explicit checks of assumptions that may affect the comparative conclusion [12, 41, 42]. In this thesis, uncertainty is not treated as a probabilistic distribution and no confidence intervals are estimated. Instead, uncertainty is treated through two deterministic checks. The threshold analysis asks which operating conditions would have to hold for a reusable scenario to reach or keep parity with S1. The one-way sensitivity analysis asks whether the result ordering changes when selected assumptions are moved within transparent low/base/high ranges.

3.5.1. Break-Even and Threshold Analysis

Effective reuse cycles are treated separately from ordinary low/base/high sensitivity because N_{eff} is the central allocation variable for reusable packaging. Rather than simply testing one low and one high value, the model calculates the reuse-cycle thresholds at which S2 or S3 reaches parity with the S1 baseline.

For climate-change impact, the break-even condition is defined in Equation 3.12 as the point at which the total climate-change impact of a reusable scenario is equal to or lower than the S1 single-use baseline:

$$E_s^{\text{total}}(x) \leq E_{S1}^{\text{total}}, \quad (3.12)$$

where x denotes the parameter being varied, such as N_{eff} or the S3 depot-return fraction. For provider-side cost, the equivalent condition is defined in Equation 3.13:

$$C_s^{\text{total}}(x) \leq C_{S1}^{\text{total}}. \quad (3.13)$$

The threshold calculations are based on the integrated model described in the previous sections. For N_{eff} , the threshold indicates the minimum number of successful reuse cycles required for a reusable package to reach climate or cost parity with S1. For S2 maintenance labour and acquisition cost, the threshold indicates the maximum labour time or package price that would still allow S2 to reach cost parity. For the S3 depot-return fraction, the threshold indicates the maximum share of returned packages that can require depot-side maintenance and redistribution before S3 loses its advantage relative to S1 or S2. The supporting threshold calculations and reuse-cycle numerical points used to plot the break-even figure are reported in Tables A.10 and A.11.

3.5.2. One-Way Sensitivity Analysis

The sensitivity analysis is organized around assumptions that are both uncertain and structurally important in the model. Route fill-rate variation is included as a route-layer sensitivity check because it changes the demand assigned to the VRP route inputs. The remaining one-way sensitivity cases change one packaging-loop or cost parameter, or one small parameter set, while keeping the other model inputs at their base values. This structure makes it possible to identify whether the result is driven mainly by route-demand conditions, route service time, maintenance labour, cleaning resources, the share of S3 packages that cannot be reused locally, attributed redistribution vehicle distance or capacity-based allocation quantity. The base values used in the threshold and sensitivity analysis are taken from the route, maintenance, climate-inventory and cost-model assumptions reported in Tables 3.3, 3.4, 3.5 and 3.6. The consolidated low/base/high ranges and the supporting numerical sensitivity data are reported in Tables A.8 and A.9.

Table 3.7: One-way sensitivity parameters used in the model.

Parameter	Scenario	Base value	Tested values	Interpretation
Locker service time	S2; S3	35 s/parcel; 42 s/parcel	S2: 30, 35 and 50 s/parcel; S3: 33, 42 and 65 s/parcel	Tests the cost effect of returned-package handling and local-stock inspection time.
S2 central maintenance labour	S2	45 s/package	35, 45 and 60 s/package	Tests whether the centralized reconditioning loop remains cost-sensitive to manual inspection, label removal and light cleaning.
S2 cleaning resource set	S2	0.008333 kWh, 0.1519 L water and 0.0003038 kg detergent per package	Low, base and high heat-gun inputs of 0.004167, 0.008333 and 0.014583 kWh, with the corresponding water and detergent sets	Tests whether the physical cleaning proxy changes the climate or provider-cost comparison materially.
S3 depot-return fraction r_{dep}	S3	50%	25%, 50% and 100%	Tests whether S3 remains feasible if fewer returned packages can be reused locally at the parcel-locker node.
S3 depot maintenance labour	S3	30 s/depot-returned package	25, 30 and 45 s/depot-returned package	Tests the cost effect of dry maintenance and reintegration for the fraction sent back to the depot.
Attributed redistribution vehicle distance D_{attr}	S2; S3	50 km/modelled movement	25, 50 and 100 km/modelled movement	Low is a 25 km outward movement; base is the 50 km outward movement with return absorbed; high attributes the 50 km outward movement plus a 50 km empty return. Loading and unloading are counted once.
Truck space utilisation and capacity-based allocation quantity	S2; S3	75%; $Q_{S2}^{\text{cap}} = 8,000$, $Q_{S3}^{\text{cap}} = 12,000$	60%, 75% and 90%; S2 $Q_{S2}^{\text{cap}} = 6,400/8,000/9,090$, S3 $Q_{S3}^{\text{cap}} = 9,600/12,000/14,400$	Tests the derived capacity-based allocation quantity while retaining the 5 t payload check.

The locker service-time check varies the additional returned-package handling and local-stock inspection time around the base scenario definitions. The ordinary S1 drop-off time remains fixed at 20 s/parcel. Route-demand sensitivity is tested separately through the fill-rate groups. Attributed redistribution vehicle distance and capacity-based allocation

quantity are varied independently while the single destination remains fixed; all centrally processed S2 packages enter the leg, whereas S3 follows the base depot-return fraction. D_{attr} is tested at 25, 50 and 100 km per modelled movement. The high case attributes an additional 50 km empty return after the 50 km outward movement and retains one loading-and-unloading allowance. This treatment of uncertainty should therefore be read as a robustness test of a deterministic scenario model. It does not claim to estimate the probability that a real provider will achieve a particular reuse rate, maintenance time, attributed redistribution distance or depot-return share. Instead, it shows which assumptions would need to hold for each reusable packaging loop to remain cost-competitive or climate-competitive in the Milan parcel-locker setting. Utility prices, water price, detergent price and EOL monetary handling cost are retained in the base model, but they are not interpreted as central uncertainty drivers because their expected contribution is small compared with reuse cycles, acquisition cost, maintenance labour and route-operation conditions.

4 | Results

4.1. Base-Case Results

This chapter reports the outputs of the integrated route, packaging and provider-side cost model described in Chapter 3. The base case is the Milan base-network subset under the 0.8–0.9 locker fill-rate group. Results are expressed per functional unit, namely one parcel delivered through the parcel-locker-based last-mile system. All values in this chapter are deterministic model outputs rather than measured commercial operating results.

Table 4.1 and Figure 4.1 summarize the base-case comparison. S1, the single-use cardboard baseline, has a total provider-side cost of 0.770 EUR/parcel and a climate-change impact of 0.319 kg CO₂e/parcel. S2, the centralized reusable loop, reduces this impact to 0.102 kg CO₂e/parcel, 68.1% below S1, but increases provider-side cost to 1.029 EUR/parcel, 33.6% above S1. Under the base proxy assumptions for the local-circulation loop, S3 has the lowest modelled result for both indicators: 0.615 EUR/parcel and 0.047 kg CO₂e/parcel. Relative to S1, this corresponds to a cost reduction of 20.1% and a climate-impact reduction of 85.1%.

Table 4.1: Base-case provider-side cost and climate-impact results for the Milan base-network case. Cost is reported in EUR/parcel and CO₂e in kg CO₂e/parcel.

Scenario	Cost	Cost vs S1	CO ₂ e	CO ₂ e vs S1
S1	0.770	Reference	0.319	Reference
S2	1.029	+0.259 (+33.6%)	0.102	-0.217 (-68.1%)
S3	0.615	-0.155 (-20.1%)	0.047	-0.271 (-85.1%)

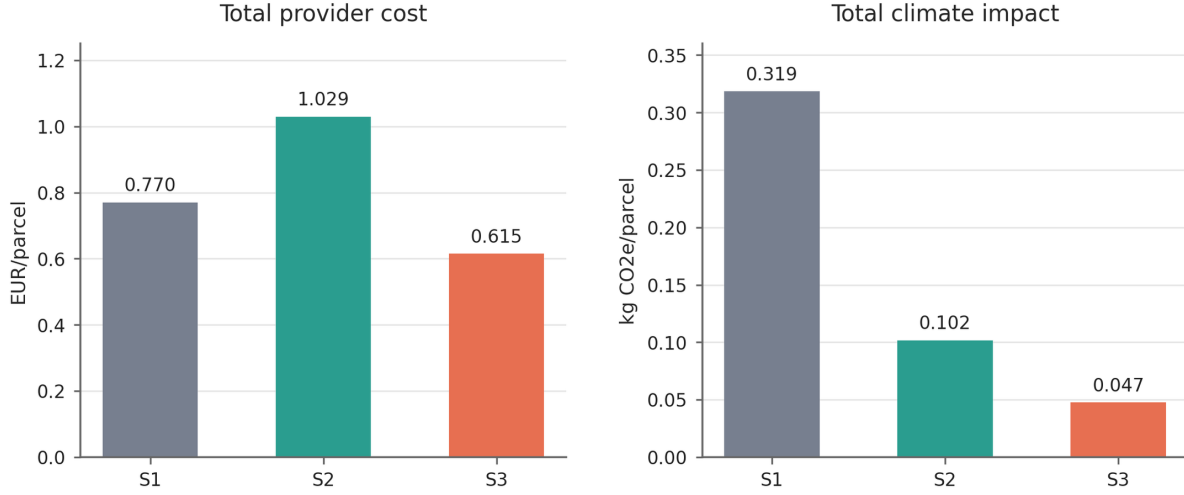


Figure 4.1: Base-case comparison of total provider-side cost and climate-change impact for S1, S2 and S3 in the Milan base-network case.

The comparison shows that reusable packaging does not have a uniform result. S2 and S3 both reduce climate-change impact because production and end-of-life burdens are allocated over repeated use. However, the provider-side cost outcome differs sharply between the two reusable loops. S2 is cost-disadvantaged because the centralized reusable package has a high acquisition cost and requires central maintenance and redistribution for every returned package. S3 is cost-advantaged in the base case because the reusable cardboard proxy has a lower acquisition cost and only the depot-returned fraction is assigned depot-side maintenance and redistribution.

4.2. Contribution Breakdown

Figure 4.2 decomposes the base-case results into route, package acquisition or production, maintenance, redistribution and end-of-life components. On the cost side, S1 is split between route cost and packaging acquisition, with route cost equal to 0.370 EUR/parcel and single-use packaging acquisition equal to 0.400 EUR/parcel. In S2, route cost is 0.440 EUR/parcel, allocated package acquisition is 0.365 EUR/parcel, maintenance is 0.213 EUR/parcel and redistribution is 0.00883 EUR/parcel. This explains why S2 remains more expensive than S1 despite reuse-cycle allocation. In S3, route cost is 0.472 EUR/parcel and therefore dominates the total, while package acquisition, depot maintenance and redistribution remain comparatively small at 0.068, 0.071 and 0.00294 EUR/parcel.

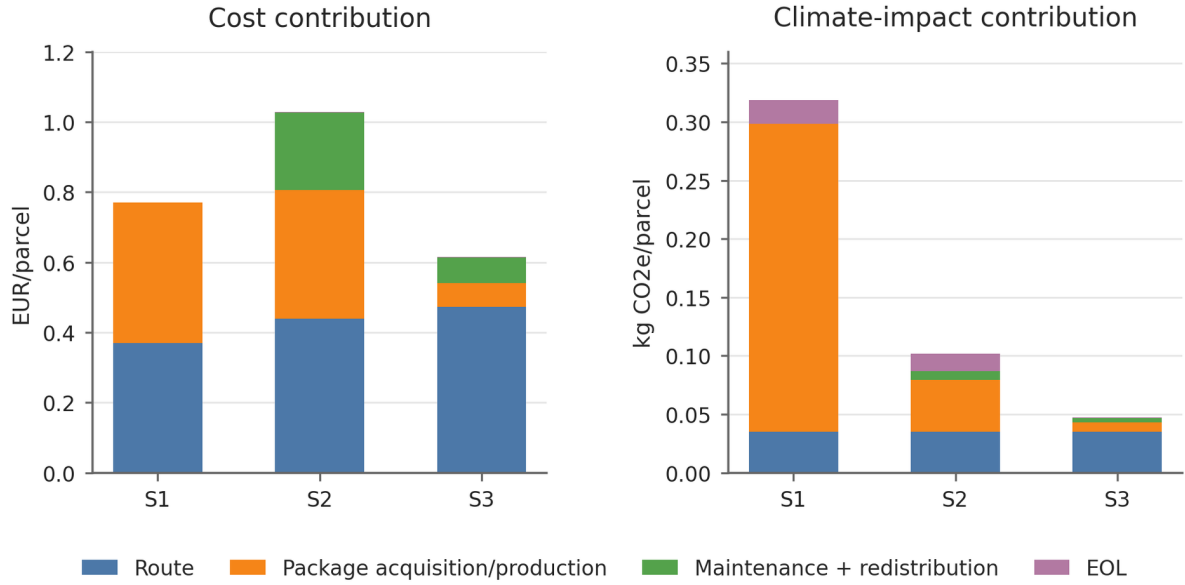


Figure 4.2: Contribution breakdown of base-case provider-side cost and climate-change impact. The green component combines maintenance and redistribution; their separate inventory values are reported in Tables A.3 and A.4.

The climate-impact breakdown is different from the cost breakdown. In S1, packaging production is the dominant climate contributor, at 0.264 kg CO₂e/parcel, with a further 0.020 kg CO₂e/parcel from end-of-life treatment and 0.035 kg CO₂e/parcel from the route layer. In S2, production contributes 0.0446 kg CO₂e/parcel, maintenance contributes 0.00370 kg CO₂e/parcel and redistribution contributes 0.003925 kg CO₂e/parcel, while route emissions remain 0.0348 kg CO₂e/parcel. In S3, the route layer becomes the largest climate contributor because allocated production, maintenance and redistribution emissions are low. Route emissions account for 0.0348 kg CO₂e/parcel, compared with 0.00836 kg CO₂e/parcel from production, 0.00229 kg CO₂e/parcel from depot maintenance and 0.001308 kg CO₂e/parcel from redistribution.

This decomposition clarifies the main difference between the reusable configurations. S2 achieves a climate reduction but pays for it through acquisition, central reconditioning and redistribution. S3 shifts the result toward route and handling assumptions, because the packaging-process burden per parcel is smaller. Therefore, the base-case advantage of S3 comes from the combination of lower acquisition cost, lower embodied packaging burden and a loop structure in which depot maintenance and redistribution are applied only to the depot-returned fraction.

4.3. Break-Even and Threshold Results

The break-even and threshold analysis tests whether the base-case reusable assumptions are sufficient to reach parity with S1. Table 4.2 reports the main thresholds needed for interpretation, while the full threshold calculations, including the S3 depot-return fraction checks, and the reuse-cycle numerical points are retained in Tables A.10 and A.11. For S2, the climate break-even threshold is 10.73 effective reuse cycles, and the base value of 50 cycles exceeds this threshold. However, the S2 cost break-even threshold is 169.01 cycles, far above the base value. This means that, under the base acquisition, maintenance and redistribution assumptions, the centralized reusable loop is climate-competitive but not cost-competitive with S1.

For S3, the thresholds are much lower. The continuous climate break-even threshold is 0.974 effective uses. Because the operational domain begins at the minimum feasible value of $N_{\text{eff}} = 1$, S3 is already below the S1 climate baseline at its first feasible use. The cost break-even threshold is 9.27 cycles. The base value of 30 cycles therefore exceeds both thresholds. The depot-return fraction thresholds are above the practical 0–100% range, which means that S3 remains below S1 for both provider-side cost and climate-change impact even when all returned packages are assumed to require depot-side maintenance and redistribution in the tested model.

Table 4.2: Break-even and threshold checks for reusable scenarios in the Milan base-network case.

Scenario	Metric	Variable	Threshold	Base value	Interpretation
S2	Climate	N_{eff}	10.73 cycles	50 cycles	Passes climate break-even.
S2	Cost	N_{eff}	169.01 cycles	50 cycles	Does not pass cost break-even.
S3	Climate	N_{eff}	0.974 cycles	30 cycles	Passes at the minimum feasible value $N_{\text{eff}} = 1$.
S3	Cost	N_{eff}	9.27 cycles	30 cycles	Passes cost break-even.
S2	Cost	Maintenance labour	No feasible non-negative threshold; calculated threshold is -10.86 s/package	45 s/package	Labour reduction alone cannot close the S2 cost gap.
S2	Cost	Package acquisition cost	5.31 EUR/unit	18.27 EUR/unit	Acquisition cost would need to be much lower for S2 cost parity.

The negative labour threshold for S2 is not an operational target. It indicates that changing central maintenance labour alone cannot make S2 cost-competitive with S1 while keeping the other base assumptions unchanged. Even at zero maintenance labour, the modelled S2 acquisition, route-cost, redistribution and end-of-life components remain too high for cost parity. The acquisition-cost threshold points to the same conclusion: S2 would need a package acquisition cost of about 5.31 EUR/unit, compared with the base 18.27 EUR/unit, to reach cost parity under the remaining base assumptions.

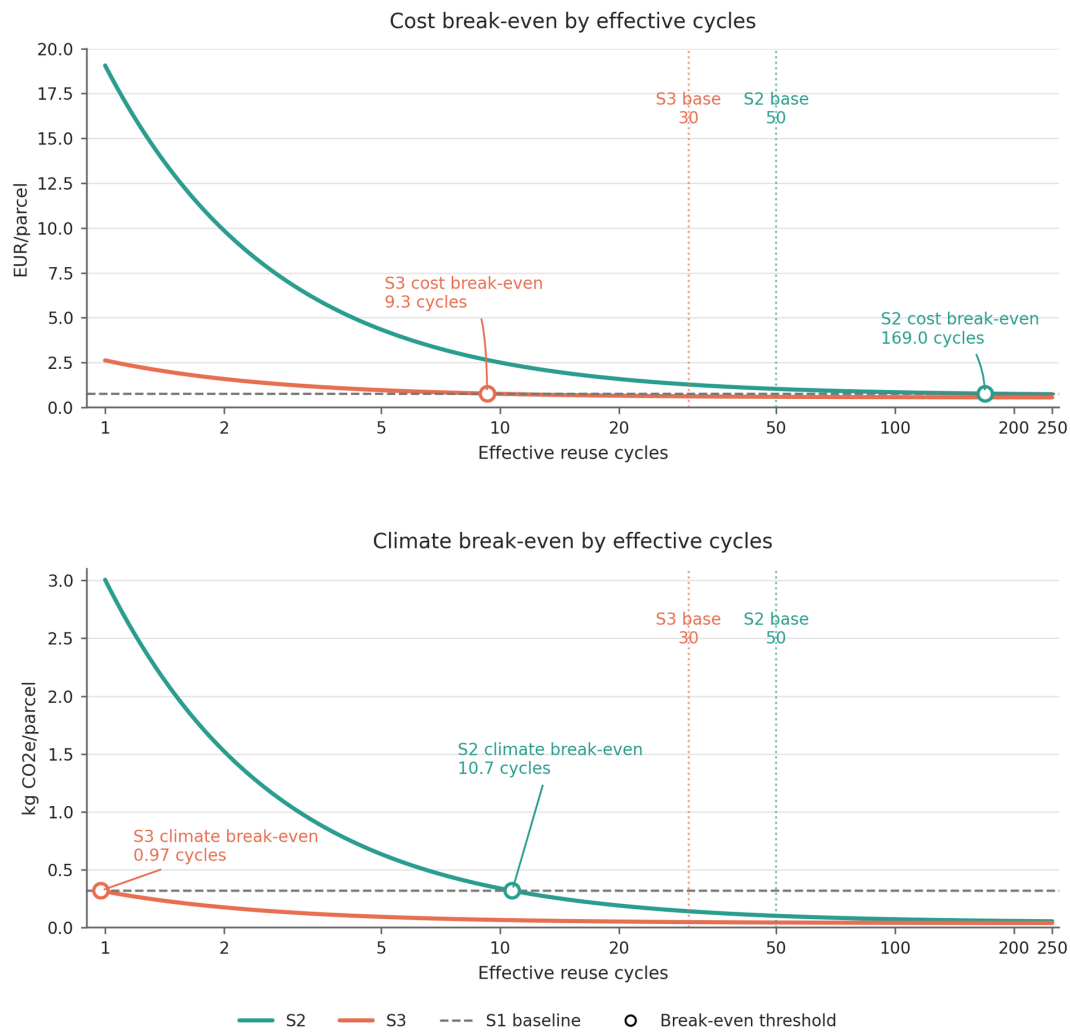


Figure 4.3: Reuse-cycle break-even curves for S2 and S3. Dashed horizontal lines show the S1 baseline; dotted vertical lines show the base effective reuse-cycle assumptions; open circles mark the calculated break-even thresholds.

Figure 4.3 visualizes the reuse-cycle effect. The S2 climate curve falls below the S1 baseline after 10.73 effective uses, but the S2 cost curve reaches parity only at 169.01 effective uses, far beyond the base assumption of 50 cycles. In contrast, S3 reaches cost parity at 9.27

effective uses and has a continuous climate threshold of 0.974 effective uses. Because the operational domain begins at $N_{\text{eff}} = 1$, climate parity is already achieved at the first feasible use, well below the base assumption of 30 cycles. This reinforces the difference between environmental feasibility and provider-side cost feasibility.

4.4. Sensitivity Analysis

The deterministic sensitivity analysis checks whether the base-case ordering changes when selected operational assumptions are varied one at a time. Table 3.7 defines the tested ranges, Figure 4.4 reports the change relative to each scenario's own base case, and Tables A.8 and A.9 provide the supporting numerical values. The purpose is not to produce probability ranges or statistical confidence intervals. It is to show which assumptions materially affect the modeled comparison.

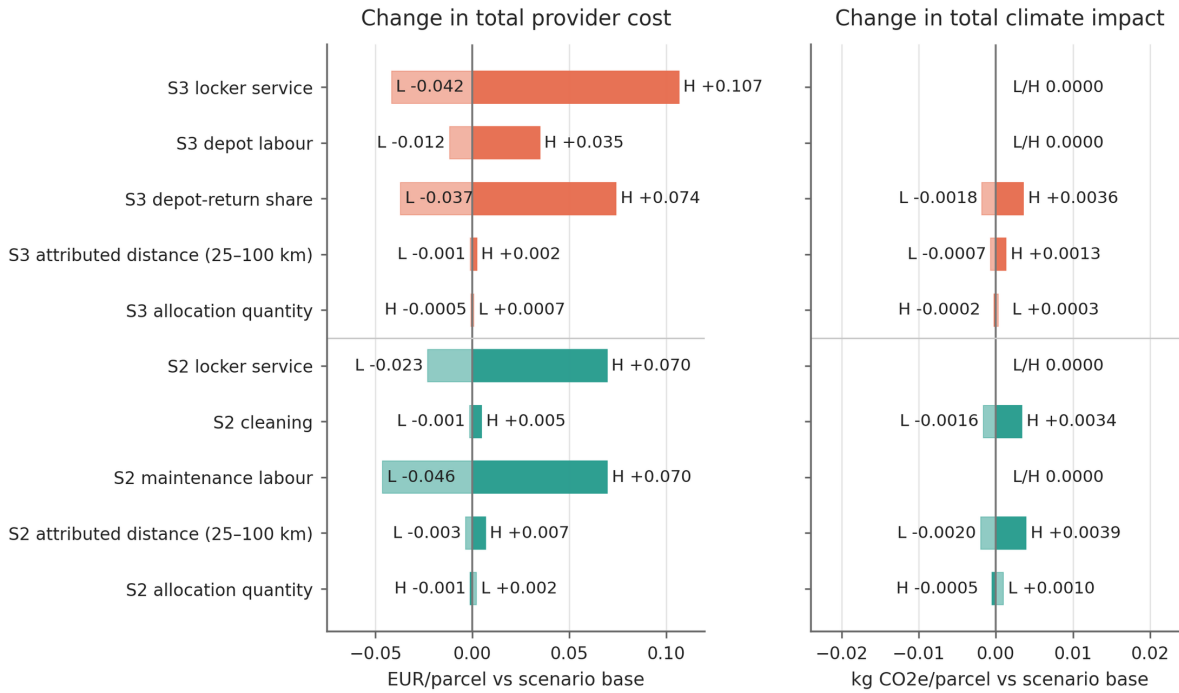


Figure 4.4: One-way sensitivity changes in provider-side cost and climate-change impact.

L and H denote the low and high cases on each parameter row. Values are changes relative to each scenario's own base-case result. For attributed redistribution vehicle distance, low/base/high are 25/50/100 km per modelled movement: low is 25 km outward, base is 50 km outward with the return absorbed, and high comprises 50 km outward plus a 50 km empty return; loading and unloading are counted once.

The route service-time check shows how locker-side handling time changes provider-side cost, without overturning the main ordering. For S2, reducing locker service time from 35 to 30 s/parcel lowers total cost by 0.023 EUR/parcel, while increasing it to 50 s/parcel raises cost by 0.070 EUR/parcel. Even in the low service-time case, S2 remains above the S1 base cost. For S3, reducing locker service time from 42 to 33 s/parcel lowers cost by 0.042 EUR/parcel, while increasing it to 65 s/parcel raises cost by 0.107 EUR/parcel. The high S3 service-time case remains below the S1 base cost.

For S2, central maintenance labour is the main cost-sensitive operational parameter among the tested one-way cases. Reducing labour from 45 to 35 s/package lowers S2 cost by 0.046 EUR/parcel, while increasing labour to 60 s/package raises S2 cost by 0.070 EUR/parcel. Even under the low-labour case, S2 total cost remains 0.983 EUR/parcel, still above the S1 base value of 0.770 EUR/parcel. Labour changes do not affect S2 climate-change impact in the current model because the labour input is monetized but not assigned a direct climate burden.

The S2 cleaning resource set has a smaller effect. The low cleaning-resource case reduces S2 climate-change impact from 0.1017 to 0.1001 kg CO₂e/parcel and reduces provider-side cost from 1.0292 to 1.0279 EUR/parcel. The high cleaning-resource case increases total climate-change impact to 0.1051 kg CO₂e/parcel and provider-side cost to 1.0339 EUR/parcel. Therefore, the tested cleaning resource assumptions do not determine the main S2 conclusion. S2 remains below S1 in climate terms and above S1 in provider-side cost terms.

For S3, the depot-return fraction is more important than depot labour and scales both depot maintenance and subsequent redistribution. When the depot-return fraction is reduced from 50% to 25%, S3 cost falls from 0.6154 to 0.5783 EUR/parcel and climate-change impact falls from 0.0475 to 0.0457 kg CO₂e/parcel. When all returned packages are assumed to require depot-side handling and redistribution, S3 cost rises to 0.6896 EUR/parcel and climate-change impact to 0.0511 kg CO₂e/parcel. Even this high depot-return case remains below both S1 and S2 in the base-case comparison. Varying S3 depot labour between 25 and 45 s/depot-returned package changes cost between 0.6038 and 0.6502 EUR/parcel and does not affect climate-change impact because this is a pure labour one-way sensitivity in which heat-gun energy and CO₂e are held at their base values.

Attributed redistribution vehicle distance and the derived capacity-based allocation quantity have limited effects within the tested ranges. At the 25 km low case and the 100 km high case, S2 cost is 1.0259 and 1.0360 EUR/parcel, while climate impact is 0.0997 and

0.1056 kg CO₂e/parcel. The corresponding S3 values are 0.6143–0.6176 EUR/parcel and 0.0468–0.0488 kg CO₂e/parcel. The high case represents 50 km outward plus a 50 km empty return, with handling counted once; relative to the 50 km base totals, it raises S2 cost and climate impact by 0.66% and 3.86%, and S3 cost and climate impact by 0.37% and 2.75%. Capacity-allocation variation gives S2 totals of 1.0314 EUR/parcel at $Q_{S2}^{\text{cap}} = 6,400$ and 1.0282 EUR/parcel at $Q_{S2}^{\text{cap}} = 9,090$; S3 totals are 0.6161 EUR/parcel at $Q_{S3}^{\text{cap}} = 9,600$ and 0.6149 EUR/parcel at $Q_{S3}^{\text{cap}} = 14,400$. These transport cases retain the base ordering.

Table 4.3 reports the route fill-rate sensitivity check. Lower fill-rate groups change route cost and route emissions, while the packaging-process and redistribution layers are held at the base value. The absolute values change slightly, but the scenario ordering does not change: S2 remains the highest-cost scenario, S3 remains the lowest-cost scenario, and both reusable scenarios remain below S1 in climate-change impact.

Table 4.3: Route fill-rate sensitivity results for the Milan base-network case, reported as EUR/parcel and kg CO₂e/parcel.

Fill-rate group	S1 cost	S2 cost	S3 cost	S1 CO ₂ e	S2 CO ₂ e	S3 CO ₂ e
0.8–0.9	0.770	1.029	0.615	0.319	0.102	0.047
0.7–0.8	0.796	1.056	0.642	0.322	0.105	0.051
0.6–0.7	0.773	1.032	0.618	0.318	0.101	0.047

4.5. Scenario Comparison

The results answer the three empirical questions of the model in different ways. For provider-side cost, S2 is not competitive with S1 in the base case, while S3 is competitive with S1 within the base proxy scenario. For climate-change impact, both reusable scenarios reduce impacts relative to S1, and S3 has the lowest modelled climate-change impact among the three scenarios. For the selected threshold and sensitivity checks, the main result is asymmetric: S2 is competitive in climate terms but not in provider-side cost under the base assumptions. S3 is competitive in both indicators at the base $N_{\text{eff}} = 30$ and throughout the reported operational and route one-way checks; it loses provider-side cost parity if realized reuse falls below the calculated threshold of $N_{\text{eff}} = 9.270$.

Figure 4.5 summarizes the auxiliary route inputs used for the network and zone robustness check. The figure is used as a robustness check rather than as a separate commercial comparison of parcel-locker operators. Across these route inputs, the same modelled within-network ordering is observed. S2 remains more expensive than the corresponding

S1 case because its packaging-process, maintenance and redistribution costs offset the climate advantage of reuse. Under the same proxy assumptions, S3 remains below the corresponding S1 and S2 cases for both modelled provider-side cost and climate-change impact. Complete numerical results are reported in Table A.12.

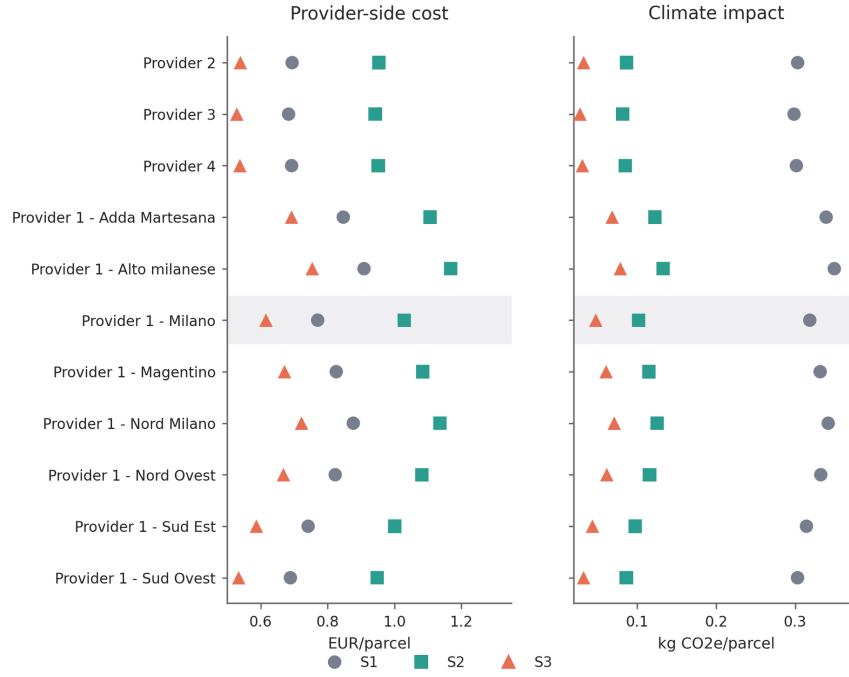


Figure 4.5: Network and zone robustness of total cost and climate-impact results. The shaded row marks the Milan base-network case used for the main interpretation.

The absolute cost range across the retained route inputs is 0.683–0.909 EUR/parcel for S1, 0.942–1.168 EUR/parcel for S2 and 0.528–0.754 EUR/parcel for S3. The corresponding climate-impact ranges are 0.299–0.350 kg CO₂e/parcel for S1, 0.082–0.133 kg CO₂e/parcel for S2 and 0.028–0.079 kg CO₂e/parcel for S3.

Across the retained route inputs, with N_{eff} and the packaging-process and redistribution assumptions held at their base values, the modelled scenario ordering remains stable: S2 is cost-disadvantaged but climate-beneficial, while S3 remains below S1 and S2 in both modelled indicators. This route robustness does not remove the reuse-cycle condition: S3 would lose provider-side cost parity below $N_{\text{eff}} = 9.270$. The interpretation of this asymmetric pattern is developed in the discussion chapter.

5 | Discussion

5.1. Interpreting the Cost-Climate Trade-off

The results point to a cost-climate asymmetry rather than to a simple ranking of reusable and single-use packaging. Both reusable scenarios reduce climate-change impact compared with the single-use cardboard baseline, but they place different operational burdens inside the provider-side system. The central question for interpretation is therefore not whether the package is reusable, but how the reuse loop is organised and where acquisition cost, handling labour, maintenance effort, redistribution, return reliability and residual end-of-life burdens enter the system.

For provider-side cost, the contrast between S2 and S3 is mainly a contrast between loop structures. S2 combines reusable-package acquisition, additional route handling, central reconditioning and redistribution; the negative maintenance-labour threshold reported in Chapter 4 shows that reducing central labour alone would not close the cost gap. S3 has a lower acquisition burden and assigns depot-side maintenance and redistribution only to the depot-returned fraction, so its cost advantage is a consequence of the local-circulation structure rather than of reusability alone.

For climate-change impact, repeated-use allocation makes both reusable scenarios favourable relative to S1, which is consistent with reusable-packaging LCA literature emphasizing reuse cycles, transport distances and washing or maintenance burdens [10, 56, 57]. The break-even results sharpen this interpretation: S2 reaches climate parity at a much lower reuse level than cost parity, while S3 reaches both thresholds at much lower values. The discussion therefore focuses on reuse-loop governance as the mechanism behind the asymmetric results.

5.2. Reuse-Loop Structure as Burden Allocation

Figure 5.1 does not restate the scenario boundaries from the methodology chapter. It reframes the three scenarios as different allocations of operational burden and reuse gov-

ernance. The horizontal axis represents the degree to which recurring work is carried inside the parcel-locker provider's operating system. The vertical axis represents the amount of reuse-specific governance required for the loop to function, including return discipline, asset tracking, stock control and quality rules. Under this framing, S1 sits low on reuse governance but high on material throughput, S2 internalises control and recurring work inside a centralized provider loop, and S3 reduces central processing while shifting feasibility toward local circulation and return reliability. This is the mechanism behind the asymmetric results.

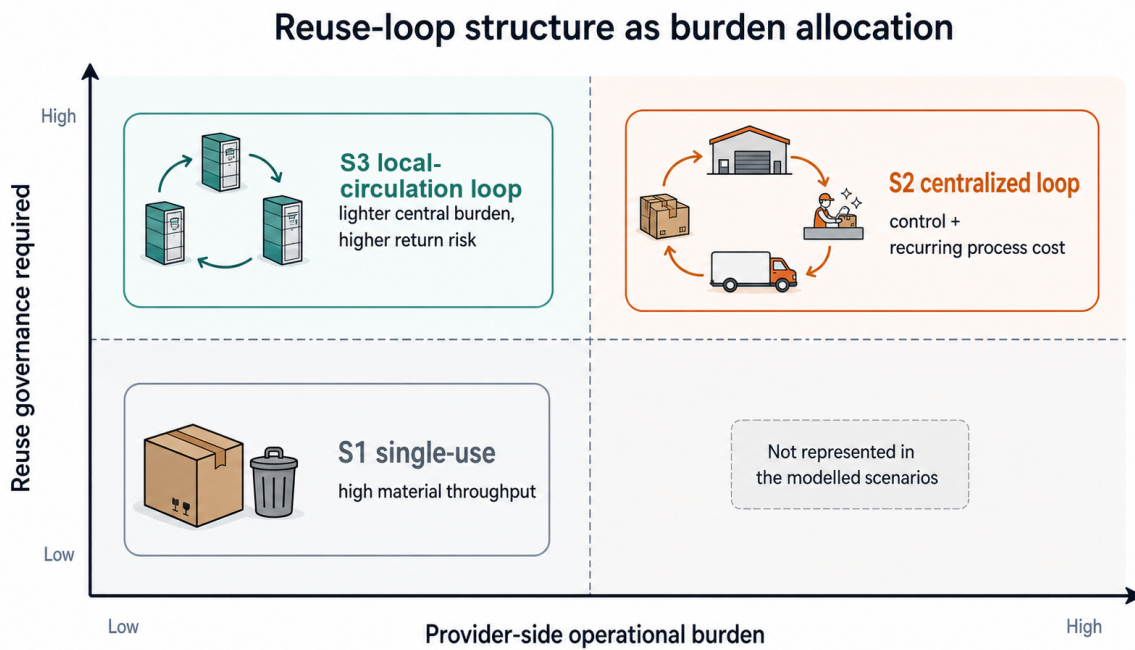


Figure 5.1: Reuse-loop structure as burden allocation. The figure is a qualitative discussion map, not an additional model result. S2 concentrates control and recurring process cost inside a centralized loop, while S3 reduces central-loop burden but depends more strongly on local return reliability, stock control and user cooperation.

The S2 result is therefore not surprising when interpreted as a centralized asset loop. Centralization reduces ambiguity about where packages should go after use, and it may support consistent quality control. At the same time, it makes the provider bear recurring process costs and redistribution for every returned package. Such asset-management requirements are consistent with the reusable transport item and closed-loop supply-chain literature, which identifies return logistics, cleaning or repair, inventory control, replacement and tracking as central operational tasks for reusable packaging systems [5, 34, 51]. The model captures this through central maintenance labour, heat-gun electricity, water,

detergent, capacity-based allocation of empty-package redistribution and reusable-package acquisition amortisation. The sensitivity results show that the cleaning resource quantities and redistribution distance are not the main drivers of S2's cost disadvantage. The more important mechanism is that the package is relatively expensive and that the centralized loop requires repeated handling and reconditioning. This explains why S2 can be climate-beneficial but cost-fragile.

S3 represents a different adoption logic. It reduces the central-loop burden by allowing reusable cardboard packages to remain in or around parcel-locker nodes as local stock, with only the depot-returned fraction receiving depot-side maintenance and subsequent redistribution. This is why S3 performs well in the model: its advantage comes from lower acquisition burden, lower allocated production emissions and reduced exposure to central maintenance and redistribution. However, the same position in Figure 5.1 also explains why S3 cannot be treated as automatically validated. If packages are locally reused, the system must still know whether packages are available, clean enough, undamaged, assigned to the right user or flow, and eventually removed from circulation when they fail quality requirements. The burden has not disappeared; part of it has moved from central operations into local governance.

This distinction is important because some reusable-packaging discussions focus on the number of cycles as if it were an independent technical parameter. In practice, effective reuse cycles are produced by a system: customers must return or release packages, operators must inspect and redistribute them, and loss or damage must remain low enough for the assumed lifespan to be realistic. The literature on reusable e-commerce packaging and returnable transport items points to the same issue: reuse performance is influenced by return behaviour, system design, management responsibility and the distance or burden associated with reverse flows [7, 10, 35]. The thesis model adds a parcel-locker provider-side perspective to this discussion by showing how these loop features translate into cost and climate indicators per delivered parcel.

5.3. Return Reliability and the Credibility of S3

The favourable S3 result should not be interpreted as proof that a local-circulation reusable cardboard loop would automatically work in real operation. It is better read as a feasibility signal under a specific set of assumptions. The most important assumption is the effective reuse cycle count. In the base model, S3 uses 30 effective cycles based on the Re-Zip/Tang proxy. If this value is read as realized N_{eff} , then the model already assumes that loss, non-return and unusable circulation outcomes have been absorbed into

the effective-use value. If the same number is read instead as a technical or material lifetime M , then a behavioural return-rate bridge is needed before the value can be used as an effective cycle count.

Grimes-Casey et al. [36] relate the average number of uses u of refillable packaging to a constant return rate R through $R = (u - 1)/u$, which implies $u = 1/(1 - R)$. This is the unbounded geometric-series relationship between return and repeated use. To represent the finite technical lifetime of the S3 packaging proxy, the same sequence is truncated here after M potential uses. In Equation 5.1, r is the conditional probability that a package remains available after each circulation. Assuming that r is constant across cycles, the probability of reaching use $i + 1$ is r^i , and summing these probabilities gives:

$$N_{\text{eff}}(r, M) = \sum_{i=0}^{M-1} r^i = \begin{cases} \frac{1 - r^M}{1 - r}, & 0 \leq r < 1, \\ M, & r = 1. \end{cases} \quad (5.1)$$

Equation 5.1 is therefore an illustrative finite-lifetime extension of the established return-rate relationship, rather than an empirical fit to observed S3 data or an additional probabilistic module in the base model. It is also consistent with the PEFCR principle that reusable-packaging burdens should be allocated over an observed or otherwise justified number of uses rather than a nominal technical maximum [22].

Table 5.1 translates this bridge into illustrative values for $M = 30$. It shows the nonlinear character of the assumption: moving from 80% to 90% return or retention almost doubles realized effective use, while the 100% case is the limiting case in which $N_{\text{eff}} = M$.

Table 5.1: Illustrative conversion from per-cycle return/retention rate to realized effective uses for $M = 30$.

Per-cycle return/retention rate r	Realized N_{eff} , $M = 30$
50%	2.0
75%	4.0
80%	5.0
85%	6.6
90%	9.6
95%	15.7
100%	30.0

This distinction is consistent with reuse-system literature that treats return rates, use cycles and asset availability as central performance metrics [3, 17]. It is also consistent with the practical warning that open reuse systems often achieve far fewer realized uses than the physical durability of the package might suggest; for example, Closed Loop Partners links 80% and 90% return rates to approximately five and ten average uses, respectively [8]. The WWF-Singapore e-commerce pilot similarly reported a return rate above 50%, with survey evidence suggesting that education and convenience could raise it above 75% [71].

Figure 5.2 visualizes this bridge between technical package lifetime and realized effective use.

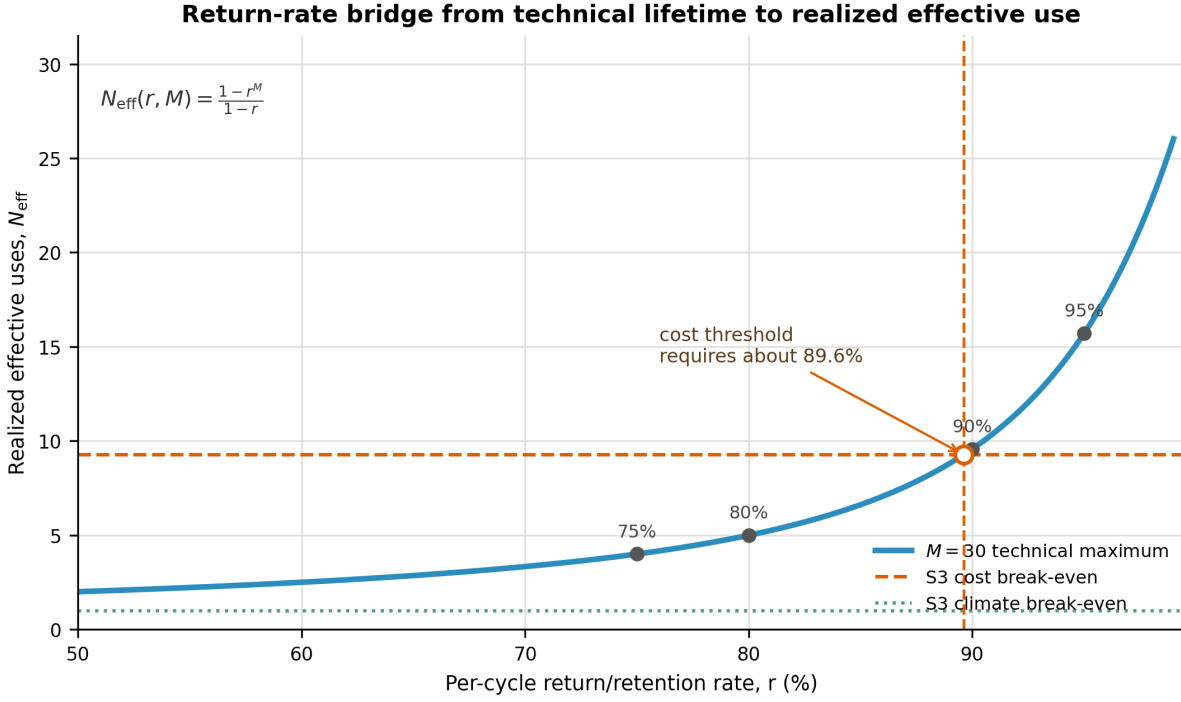


Figure 5.2: Return-rate bridge from technical lifetime to realized effective use for S3, shown for a technical maximum of $M = 30$ uses. The figure does not replace the base model; it illustrates that if 30 uses are interpreted as technical durability rather than realized N_{eff} , the S3 cost break-even threshold of 9.27 effective uses would require a per-cycle return or retention rate of about 89.6%.

The first risk is therefore user behaviour. Unlike a centrally enforced return system, a local-circulation loop depends on users accepting the idea that packaging is not waste but a reusable asset. If the package remains at the parcel locker or is transferred to another user, the system must create a low-friction path for the package to re-enter circulation. Otherwise, packages may be taken home, discarded, stored privately, or returned through channels that the operator cannot efficiently use. Consumer acceptance and cooperation are therefore not soft secondary issues. They directly affect realized N_{eff} , loss rates and the credibility of local circulation. The S3 result is therefore strongest when 30 cycles can be defended as realized effective reuse, not merely as package durability.

The second risk is local stock imbalance. Parcel lockers are not uniform storage nodes. Demand, parcel size mix, sender behaviour and locker utilization vary across locations. A local-loop design may have too many reusable packages at one locker and too few at another. If this happens frequently, the operator must rebalance stock through additional depot returns, manual handling or route-side interventions. In the current model this

complexity is represented only through the depot-return fraction, not through a dynamic locker-level inventory simulation. This is a reasonable simplification for the scope of the thesis, but it should be acknowledged as a limitation of the S3 result.

The third risk is quality control. Cardboard-based reusable packaging may be attractive because of lower acquisition and climate burdens, but quality and hygiene requirements still matter. A local package that is visibly damaged, wet, contaminated or missing closure components cannot simply remain in circulation. The model includes depot-side heat-gun maintenance and labour for the depot-returned fraction, but it does not simulate every local inspection decision. In practice, a local-circulation loop would require clear rules on who checks package quality, when a package is removed from stock, how reusable labels or seals are managed, and how liability is allocated between the parcel-locker provider, merchant, customer and any reusable-packaging service provider.

These risks do not invalidate S3. They define the conditions under which the S3 result can be used. If a provider can create simple return incentives, clear local-stock procedures, robust package-identification rules and low-friction inspection routines, then the local-loop mechanism identified in the model becomes plausible. If not, S3's apparent advantage may be weakened by lower realized reuse cycles, higher depot-return fractions or higher loss rates. Under the modelled assumptions, the local-circulation loop has a more favourable cost-climate structure than the centralized loop, but its real-world feasibility depends on governance of return reliability and local stock.

5.4. Robustness Checks and External Cost Trends

The sensitivity analysis in Chapter 4 is deterministic. It is not a probabilistic uncertainty analysis and it does not estimate statistical confidence intervals. The same distinction applies to the discussion-level counterfactual and trend checks in this section. They are not additional formal scenarios and they should not be read as forecasts. Their purpose is to connect the model mechanism to plausible operational questions: whether the S2 cleaning assumption drives the result, whether labour and utility-price trends change the interpretation, how redistribution transport affects the loop, and how fleet electrification would affect the climate layer.

5.4.1. Does Cleaning Drive the S2 Cost Gap?

The most immediate counterfactual concerns the S2 wet-cleaning assumption. Because the base model includes light water and detergent inputs for S2, it is reasonable to ask

whether S2 is being penalised by an extra cleaning action. Figure 5.3 shows why this is not the central mechanism. Even the broader low-cleaning-resource sensitivity reported in Chapter 4 reduces S2 cost only from 1.0292 to 1.0279 EUR/parcel, a change of approximately 0.0014 EUR/parcel, and the result remains well above the S1 cost baseline of 0.7701 EUR/parcel. A counterfactual that removed only water and detergent would not remove central inspection, sorting, label handling, package tracking, acquisition amortisation or redistribution. The stronger interpretation is therefore not that S2 requires exactly the base wet-cleaning input. It is that any credible centralized reusable loop requires recurring reconditioning and asset-management processes, which are known operational tasks in reusable transport item systems [34, 51].

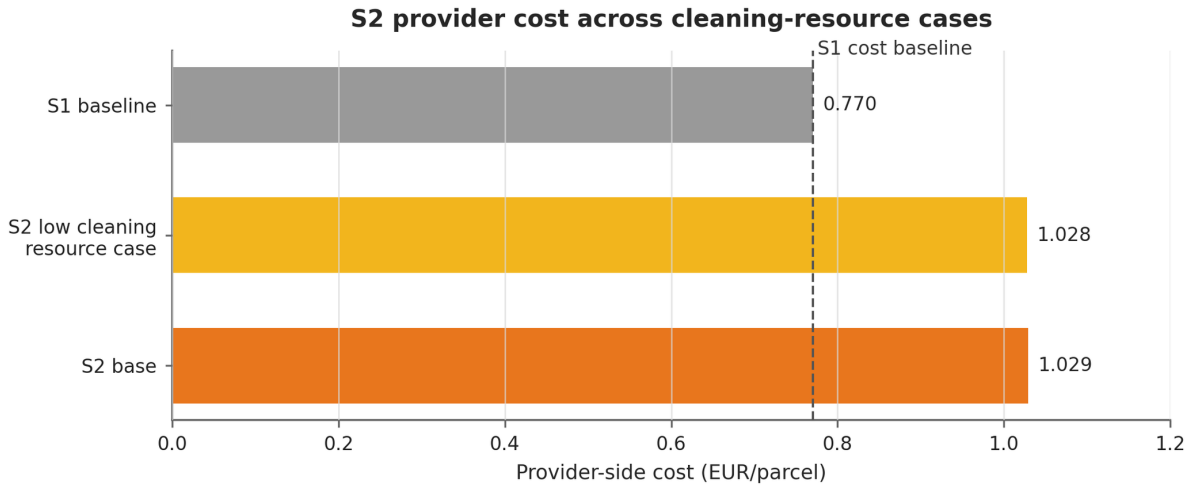


Figure 5.3: S2 wet-cleaning counterfactual and cost gap. The low-cleaning-resource case reduces S2 provider-side cost relative to the base S2 result, but it remains far above the S1 cost baseline.

5.4.2. Cost-Trend Stress Tests

The labour-cost trend varies the hourly labour-cost rate while holding handling times fixed. Chapter 4 already reports deterministic sensitivity to maintenance time in seconds. The external trend question asks how a higher EUR/hour rate affects total provider-side cost when route, locker-service, maintenance, redistribution driving, loading and unloading times remain unchanged. Eurostat reports that hourly labour costs increased by 4.1% in the EU and 3.8% in the euro area in 2025, and that they continued to rise in the first quarter of 2026 [29, 30]. In the thesis model, this affects the route driver-time component, the maintenance-labour component and redistribution-truck driver occupied time, while packaging acquisition, distance-based vehicle cost, end-of-life handling and

physical utility quantities are kept fixed.

Figure 5.4 plots the total provider-side cost of S1, S2 and S3 under two deterministic price checks. The left panel varies the hourly wage-rate proxy adopted in the model, with 16.7 EUR/hour as the base value; the right panel varies electricity, water and detergent prices while operating times and physical input quantities remain fixed.

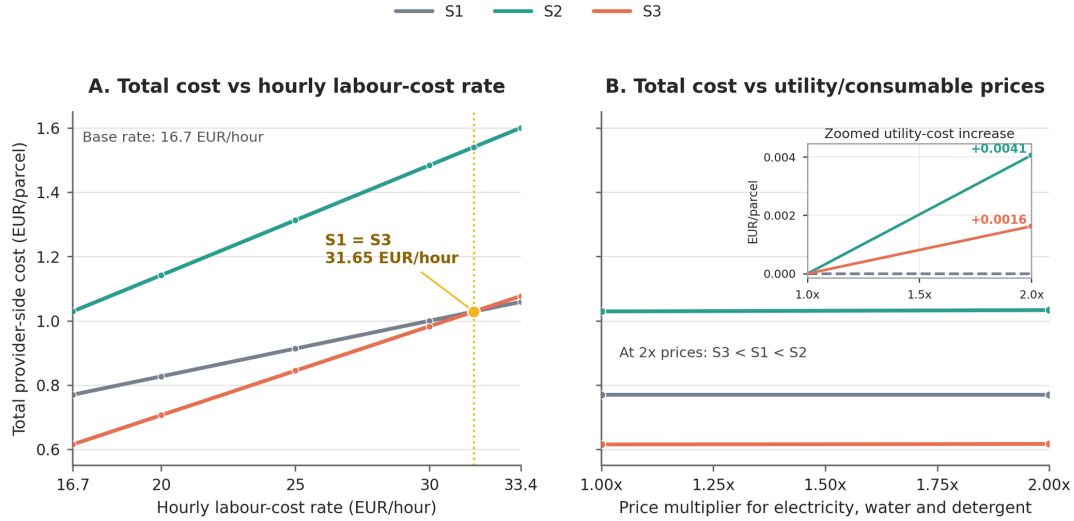


Figure 5.4: Total provider-side cost under hourly labour-cost and utility/consumable price checks for the Milan base-network case. Panel A varies the hourly wage-rate proxy; Panel B varies electricity, water and detergent prices, with the inset magnifying the resulting cost changes. Both panels use a common total-cost scale, while operating times and physical input quantities remain fixed.

Increasing the hourly rate from 20 to 25 EUR/hour raises total cost from 0.827 to 0.914 EUR/parcel for S1, from 1.142 to 1.313 EUR/parcel for S2, and from 0.707 to 0.845 EUR/parcel for S3. S2 remains above S1 throughout the tested range. S3 reaches parity with S1 at approximately 31.65 EUR/hour, equivalent to an 89.5% increase from the base rate. This is a deterministic threshold under fixed processing times.

Energy and utility prices should be treated more cautiously. Eurostat data for non-household electricity prices show recent movement and country variation [31, 32]. In the right panel of Figure 5.4, doubling electricity, water and detergent prices increases S2 total cost from 1.0292 to 1.0333 EUR/parcel and S3 total cost from 0.6154 to 0.6170 EUR/parcel; S1 remains at 0.7701 EUR/parcel because these maintenance inputs are absent from its cost inventory. The ordering therefore remains $S3 < S1 < S2$. Within the tested provider-side boundary, utility prices have little leverage on total cost, whereas

higher hourly labour-cost rates widen S2's disadvantage and gradually erode S3's cost buffer.

5.4.3. Fleet Electrification and Route Emissions

Vehicle electrification affects the interpretation in a different way. EEA provisional data indicate that average emissions from new vans decreased in 2025 and that fully electric vans increased their fleet share, while ACEA still reports diesel as the dominant fuel type among new EU van registrations in 2025 [21, 25]. The direction of travel is therefore toward lower van emissions, but the transition is incomplete. Figure 5.5 separates the last-mile van route, the redistribution rigid-truck leg and the remaining packaging, maintenance and end-of-life components. If the delivery fleet becomes less carbon-intensive, the last-mile route-emission component would decrease. Decarbonisation of the facility-to-facility vehicle would separately reduce the redistribution component. The relative importance of packaging production, maintenance and end-of-life modelling would then increase. This would not make loop structure irrelevant. It would make the differences in acquisition burden, reconditioning responsibility and realized reuse cycles even more central to the climate interpretation.

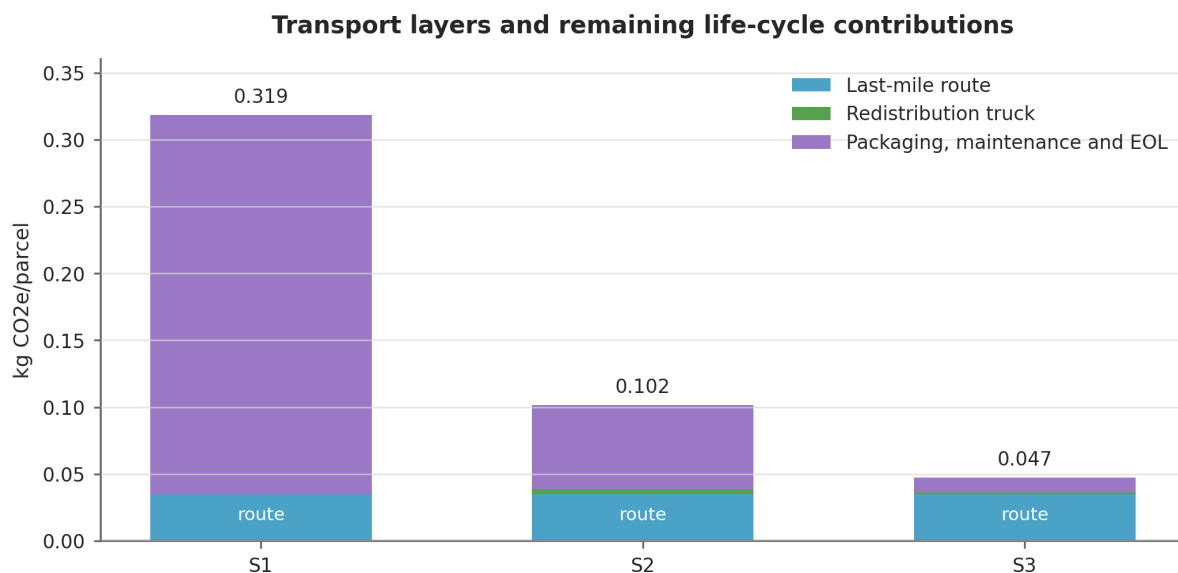


Figure 5.5: Base-case climate contributions separated into last-mile route emissions, redistribution-truck emissions and remaining packaging, maintenance and end-of-life components. Lower van emissions would reduce the blue route component, while decarbonisation of the facility-to-facility vehicle would reduce the green redistribution component.

5.5. Provider Implications and Boundary Conditions

For parcel-locker providers, the main managerial implication is that reusable packaging should be designed as an operating system rather than purchased as a packaging substitute. A centralized reusable loop may be attractive when quality control, tracking and standardisation are priorities, but it requires strong control of acquisition cost, maintenance labour, return-processing efficiency, capacity-based allocation quantity and facility-to-packing-point redistribution. The S2 result suggests that a provider adopting such a system would need either much cheaper reusable units, substantially higher realized cycles, shared-cost arrangements with merchants or reusable-packaging service providers, or operational automation that reduces recurring handling effort. Without such changes, the climate case for S2 may be stronger than the business case.

For local-circulation reuse designs, the managerial challenge is different. S3's cost and climate advantage depends less on central maintenance efficiency and more on whether the provider can maintain circulation reliability without converting the local loop back into a hidden central return operation. The provider would need rules for package availability, quality inspection, damage reporting, package identification, customer incentives and stock balancing across lockers. If these controls are simple and low-cost, the S3 logic becomes credible. If they require frequent manual intervention or additional repositioning trips, part of the modelled advantage may disappear.

The results also suggest that reusable-packaging partnerships should be evaluated through shared operational responsibilities. A parcel-locker provider may not want to own every package or perform every maintenance step. Merchants, reusable-packaging operators and logistics providers may each hold part of the responsibility for package acquisition, customer communication, cleaning, replacement and data tracking. The thesis model takes the logistics-provider perspective, so it helps identify which burdens fall inside the provider boundary. It does not determine how those burdens should be contractually shared. This is an important practical extension for future work.

Several limitations should be kept explicit. First, the study uses deterministic scenario and sensitivity analysis. Its values are model outputs under specified assumptions and do not represent probability distributions or statistical confidence intervals. The modelled S2 and S3 configurations have not been implemented as operating parcel-locker services in Milan, so the study lacks an independent real-case dataset for external validation and may retain parameter or structural error. Second, several inputs are proxies. HeyCircle, Re-Zip/Tang, ecoinvent process matches, S2 maintenance labour and S3 depot-return assumptions are used to build a transparent model, but they are not direct measure-

ments from an implemented S2 or S3 parcel-locker service in Milan. The redistribution component adds engineering assumptions for one destination, a 50 km one-way facility separation, folded-package thickness, 75% space utilisation, 5 t usable payload, capacity-based allocation and 60 minutes of loading and unloading. The base case assumes that the subsequent vehicle return is absorbed within existing backhaul or fleet activity. The high attributed-distance sensitivity case sets $D_{\text{attr}} = 100$ km by fully assigning an additional 50 km empty return; it does not change the scenario ordering. Third, the model focuses on climate-change impact and provider-side cost per parcel. It does not provide a full multi-impact LCA result and it does not include all possible social, behavioural or customer-convenience outcomes.

Fourth, customer travel to and from parcel lockers is outside the quantitative boundary. This is appropriate for the provider-side research question, but it means the model should not be read as a complete societal comparison of home delivery, parcel lockers and reusable packaging. Fifth, the route model represents planned last-mile operations and selected robustness cases, not a full dynamic operational simulation with failed deliveries, parcel expiry, stochastic demand, real-time locker capacity constraints or explicit local stock flows. These omissions are acceptable for the thesis scope, but they matter for implementation.

Overall, the discussion supports a cautious but clear conclusion. The provider-side feasibility of reusable packaging in parcel-locker delivery depends on the structure and governance of the reuse loop. S2 demonstrates the risk of a climate-beneficial but cost-fragile centralized loop. S3 demonstrates the potential of a lighter local-loop configuration, while also exposing the need for credible return behaviour, local stock control and effective reuse.

6 | Conclusions

6.1. Main Conclusions

This thesis evaluated whether reusable packaging can be provider-side feasible in a parcel-locker-based last-mile delivery system in Milan. The analysis compared three scenario configurations: S1 as a single-use cardboard baseline, S2 as a centralized reusable plastic loop, and S3 as a local-circulation reusable cardboard loop. Using one parcel delivered through the parcel-locker last-mile system as the functional unit, the model integrated route-operation outputs, packaging climate-impact accounting, capacity-based allocation of empty-package redistribution, provider-side cost components, threshold analysis and sensitivity analysis.

The first research question asked how provider-side cost differs across the three packaging-loop designs. In the Milan base-network case, S1 costs 0.770 EUR/parcel, S2 costs 1.029 EUR/parcel and S3 costs 0.615 EUR/parcel. The centralized S2 loop therefore exceeds the single-use baseline, while the local-circulation S3 loop remains below it under the base assumptions. S1 assigns 0.40 EUR/parcel to a new cardboard package, while the 18.27 EUR S2 package still contributes 0.365 EUR/parcel when allocated across 50 effective uses. S2 therefore saves only about 0.035 EUR/parcel in package acquisition before additional route handling, central maintenance and capacity-allocated empty-package redistribution are included. These recurring loop costs more than offset the small acquisition saving and produce a total S2 premium of approximately 0.259 EUR/parcel. The S3 result is more favourable because its lower acquisition burden is combined with local circulation and a base assumption that only 50% of returned packages require depot-side maintenance and redistribution. Its provider-side advantage therefore depends on achieving 30 effective uses while keeping depot intervention and local stock imbalance under control.

The second research question asked how the scenarios compare in climate-change impact. S1 reaches 0.319 kg CO₂e/parcel, compared with 0.102 kg CO₂e/parcel for S2 and 0.047 kg CO₂e/parcel for S3. Repeated use spreads packaging production and end-of-life burdens across several parcel deliveries, producing lower base-case impacts for both reusable

configurations. Capacity-allocated empty-package redistribution contributes 0.003925 kg CO₂e/parcel in S2 and 0.001308 kg CO₂e/parcel in S3, so it does not overturn this ordering. Packaging production remains the dominant climate contributor in S1 and the largest packaging-process contributor in S2. The lower packaging-process burden in S3 makes the route layer its largest climate contributor. These results establish a climate advantage for the two modelled reusable loops within the provider-side boundary and specified operating assumptions.

The third research question concerned the conditions under which reusable packaging becomes competitive with S1 in both indicators. The break-even results show a marked difference between economic and climate requirements. S2 reaches climate parity after approximately 10.73 effective uses, while provider-side cost parity requires approximately 169.01 uses, far above its base assumption of 50. This exceptionally high cost threshold reflects the mechanism identified under the first research question. Because the single-use package is already inexpensive, the acquisition saving achieved through reuse cannot offset the recurring handling, maintenance and redistribution costs of the centralized loop until the package burden is spread over more than three times the assumed base life. In a sector where margins are already low [2], the resulting premium is not a minor operational difference: absorbing it would further compress provider profitability, whereas passing it on would require higher fees for merchants or customers. S2 would therefore require lower package prices, a longer realized life, process automation, cost sharing or higher service prices; its climate advantage alone is insufficient to establish commercial feasibility. S3 requires approximately 9.27 effective uses for cost parity. Its continuous climate threshold is 0.974 uses, so climate parity is already reached at the first feasible integer use. The base S3 scenario consequently satisfies both thresholds, provided that the assumed effective life and local-circulation structure can be achieved in operation. The sensitivity analysis further shows that variation in attributed redistribution vehicle distance from 25 to 100 km and in capacity-based allocation quantity does not change the scenario ordering; the 100 km high case assigns an additional 50 km empty return. Overall feasibility is therefore governed by the configuration of the reuse loop: acquisition cost, realized effective uses, handling effort, depot-return share, redistribution and stock control jointly determine whether the climate benefit can be delivered at a competitive provider-side cost.

6.2. Contributions and Managerial Implications

The conceptual contribution is to connect parcel-locker delivery with reusable-packaging circulation. Parcel-locker research commonly examines route efficiency, facility location, service time and delivery cost, while reusable-packaging research emphasizes material substitution, reuse cycles, returns, maintenance and the allocation of environmental burdens. This thesis links these perspectives by treating reusable packaging as a circulating operational asset that requires retrieval, inspection, maintenance, redistribution, replacement and end-of-life handling. The different S2 and S3 outcomes demonstrate the importance of the operating structure surrounding the package.

The methodological contribution is an integrated provider-side scenario model that combines ArcGIS route outputs, scenario-specific service times, packaging climate inventory, acquisition and maintenance costs, capacity-based allocation of rigid-truck empty-package redistribution, sensitivity checks and break-even thresholds within a common functional-unit calculation. This framework makes the conditions behind each result explicit. In S2, a climate improvement coexists with a provider-side cost disadvantage. In S3, favourable base-case results depend on realized effective use and the ability to retain part of the circulation locally.

For logistics providers, the findings identify different priorities for the two reusable-loop designs. A centralized loop offers greater control over quality, cleaning, tracking and standardisation, while placing recurring labour and maintenance expenditure within the provider boundary. Its economic case would benefit from a lower package-acquisition cost, a longer realized effective life, shared-cost arrangements or automation that reduces handling effort. A local-circulation loop can reduce central processing, provided that return reliability, local availability, stock balance, quality control and user cooperation are effectively managed. Frequent depot intervention or rebalancing would erode part of the modelled S3 advantage. These operating conditions should therefore be assessed alongside the physical design of the package when providers consider a reusable-packaging service.

6.3. Limitations

Because neither S2 nor S3 has been implemented as an operating parcel-locker service in Milan, no observed operational dataset is available against which the integrated model can be validated. The results should therefore be interpreted as scenario estimates conditional on the specified assumptions, rather than as empirically validated predictions of real-world

performance. The sensitivity and break-even analyses show how the conclusions change under selected parameter variations and identify the conditions under which each scenario becomes feasible; they do not eliminate parameter or structural uncertainty, nor do they provide statistical confidence intervals.

Several inputs are public-data proxies or engineering assumptions in place of operator-specific measurements. The S2 package is informed by public HeyCircle M-type information, the S3 package by ReZip/Tang-style evidence, and the maintenance, redistribution and end-of-life components by transparent process proxies. The redistribution component assumes one destination, a 50 km one-way facility separation, folded-package dimensions, 75% space utilisation, a 5 t usable payload, capacity-based allocation and 60 minutes of loading and unloading. The base case also assumes that the vehicle return is absorbed within existing backhaul or fleet activity; the high value in the 25–100 km attributed-distance sensitivity fully assigns an additional 50 km empty return. These inputs support a transparent feasibility assessment, while their commercial accuracy remains to be tested with observed operations.

To determine whether changing the packaging loop is feasible for a logistics operator, the comparison must isolate the processes and burdens that the operator can control or finance. The calculation therefore includes last-mile route operation, package acquisition, return handling, maintenance, redistribution, replacement and provider-controlled end-of-life treatment. Because all three scenarios use the same parcel-locker delivery interface, ordinary recipient travel to collect a delivered parcel is a common background condition rather than a difference created by the packaging choice, and is held outside the comparison. Customer activity is not assumed to be unimportant: reusable-package returns could induce different journeys in practice. A system-wide assessment would need to distinguish walking, cycling, public transport and private-car travel, as well as dedicated return trips from returns combined with an already planned journey, and would also need to account for customer time and wider social costs. The conclusions of this thesis should therefore be read as applying specifically to provider-side cost and climate-change impact, rather than to total societal cost or a complete system carbon footprint.

The route and stock representations also simplify operational dynamics. The route model captures planned last-mile operation and selected robustness cases, while demand variation, parcel expiry, failed collections, real-time locker capacity, local reusable-package stocks and stochastic user behaviour are not dynamically simulated. These elements are particularly relevant to the operational credibility of S3 because local circulation requires packages to be available at the required location, time and condition.

6.4. Future Research

The first priority for future research is external validation through an operational pilot. Observed data on package return, realized effective uses, loss and damage, inspection, cleaning or repair, local stock availability, folded-package density, truck loading, dispatch volumes and facility-to-packing-point movements would allow the proxy inputs to be replaced by measured distributions. A pilot would also test whether the S3 effective-life and depot-return assumptions can be maintained in a functioning parcel-locker system.

A second direction is dynamic modelling of reusable-package circulation. Locker-level simulation could represent demand variation, customer return timing, package condition, local availability, depot rebalancing and route-side intervention over time. This extension would clarify how frequently a local system experiences shortages or excess stock and how those imbalances affect the cost advantage indicated by the base S3 scenario. Related governance research could compare logistics-provider, merchant and third-party ownership, as well as shared-cost arrangements for acquisition, maintenance, replacement, incentives and data infrastructure.

A wider system assessment should incorporate recipient travel to and from collection points. The analysis would need to distinguish walking, cycling, public transport and private-car use, together with dedicated collection trips and collection combined with an existing journey. For chained trips, the incremental detour attributable to parcel collection should be separated from the underlying journey. These distinctions can materially affect the system-level emissions assigned to out-of-home delivery [54, 59]. Further extensions could include electric delivery fleets, additional life-cycle impact categories, customer convenience and broader social outcomes. Reusable-package feasibility ultimately requires an operating system that delivers enough effective uses to justify continued circulation.

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A | Supplementary Model Documentation

A.1. Model Inputs and Inventories

This appendix documents the numerical inputs and supporting outputs used in the deterministic scenario model. The tables supplement Chapter 3, Chapter 4 and Chapter 5 by making the calculation basis traceable within the thesis. Blank cells are shown as “–”. Where a row is based on a thesis-specific modelling choice rather than a direct external citation, the source column identifies the basis as model scope, scenario assumption, engineering estimate, field survey, route-model output or model calculation. Table A.1 gives the reading logic of the appendix: the main text contains the interpretive summaries, while the appendix contains the numerical trace and calculation support.

Table A.1: Guide to supplementary model tables

Main-text role	Supplementary support	Purpose in the appendix
Scenario and model assumptions	Tables A.2, A.3, A.4	Documents the independent numerical inputs and inventory rows behind the scenario-level methodology tables.
Maintenance, cleaning and end-of-life calculations	Tables A.5 and A.6	Provides calculation detail for process proxies that are summarized more compactly in Chapter 3.
Route-layer fill-rate sensitivity	Table A.7	Keeps the full route input/output trace, including the 0.6–0.7, 0.7–0.8 and 0.8–0.9 fill-rate groups.
One-way sensitivity	Tables A.8 and A.9	Reports the low/base/high values and numerical outputs behind Figure 4.4.
Threshold and network robustness	Tables A.10, A.11 and A.12	Provides complete threshold checks, plotting data and full network/zone results behind the summarized Chapter 4 displays.

A.1.1. Independent Model Input Parameters

Table A.2 reports the independent base parameters used by the deterministic scenario model. Boundary definitions such as the functional unit, provider-side perspective and excluded processes are described in Chapter 3; the table below focuses on numerical inputs used directly in the route, climate-impact and cost calculations. Sensitivity and reference values are separated into Table A.8 to keep the base register readable. The N_{eff} rows are scenario allocation assumptions for successful reuse cycles; their uncertainty is tested through the reuse-cycle range and break-even rows.

Table A.2: Independent base model input parameter register

Parameter	Scenario	Base	Unit	Source/basis
Package weight	S1	180	g/unit	Model package proxy
Package weight	S2	550	g/unit	[38]
Package weight	S3	195	g/unit	[67]
N_{eff}	S1	1	cycles	Model scope
N_{eff}	S2	50	cycles	HeyCircle box-family proxy [39, 74]
N_{eff}	S3	30	cycles	ReZip/Tang cardboard proxy [67]
Locker service time	S1	20	s/parcel	Scenario assumption informed by [64]
Locker service time	S2	35	s/parcel	Scenario assumption informed by [64]
Locker service time	S3	42	s/parcel	Scenario assumption informed by [64]
Van capacity	All	150	parcels/vehicle	[64]
Driver wage (maintenance conversion)	All	16.7	EUR/hour	Equals 0.004639 EUR/s in maintenance formulas; [64]
ArcGIS route time-cost coefficient	All	0.278	EUR/min	Rounded coefficient embedded in route outputs; [64]
Van operating cost	All	0.36	EUR/km	[64]
Tailpipe emission factor	All	154	g CO ₂ /km	[68]
Parcel-locker slots	All	52	slots/locker	Field survey
Base fill-rate group	All	0.8-0.9	fraction interval	Route-model output
S1 cardboard material EF	S1	0.8353	kg CO ₂ e/kg	[16]
Cardboard-box conversion EF	S1/S3	0.7865	kg CO ₂ e/kg processed	[16, 67]
PP-rich material EF	S2	3.679	kg CO ₂ e/kg	[16]
Flexible-plastic conversion EF	S2	0.3698	kg CO ₂ e/kg processed	[16]
S2 maintenance emissions	S2	0.003704	kg CO ₂ e/parcel	Time-aligned maintenance model using [16, 67]
S3 depot-maintenance emissions	S3 base 50% depot return	0.002285	kg CO ₂ e/parcel	Time-aligned scenario assumption using [16, 67]
Packaging unit cost	S1	0.4	EUR/unit	Market price proxy, [18]
Packaging unit cost	S2	18.27	EUR/unit	[38]
Packaging unit cost	S3	2.03	EUR/unit	Market price proxy, [60]

Parameter	Scenario	Base	Unit	Source/basis
Cleaning share	S2	1	fraction	Scenario assumption informed by [35]
Cleaning water quantity	S2	0.1519	L/package	Scaled RPC washing proxy, [38, 48]
Cleaning detergent quantity	S2	0.000304	kg/package	Scaled RPC washing proxy and ecoinvent factor, [16, 38, 48]
Heat-gun electricity	S2	0.008333	kWh/package	Tang 1.5 kW rated-power proxy multiplied by the 20 s label-removal engineering time; Tang's 5 min/0.125 kWh assumption is not the base duration, [16, 67]
Maintenance labour time	S2	45	s/package	Engineering estimate
Depot-return fraction r_{dep}	S3	0.5	fraction	Scenario assumption applied to both depot maintenance and empty-package redistribution
Heat-gun electricity	S3	0.0125	kWh/returned unit	Tang 1.5 kW rated-power proxy multiplied by the 30 s depot-maintenance engineering time; Tang's 5 min/0.125 kWh assumption is not the base duration, [16, 67]
Maintenance labour time	S3	30	s/returned unit	Engineering estimate
EOL weighted EF	paper/cardboard	0.1119	kg CO ₂ e/kg waste	Italy 2023 shares and ecoinvent factors, [11, 16, 43]
EOL weighted EF	plastic PP-rich	1.329	kg CO ₂ e/kg waste	Italy 2023 shares and ecoinvent factors, [11, 16, 43]
Waste-management fee	S2/S3 provider-controlled scrap	0.234	EUR/kg waste	Waste-handling proxy, [44, 63]
Maintenance electricity price	S2/S3	0.2597	EUR/kWh	[32]
Maintenance water price	S2	2.43	EUR/m ³	[1]
Maintenance detergent price	S2	5	EUR/kg	Market price proxy, [69]
One-way facility separation d	S2/S3	50	km	Case-study route check for a representative central-facility-to-fulfilment empty-package movement in the Milan area
Base attributed vehicle distance D_{attr}	S2/S3	50	km/modelled movement	Outward movement attributed; vehicle return assumed absorbed within existing backhaul or fleet activity
Redistribution truck speed	S2/S3	58.8	km/h	VECTO Class 4 regional-delivery cycle, [72]

Parameter	Scenario	Base	Unit	Source/basis
Redistribution truck factor	S2/S3	0.628	kg CO2/vehicle-km	4-RD heavy-duty vehicle average, [23]
Redistribution truck running cost	S2/S3	0.7955	EUR/vehicle-km	Italian Class C midpoint, [52]
Redistribution loading and unloading	S2/S3	60	min/reference movement	Engineering assumption
Redistribution application	S2	1	fraction	Fixed at 100%; all centrally processed packages enter the redistribution leg
Rigid-truck gross mass	S2/S3	18	t	VECTO Class 4 rigid-truck specification, [72]
Rigid-truck cargo volume	S2/S3	42	m ³	16–18 Euro-pallet rigid-truck proxy, [46]
Rigid-truck usable payload	S2/S3	5	t	Thesis engineering assumption
Truck space utilisation	S2/S3	0.75	fraction	Engineering assumption
Folded empty-package volume	S2	0.0039375	m ³ /package	0.35 m × 0.25 m × 0.045 m
Folded empty-package volume	S3	0.002625	m ³ /package	0.35 m × 0.25 m × 0.030 m
Capacity-based allocation quantity Q_{S2}^{cap}	S2	8,000	packages per modelled movement	Minimum of usable-volume and payload limits
Capacity-based allocation quantity Q_{S3}^{cap}	S3	12,000	packages per modelled movement	Minimum of usable-volume and payload limits

A.1.2. Packaging Climate-Impact Inventory

Table A.3 gives the inventory rows behind packaging production, maintenance, redistribution and end-of-life climate-impact calculations. Last-mile route emissions are handled separately in the route-input table.

Table A.3: Packaging climate-impact inventory rows

Scen.	Phase	Inventory item	Activity	Emission factor	Cycles	kgCO2e /parcel	Source/basis
S1	Material production	Corrugated cardboard/paperboard material, base package mass	0.18 kg material/package	0.8353 kg CO2e/kg material	1	0.1504	[16]
S1	Manufacturing/conversion	Corrugated/cardboard box manufacturing or conversion	0.144 kg packaging processed	0.7865 kg CO2e/kg processed	1	0.1133	[16, 67]
S1	Production subtotal	S1 production subtotal before route layer	calculated	kg CO2e/parcel	1	0.2636	Model calculation
S1	End-of-life	Cardboard recycling/incineration treatment	0.18 kg packaging	0.1119 kg CO2e/kg packaging	1	0.0201	[11, 16, 43]
S2	Material production	PP-rich recyclable plastic, HeyCircle M-box proxy	0.55 kg material/package	3.679 kg CO2e/kg material	50	0.0405	[16, 37, 38]

Scen.	Phase	Inventory item	Activity	Emission factor	Cycles	kgCO ₂ e /parcel	Source/basis
S2	Manufacturing/conversion	Durable foldable plastic packaging conversion / assembly	0.5635 kg packaging processed	0.3698 kg CO ₂ e/kg processed	50	0.004168	[16, 38]
S2	Production subtotal	S2 production subtotal allocated over N_{eff}	calculated	kg CO ₂ e/parcel	50	0.0446	Model calculation
S2	End-of-life	PP-rich plastic recycling/incineration treatment	0.55 kg packaging	1.329 kg CO ₂ e/kg packaging	50	0.0146	[11, 16, 43]
S3	Material production	Virgin corrugated paperboard in Re-Zip-style box	0.1317 kg material/package	0.525 kg CO ₂ e/kg material	30	0.002304	[16, 67]
S3	Material production	Recycled corrugated paperboard in Re-Zip-style box	0.0564 kg material/package	0.7296 kg CO ₂ e/kg material	30	0.001372	[16, 67]
S3	Material production	Nylon dots in Re-Zip-style box	0.0019 kg material/package	9.869 kg CO ₂ e/kg material	30	0.000625	[16, 67]
S3	Material production	Kraft paper shipping label in Re-Zip-style box	0.005 kg material/package	0.7089 kg CO ₂ e/kg material	30	0.000118	[16, 67]
S3	Manufacturing/conversion	Corrugated/cardboard box manufacturing or conversion	0.1505 kg packaging processed	0.7865 kg CO ₂ e/kg processed	30	0.003945	[16, 67]
S3	Production subtotal	S3 production subtotal allocated over N_{eff}	calculated	kg CO ₂ e/parcel	30	0.008365	Model calculation
S3	End-of-life	Cardboard/label/nylon recycling/incineration treatment	0.195 kg packaging	0.1119 kg CO ₂ e/kg packaging	30	0.000727	[11, 16, 43]
All	Route layer	Last-mile route emissions	from route model	kg CO ₂ e/parcel	–	–	Route-model output
S2	Use-cycle processing	Heat-gun label removal electricity	0.008333 kWh/package	0.366 kg CO ₂ e/kWh	1	0.003047	Tang 1.5 kW rated-power proxy times 20 s; [16, 67]
S2	Use-cycle processing	Tap water for light surface cleaning	0.1519 kg water/package	0.000311 kg CO ₂ e/kg water	1	4.72e-05	[16, 38, 48]
S2	Use-cycle processing	Wastewater treatment from light cleaning	0.000152 m3 wastewater/package	0.409 kg CO ₂ e/m3 wastewater	1	6.21e-05	[16, 38, 48]
S2	Use-cycle processing	Cleaning agent for light surface cleaning	0.000304 kg/package	1.803 kg CO ₂ e/kg cleaning agent	1	0.000548	[16, 38, 48]
S3	Use-cycle processing	Depot heat-gun label removal electricity, base depot-return fraction	0.00625 kWh/parcel	0.366 kg CO ₂ e/kWh	1	0.002285	Tang 1.5 kW rated-power proxy times 30 s and the 50% depot-return fraction; [16, 67]
S2	Redistribution transport	Modelled outward rigid-truck movement of folded empty reusable packages to the fulfilment/packing point	0.00625 vehicle-km/parcel	0.628 kg CO ₂ /vehicle-km	1	0.003925	[23]; 50 km divided by $Q_{S2}^{\text{cap}} = 8,000$
S3	Redistribution transport	Modelled outward rigid-truck movement of folded empty reusable packages for the depot-return fraction	0.002083 vehicle-km/parcel	0.628 kg CO ₂ /vehicle-km	1	0.001308	[23]; $r_{\text{dep}} = 50\%$, 50 km and $Q_{S3}^{\text{cap}} = 12,000$

A.1.3. Provider-Side Cost Inventory

Table A.4 reports the provider-side cost inventory for acquisition, maintenance, redistribution, utility or consumable inputs and end-of-life handling. Last-mile route costs

originate from the route-operational layer.

Table A.4: Provider-side cost inventory rows

Scen.	Category	Process	Activity	Unit cost	Cycles	EUR /parcel	Source/basis
S1	Packaging	Single-use cardboard packaging purchase / replacement	1 unit	0.4 EUR/unit	1	0.4	Market price proxy, [18]
S1	End-of-life / handling	Disposal or handling cost shifted to provider	1 cycle	EUR/cycle	1	–	Excluded from provider-side base
S2	Packaging	Reusable PP packaging purchase / replacement	1 unit	18.27 EUR/unit	50	0.3654	Market price proxy, [38]
S2	Use-cycle processing	Central cleaning / sorting / depot labour	45 s/parcel	0.004639 EUR/s	1	0.2088	Labour-rate proxy from [64]; engineering time estimate
S3	Packaging	Reusable cardboard packaging purchase / replacement	1 unit	2.03 EUR/unit	30	0.0677	Market/BOM proxy, [60, 62, 67]
S3	Use-cycle processing	Depot inspection / label removal / maintenance labour, base depot-return fraction	15 s/parcel	0.004639 EUR/s	1	0.0696	Labour-rate proxy from [64]; 50% depot-return assumption
All	Route layer	Provider-side route cost	–	–	–	–	Route-model output
S2	End-of-life / handling	Provider-controlled scrapped reusable plastic packaging waste-management handling	0.55 kg waste/package	0.234 EUR/kg waste	50	0.002574	[63]
S3	End-of-life / handling	Provider-controlled scrapped reusable cardboard packaging waste-management handling	0.195 kg waste/package	0.234 EUR/kg waste	30	0.001521	[63]
S2	Use-cycle processing	Heat-gun electricity utility cost	0.008333 kWh/package	0.2597 EUR/kWh	1	0.002164	[32, 67]; 20 s time-aligned base
S2	Use-cycle processing	Tap-water utility cost for light cleaning	0.000152 m3/package	2.43 EUR/m3	1	0.000369	[1, 38, 48]
S2	Use-cycle processing	Cleaning-agent consumable cost	0.000304 kg/package	5 EUR/kg	1	0.001519	[38, 48, 69]
S3	Use-cycle processing	Depot heat-gun electricity utility cost, base depot-return fraction	0.00625 kWh/parcel	0.2597 EUR/kWh	1	0.001623	[32, 67]; 30 s time-aligned base and 50% depot-return assumption
S2	Redistribution transport	Rigid-truck distance-dependent running cost	0.00625 vehicle-km/parcel	0.7955 EUR/vehicle-km	1	0.004972	[52]; 50 km divided by $Q_{S2}^{cap} = 8,000$
S2	Redistribution transport	Rigid-truck driver time including loading and unloading	0.01388 min/parcel	0.2783 EUR/min	1	0.003863	[64, 72]; 60 min handling per modelled movement
S3	Redistribution transport	Distance-dependent running cost for the depot-return fraction	0.002083 vehicle-km/parcel	0.7955 EUR/vehicle-km	1	0.001657	[52]; $r_{dep} = 50\%$ and $Q_{S3}^{cap} = 12,000$
S3	Redistribution transport	Driver time for the depot-return fraction	0.004626 min/parcel	0.2783 EUR/min	1	0.001288	[64, 72]; 60 min handling per modelled movement

A.1.4. Maintenance and Cleaning Calculation Details

Table A.5 expands the base maintenance and cleaning assumptions, factors and module outputs. The S2 base module combines labour, heat-gun electricity, scaled water and detergent inputs, while the S3 depot module applies only to the depot-returned fraction.

The corresponding low/high values are reported in Table A.8.

Table A.5: Base maintenance and cleaning assumptions and factors

Section	Scenario	Item	Base	Unit	Formula/source note
Assumption	S2	Cleaning share	1	fraction	All returned S2 units enter standard central maintenance.
Assumption	S2	water	0.1519	L/package	Light-cleaning water scaled from RPC washing inventory by HeyCircle M / RPC crate volume [38, 48].
Assumption	S2	detergent	0.000304	kg/package	Cleaning-agent mass = 0.2% of scaled cleaning-water mass [48].
Assumption	S2	heat gun electricity	0.008333	kWh/package	Tang's 1.5 kW rated-power proxy multiplied by the 20 s label-removal engineering time. Tang's 5 min/0.125 kWh combination is retained as the source author's assumption and is not used as the base duration [67].
Assumption	S2	maintenance labour	45	s/package	10 s inspection/sorting + 20 s label removal + 15 s light cleaning.
Assumption	S3	Depot-return fraction r_{dep}	0.5	fraction	Share of returned S3 packages requiring depot-side handling and empty-package redistribution.
Assumption	S3	heat gun electricity	0.0125	kWh/returned unit	Tang's 1.5 kW rated-power proxy multiplied by the 30 s depot-maintenance engineering time; applies only to depot-returned S3 packages.
Assumption	S3	depot maintenance labour	30	s/returned unit	Condition check, label removal, repair/discard decision, reintegration.
Factor	All	IT low-voltage electricity EF	0.366	kg CO ₂ e/kWh	ecoinvent low-voltage electricity market, Italy [16].
Factor	S2	tap water EF	0.000311	kg CO ₂ e/kg	ecoinvent tap-water market, Europe without Switzerland [16].
Factor	S2	wastewater EF	0.409	kg CO ₂ e/m ³	ecoinvent wastewater market, Europe without Switzerland [16].
Factor	S2	detergent EF	1.803	kg CO ₂ e/kg	ecoinvent alkylbenzene sulfonate market proxy [16].
Module result	S2	maintenance CO ₂	0.003704	kg CO ₂ e/parcel	Heat gun + scaled tap water + scaled wastewater + scaled detergent.
Module result	S2	maintenance cost	0.2128	EUR/parcel	45 s labour; 20 s time-aligned heat-gun electricity; scaled water and detergent; utility/consumable costs monetised.
Module result	S3	depot maintenance CO ₂ , 25% return	0.001143	kg CO ₂ e/parcel	Depot-return fraction sensitivity using the base 30 s process; only the return fraction changes.
Module result	S3	depot maintenance CO ₂ , 50% return	0.002285	kg CO ₂ e/parcel	S3 base 50% depot-return case using the base 30 s process.
Module result	S3	depot maintenance CO ₂ , 100% return	0.004570	kg CO ₂ e/parcel	Depot-return fraction sensitivity using the base 30 s process; only the return fraction changes.
Module result	S3	depot maintenance cost, 25% return	0.03560	EUR/parcel	Depot-return fraction sensitivity using base labour and energy per depot-returned package.
Module result	S3	depot maintenance cost, 50% return	0.07121	EUR/parcel	S3 base case including labour and time-aligned heat-gun electricity.
Module result	S3	depot maintenance cost, 100% return	0.14241	EUR/parcel	Depot-return fraction sensitivity using base labour and energy per depot-returned package.
Factor	S2/S3	electricity price	0.2597	EUR/kWh	Italy non-household, 20-499 MWh band, 2025-S1, excluding VAT/recoverable taxes [32].
Factor	S2	water price	2.43	EUR/m ³	National average 365 EUR/year for 150 m ³ = 2.43 EUR/m ³ [1].
Factor	S2	detergent price	5	EUR/kg	Rounded professional alkaline-detergent proxy; not operator-specific [69].

A.1.5. End-of-Life Treatment Shares and Factors

Table A.6 reports the end-of-life shares, treatment factors and resulting weighted factors used for paper/cardboard and PP-rich plastic packaging. Italy 2023 treatment shares are combined with ecoinvent treatment factors [11, 16, 43]. These are weighted scenario factors, not raw single-process factors. Applying these factors gives scenario-level EOL values of 0.0201 kg CO₂e/parcel for S1, 0.0146 kg CO₂e/parcel and 0.002574 EUR/parcel for S2, and 0.000727 kg CO₂e/parcel and 0.001521 EUR/parcel for S3. The S1 provider-side EOL monetary cost is excluded from the base case because the single-use package leaves the provider-controlled loop after customer collection.

Table A.6: End-of-life treatment shares and weighted factors

Section	Material scenario	Pathway item	Share value	Unit	Factor	Factor unit	Weighted result	Notes
EOL share	paper/cardboard	recycling preparation	0.923	fraction	0.0845	kg CO ₂ e/kg	0.078	Italy 2023 paper/cardboard recycling share; ecoinvent paperboard sorting [16, 43]
EOL share	paper/cardboard	energy recovery/incineration	0.0577	fraction	0.035	kg CO ₂ e/kg	0.00202	CONAI 2023 energy-recovery quantity; ecoinvent paperboard municipal incineration [11, 16]
EOL share	paper/cardboard	residual disposal	0.0193	fraction	1.652	kg CO ₂ e/kg	0.0319	Residual after recycling and energy recovery; ecoinvent sanitary landfill proxy [16]
Weighted factor	paper/cardboard	all EOL pathways	1	fraction	–	–	0.1119	Weighted factor used for S1/S3
EOL share	plastic PP-rich	recycling preparation proxy	0.48	fraction	0.411	kg CO ₂ e/kg	0.1973	Italy 2023 plastic packaging recycling share; PE sorted recycling as polyolefin proxy [16, 43]
EOL share	plastic PP-rich	energy recovery/incineration	0.4279	fraction	2.619	kg CO ₂ e/kg	1.121	CONAI 2023 plastic energy-recovery quantity; ecoinvent waste polypropylene municipal incineration [11, 16]
EOL share	plastic PP-rich	residual disposal	0.0921	fraction	0.1204	kg CO ₂ e/kg	0.0111	Residual after recycling and energy recovery; ecoinvent waste polypropylene landfill proxy [16]
Weighted factor	plastic PP-rich	all EOL pathways	1	fraction	–	–	1.329	Weighted factor used for S2

A.1.6. Route Input and Route-Output Traceability Table

Table A.7 reports the key route-operational outputs used in the integrated model. It covers three fill-rate groups, eleven route inputs and three scenarios. To keep the ap-

pendix readable, the table retains the parcel totals and the route cost and route-emission components that feed the integrated model.

Table A.7: Compressed route input and route-output traceability table

Fill rate	Route input	Scenario	Parcels	Route cost EUR/parcel	Route CO2e kg/parcel
0.6-0.7	Provider 2	S1	6202	0.292	0.019
0.6-0.7	Provider 2	S2	6202	0.362	0.019
0.6-0.7	Provider 2	S3	6202	0.394	0.019
0.6-0.7	Provider 3	S1	563	0.310	0.018
0.6-0.7	Provider 3	S2	563	0.380	0.018
0.6-0.7	Provider 3	S3	563	0.413	0.018
0.6-0.7	Provider 1 – Adda Martesana	S1	1344	0.443	0.054
0.6-0.7	Provider 1 – Adda Martesana	S2	1344	0.513	0.054
0.6-0.7	Provider 1 – Adda Martesana	S3	1344	0.545	0.054
0.6-0.7	Provider 1 – Alto milanese	S1	753	0.505	0.065
0.6-0.7	Provider 1 – Alto milanese	S2	753	0.575	0.065
0.6-0.7	Provider 1 – Alto milanese	S3	753	0.607	0.065
0.6-0.7	Provider 1 – Magentino e Abbiatense	S1	614	0.462	0.053
0.6-0.7	Provider 1 – Magentino e Abbiatense	S2	614	0.531	0.053
0.6-0.7	Provider 1 – Magentino e Abbiatense	S3	614	0.564	0.053
0.6-0.7	Provider 1 – Milano	S1	4629	0.373	0.035
0.6-0.7	Provider 1 – Milano	S2	4629	0.442	0.035
0.6-0.7	Provider 1 – Milano	S3	4629	0.475	0.035
0.6-0.7	Provider 1 – Nord Milano	S1	737	0.481	0.058
0.6-0.7	Provider 1 – Nord Milano	S2	737	0.551	0.058
0.6-0.7	Provider 1 – Nord Milano	S3	737	0.583	0.058
0.6-0.7	Provider 1 – Nord Ovest	S1	1412	0.440	0.051
0.6-0.7	Provider 1 – Nord Ovest	S2	1412	0.510	0.051
0.6-0.7	Provider 1 – Nord Ovest	S3	1412	0.542	0.051
0.6-0.7	Provider 1 – Sud Est	S1	646	0.343	0.031
0.6-0.7	Provider 1 – Sud Est	S2	646	0.413	0.031
0.6-0.7	Provider 1 – Sud Est	S3	646	0.445	0.031
0.6-0.7	Provider 1 – Sud Ovest	S1	747	0.306	0.022
0.6-0.7	Provider 1 – Sud Ovest	S2	747	0.375	0.022
0.6-0.7	Provider 1 – Sud Ovest	S3	747	0.408	0.022
0.6-0.7	Provider 4	S1	1244	0.305	0.019
0.6-0.7	Provider 4	S2	1244	0.374	0.019
0.6-0.7	Provider 4	S3	1244	0.407	0.019
0.7-0.8	Provider 2	S1	7167	0.312	0.021
0.7-0.8	Provider 2	S2	7167	0.381	0.021
0.7-0.8	Provider 2	S3	7167	0.413	0.021
0.7-0.8	Provider 3	S1	655	0.318	0.016
0.7-0.8	Provider 3	S2	655	0.387	0.016
0.7-0.8	Provider 3	S3	655	0.420	0.016
0.7-0.8	Provider 1 – Adda Martesana	S1	1552	0.473	0.060
0.7-0.8	Provider 1 – Adda Martesana	S2	1552	0.542	0.060
0.7-0.8	Provider 1 – Adda Martesana	S3	1552	0.575	0.060
0.7-0.8	Provider 1 – Alto milanese	S1	866	0.563	0.074
0.7-0.8	Provider 1 – Alto milanese	S2	866	0.632	0.074
0.7-0.8	Provider 1 – Alto milanese	S3	866	0.664	0.074
0.7-0.8	Provider 1 – Magentino e Abbiatense	S1	707	0.470	0.054
0.7-0.8	Provider 1 – Magentino e Abbiatense	S2	707	0.540	0.054
0.7-0.8	Provider 1 – Magentino e Abbiatense	S3	707	0.572	0.054
0.7-0.8	Provider 1 – Milano	S1	5345	0.396	0.038
0.7-0.8	Provider 1 – Milano	S2	5345	0.466	0.038
0.7-0.8	Provider 1 – Milano	S3	5345	0.498	0.038
0.7-0.8	Provider 1 – Nord Milano	S1	853	0.483	0.059
0.7-0.8	Provider 1 – Nord Milano	S2	853	0.553	0.059
0.7-0.8	Provider 1 – Nord Milano	S3	853	0.585	0.059
0.7-0.8	Provider 1 – Nord Ovest	S1	1632	0.464	0.055
0.7-0.8	Provider 1 – Nord Ovest	S2	1632	0.533	0.055
0.7-0.8	Provider 1 – Nord Ovest	S3	1632	0.566	0.055
0.7-0.8	Provider 1 – Sud Est	S1	749	0.345	0.031
0.7-0.8	Provider 1 – Sud Est	S2	749	0.414	0.031
0.7-0.8	Provider 1 – Sud Est	S3	749	0.447	0.031
0.7-0.8	Provider 1 – Sud Ovest	S1	862	0.315	0.022

Fill rate	Route input	Scenario	Parcels	Route cost EUR/parcel	Route CO ₂ e kg/parcel
0.7-0.8	Provider 1 – Sud Ovest	S2	862	0.385	0.022
0.7-0.8	Provider 1 – Sud Ovest	S3	862	0.417	0.022
0.7-0.8	Provider 4	S1	1440	0.306	0.019
0.7-0.8	Provider 4	S2	1440	0.375	0.019
0.7-0.8	Provider 4	S3	1440	0.408	0.019
0.8-0.9	Provider 2	S1	8120	0.294	0.019
0.8-0.9	Provider 2	S2	8120	0.363	0.019
0.8-0.9	Provider 2	S3	8120	0.396	0.019
0.8-0.9	Provider 3	S1	741	0.283	0.015
0.8-0.9	Provider 3	S2	741	0.353	0.015
0.8-0.9	Provider 3	S3	741	0.385	0.015
0.8-0.9	Provider 1 – Adda Martesana	S1	1760	0.447	0.056
0.8-0.9	Provider 1 – Adda Martesana	S2	1760	0.516	0.056
0.8-0.9	Provider 1 – Adda Martesana	S3	1760	0.549	0.056
0.8-0.9	Provider 1 – Alto milanese	S1	978	0.509	0.066
0.8-0.9	Provider 1 – Alto milanese	S2	978	0.578	0.066
0.8-0.9	Provider 1 – Alto milanese	S3	978	0.611	0.066
0.8-0.9	Provider 1 – Magentino e Abbiatense	S1	801	0.426	0.048
0.8-0.9	Provider 1 – Magentino e Abbiatense	S2	801	0.495	0.048
0.8-0.9	Provider 1 – Magentino e Abbiatense	S3	801	0.528	0.048
0.8-0.9	Provider 1 – Milano	S1	6054	0.370	0.035
0.8-0.9	Provider 1 – Milano	S2	6054	0.440	0.035
0.8-0.9	Provider 1 – Milano	S3	6054	0.472	0.035
0.8-0.9	Provider 1 – Nord Milano	S1	967	0.477	0.058
0.8-0.9	Provider 1 – Nord Milano	S2	967	0.546	0.058
0.8-0.9	Provider 1 – Nord Milano	S3	967	0.579	0.058
0.8-0.9	Provider 1 – Nord Ovest	S1	1852	0.423	0.049
0.8-0.9	Provider 1 – Nord Ovest	S2	1852	0.492	0.049
0.8-0.9	Provider 1 – Nord Ovest	S3	1852	0.524	0.049
0.8-0.9	Provider 1 – Sud Est	S1	846	0.342	0.031
0.8-0.9	Provider 1 – Sud Est	S2	846	0.411	0.031
0.8-0.9	Provider 1 – Sud Est	S3	846	0.443	0.031
0.8-0.9	Provider 1 – Sud Ovest	S1	979	0.289	0.019
0.8-0.9	Provider 1 – Sud Ovest	S2	979	0.358	0.019
0.8-0.9	Provider 1 – Sud Ovest	S3	979	0.390	0.019
0.8-0.9	Provider 4	S1	1631	0.292	0.018
0.8-0.9	Provider 4	S2	1631	0.362	0.018
0.8-0.9	Provider 4	S3	1631	0.394	0.018

A.1.7. Sensitivity Analysis Supporting Numerical Data

Table A.8 collects the low, base and high values used for sensitivity ranges, route-layer fill-rate checks or reference-value ranges. Not every row is varied in the one-way sensitivity figure: some rows are retained to document input uncertainty or break-even ranges.

Table A.8: Sensitivity and reference input ranges

Parameter	Scen.	Low	Base	High	Unit	Use
N_{eff}	S2	10	50	80	cycles	Reuse-cycle range and break-even support
N_{eff}	S3	5	30	50	cycles	Reuse-cycle range and break-even support
Parcel-locker slots	All	36	52	88	slots/locker	Field-survey reference range
fill-rate group	All	0.6–0.7; 0.7–0.8	0.8–0.9	–	interval	Route-layer sensitivity check

Parameter	Scen.	Low	Base	High	Unit	Use
Locker service time	S2	30	35	50	s/parcel	Service-time sensitivity
Locker service time	S3	33	42	65	s/parcel	Service-time sensitivity
S3 depot maintenance CO2	S3	0.001143	0.002285	0.004570	kg CO2e/parcel	Derived by varying depot-return fraction while holding the base 30 s process fixed
Packaging unit cost	S1	0.34	0.40	0.51	EUR/unit	Market-price reference range
Packaging unit cost	S2	–	18.27	21.49	EUR/unit	Product-price reference range
Packaging unit cost	S3	1.94	2.03	–	EUR/unit	Market-price reference range
Cleaning water quantity	S2	0.1303	0.1519	0.4	L/package	Cleaning-resource range
Cleaning detergent quantity	S2	0.000261	0.000304	0.0008	kg/package	Cleaning-resource range
Heat-gun electricity	S2	0.004167	0.008333	0.014583	kWh/package	Time-aligned 10/20/35 s label-removal range
Maintenance time	labour S2	35	45	60	s/package	One-way sensitivity
Depot-return fraction r_{dep}	S3	0.25	0.5	1	fraction	One-way sensitivity for maintenance and empty-package redistribution
Heat-gun electricity	S3	0.010417	0.0125	0.01875	kWh/returned unit	Time-aligned 25/30/45 s reference range; not coupled to the formal labour one-way sensitivity
Maintenance time	labour S3	25	30	45	s/returned unit	Pure labour one-way sensitivity; heat-gun energy and CO2e held at base
Attributed redistribution vehicle distance D_{attr}	S2/S3	25	50	100	km/modelled movement	Low is 25 km outward; base is 50 km outward with return absorbed; high adds a 50 km empty return; handling counted once
Truck space utilisation	S2/S3	0.60	0.75	0.90	fraction	Capacity-allocation sensitivity
Capacity-based allocation quantity Q_{S2}^{cap}	S2	6,400	8,000	9,090	packages per modelled movement	Derived from space utilisation and 5 t payload limit
Capacity-based allocation quantity Q_{S3}^{cap}	S3	9,600	12,000	14,400	packages per modelled movement	Derived from space utilisation and 5 t payload limit

Parameter	Scen.	Low	Base	High	Unit	Use
Waste-management fee	S2/S3	0.145	0.234	0.398	EUR/kg waste	Waste-cost reference range

For S3, the heat-gun row documents the time-aligned energy range associated with the low, base and high maintenance-duration references. It is not coupled to the formal S3 depot-labour one-way sensitivity reported below. That sensitivity changes labour time only and holds heat-gun electricity and climate-change impact at their base values; the depot-return-fraction sensitivity scales both depot processing and subsequent redistribution while retaining the base 30 s per-return process.

Table A.9 reports the supporting numerical data behind the one-way sensitivity figure. Low and high perturbation cases are listed because base values are already reported in Table A.8. For attributed redistribution vehicle distance, the 100 km high case comprises 50 km outward plus a 50 km empty return, with handling counted once. Deltas are calculated relative to each scenario base case. Route fill-rate sensitivity is summarized in Table 4.3 and traced through the route input/output rows in Table A.7, rather than being mixed into the one-way sensitivity table.

Table A.9: One-way sensitivity supporting numerical data

Group	Case	Scen.	Value	Cost	Δ cost	CO2e	Δ CO2e
S2 locker service time	low	S2	30 s/parcel	1.0061	-0.0232	0.1017	0
S2 locker service time	high	S2	50 s/parcel	1.0987	0.0695	0.1017	0
S3 locker service time	low	S3	33 s/parcel	0.5737	-0.0417	0.0475	0
S3 locker service time	high	S3	65 s/parcel	0.7220	0.1066	0.0475	0
S2 maintenance labour	low	S2	35 s/package	0.9829	-0.0464	0.1017	0
S2 maintenance labour	high	S2	60 s/package	1.0988	0.0696	0.1017	0
S2 cleaning emissions	low	S2	0.004167 kWh; 0.1303 L; 0.000261 kg/package	1.0279	-0.0014	0.1001	-0.0016
S2 cleaning emissions	high	S2	0.014583 kWh; 0.4 L; 0.0008 kg/package	1.0339	0.0047	0.1051	0.0034
S3 depot-return fraction	low	S3	0.25 fraction	0.5783	-0.0371	0.0457	-0.0018
S3 depot-return fraction	high	S3	1 fraction	0.6896	0.0742	0.0511	0.0036
S3 depot labour	low	S3	25 s/depot-returned package; energy held at base	0.6038	-0.0116	0.0475	0
S3 depot labour	high	S3	45 s/depot-returned package; energy held at base	0.6502	0.0348	0.0475	0
S2 attributed vehicle distance	low	S2	25 km outward; return absorbed	1.0259	-0.0034	0.0997	-0.0020
S2 attributed vehicle distance	high	S2	100 km total: 50 km outward + 50 km empty return; handling counted once	1.0360	0.0067	0.1056	0.0039
S3 attributed vehicle distance	low	S3	25 km outward; return absorbed	0.6143	-0.0011	0.0468	-0.0007
S3 attributed vehicle distance	high	S3	100 km total: 50 km outward + 50 km empty return; handling counted once	0.6176	0.0022	0.0488	0.0013
S2 capacity-based allocation quantity	low	S2	60%; $Q_{S2}^{\text{cap}} = 6,400$	1.0314	0.0022	0.1027	0.0010
S2 capacity-based allocation quantity	high	S2	90%; $Q_{S2}^{\text{cap}} = 9,090$	1.0282	-0.0011	0.1012	-0.0005
S3 capacity-based allocation quantity	low	S3	60%; $Q_{S3}^{\text{cap}} = 9,600$	0.6161	0.0007	0.0478	0.0003

Group	Case	Scen.	Value	Cost	Δ cost	CO ₂ e	Δ CO ₂ e
S3 capacity-based allocation quantity	alloca- high	S3	90%; $Q_{S3}^{cap} = 14,400$	0.6149	-0.0005	0.0473	-0.0002

A.1.8. Break-Even and Threshold Analysis Supporting Numerical Data

Table A.10 reports the threshold calculations used in the integrated model. Values above 100% for the S3 depot-return fraction indicate that no practical threshold exists within the feasible 0–100% range under the tested assumptions. The S3 depot-return fraction scales both depot maintenance and redistribution.

Table A.10: Break-even threshold supporting numerical data

Check	Scen.	Metric	Variable	Limit	Unit	Base	Relation	Interpretation
S2 climate parity	S2	CO ₂ e	N_{eff}	10.731	cycles	50	Base above threshold	Base N_{eff} exceeds CO ₂ e threshold.
S2 cost parity	S2	Cost	N_{eff}	169.008	cycles	50	Base below threshold	Base N_{eff} remains below cost threshold.
S3 climate parity	S3	CO ₂ e	N_{eff}	0.974	cycles	30	Feasible domain starts at 1	Climate parity is reached at the first feasible use.
S3 cost parity	S3	Cost	N_{eff}	9.270	cycles	30	Base above threshold	Base N_{eff} exceeds cost threshold.
S2 labour threshold	S2	Cost	maintenance labour	-10.856	s/package	45	Base above threshold	Remaining components exceed the S1 cost baseline.
S2 package-cost threshold	S2	Cost	packaging acquisition cost	5.314	EUR/unit	18.27	Base above threshold	Cost parity requires a lower unit price.
S3 depot-return threshold vs S1	S3	Cost	depot-return fraction	1.543	fraction	0.5	Above tested range	S3 remains below S1 across 0–100%.
S3 depot-return threshold vs S1	S3	CO ₂ e	depot-return fraction	38.215	fraction	0.5	Above tested range	S3 remains below S1 across 0–100%.
S3 depot-return threshold vs S2	S3	Cost	depot-return fraction vs S2	3.291	fraction	0.5	Above tested range	S3 remains below S2 across 0–100%.
S3 depot-return threshold vs S2	S3	CO ₂ e	depot-return fraction vs S2	8.041	fraction	0.5	Above tested range	S3 remains below S2 across 0–100%.

Table A.11 reports the reuse-cycle numerical points used for the break-even figure in Chapter 4.

Table A.11: Reuse-cycle curve numerical points

N_{eff}	S2 cost	S2 CO ₂ e	S3 cost	S3 CO ₂ e	S1 cost base-line	S1 CO ₂ e base-line
1	19.0600	3.0053	2.6218	0.3112	0.7701	0.3186
2	9.8606	1.5239	1.5840	0.1748	0.7701	0.3186
3	6.7942	1.0301	1.2381	0.1293	0.7701	0.3186
5	4.3410	0.6350	0.9613	0.0930	0.7701	0.3186
10	2.5011	0.3387	0.7538	0.0657	0.7701	0.3186
20	1.5812	0.1906	0.6500	0.0520	0.7701	0.3186
30	1.2746	0.1412	0.6154	0.0475	0.7701	0.3186
50	1.0292	0.1017	0.5877	0.0439	0.7701	0.3186

N_{eff}	S2 cost	S2 CO2e	S3 cost	S3 CO2e	S1 cost base-line	S1 CO2e base-line
75	0.9066	0.0819	0.5739	0.0420	0.7701	0.3186
100	0.8453	0.0721	0.5670	0.0411	0.7701	0.3186

A.2. Complete Network and Zone Results

Table A.12 reports the complete deterministic model outputs for the route inputs used in the integrated model. The Provider 1 – Milano row is the base case used for the main interpretation in Chapter 4; the other networks and homogeneous-zone inputs are used as robustness checks of the route layer.

Table A.12: Complete network and zone model results

Route input	S1 cost	S2 cost	S3 cost	S1 CO2e	S2 CO2e	S3 CO2e
Provider 2	0.694	0.953	0.539	0.303	0.086	0.032
Provider 3	0.683	0.942	0.528	0.299	0.082	0.028
Provider 1 – Adda Martesana	0.847	1.106	0.692	0.339	0.122	0.068
Provider 1 – Alto milanese	0.909	1.168	0.754	0.350	0.133	0.079
Provider 1 – Magentino e Abbiatense	0.826	1.085	0.671	0.332	0.115	0.061
Provider 1 – Milano	0.770	1.029	0.615	0.319	0.102	0.047
Provider 1 – Nord Milano	0.877	1.136	0.722	0.342	0.125	0.071
Provider 1 – Nord Ovest	0.823	1.082	0.668	0.332	0.116	0.061
Provider 1 – Sud Est	0.742	1.001	0.587	0.314	0.097	0.043
Provider 1 – Sud Ovest	0.689	0.948	0.534	0.303	0.086	0.032
Provider 4	0.692	0.951	0.538	0.302	0.085	0.031