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Unlocking the potential: How can parcel lockers drive efficiency and environmental friendliness in E-commerce?

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Abstract

This paper analyses the efficiency and carbon footprint of different last-mile delivery solutions, including parcel lockers, pick-up points, and home deliveries. A Decision Support Tool (DST) is developed, utilizing real data on parcel deliveries and time allocation. The DST distinguishes between fixed, variable, and salary costs, revealing that time spent on delivery tasks and associated salary costs are the primary cost drivers. Deliveries to pick-up points are more efficient than deliveries to parcel lockers, but this efficiency depends on the number of parcels delivered. The environmental footprint of the solutions is influenced by how recipients collect their parcels.

Keywords

E-commerce; Parcel lockers; Home deliveries; Pick-up point; Last mile; Cost model

Introduction

The COVID-19 pandemic has enforced an increasing trend in e-commerce and home deliveries: In Norway, e-commerce turnover in current prices, increased by nearly 60 percent after the pandemic (Statistics Norway[1]) compared to pre-pandemic. The trend reversed somewhat pre-pandemic but is currently increasing, and it is expected that e-commerce will remain at a high level in the coming years.

Online consumers are known to be demanding in terms of service level, especially regarding when products are to be received and the total lead time of the order [1]. However, consumers are not always willing to pay for such a high level of service [2]. Because of the challenges in last-mile logistics, logistics service providers (LSPs) need to focus on their delivery options to be more efficient and competitive. Today, innovative last-mile solutions have emerged worldwide, including parcel lockers, pick-up points, reception boxes, drones, crowdsourcing logistics, dynamic pricing policies [3], cargo bikes [4], truck-based autonomous robots [5], and self-driving delivery robots [6].

Parcel lockers were introduced to the market as a digital and flexible self-service solution for customers. The parcel lockers are accessible 24/7 and have compartments of varying sizes for different package dimensions. The customers receive an SMS notification when their parcels are delivered to the locker, and their compartments can then be unlocked via Bluetooth using a mobile app from the LSP.

Norstat, a commercial player in market research, has interviewed 1000 random people on behalf of PostNord Norway regarding their parcel delivery preferences [7]. The survey reveals that on average, 47 % want to reduce or replace home delivery with delivery to parcel lockers if the locker is within a maximum distance of 300m from their home. Consumers exhibited varying perspectives regarding the distance to the locker, and the acceptance rate where reduced to 33 % if the distance increased to 500 m, while only 14 % accepted a distance within one kilometer. Additionally, there are notable differences based on age, with younger consumers showing greater willingness to increase the use of lockers compared to their older counterparts (PostNord Norway, E-commerce Barometer, 2022) [7].

From a last-mile efficiency perspective, parcel lockers are also more efficient than home deliveries: Distributors make one stop with several parcels, compared to home deliveries, which require one stop per parcel. A key premise of parcel lockers is customer convenience. Lockers are ideally situated outdoors and within walking distance from home or along the customer's everyday route, ensuring availability 24/7.

Challenges in last-mile service providers, particularly with home deliveries, are associated with low efficiency, leading to increased emissions and costs. This is exacerbated by the high number of driven kilometers per parcel delivered, posing adverse effects on the environment. The issue is compounded by the high number of driven kilometers per parcel delivered, resulting in adverse effects on the environment and other challenges, such as time window imbalances and low flexibility in delivery windows [8].

If there's a significant spread in geographical locations among various delivery points, it could exacerbate the inefficient utilization problem. In contrast to home deliveries, both parcel lockers and pick-up points involve consumer participation [3]. Parcel lockers offer consumers increased flexibility in parcel collection, freeing them from concerns about timing or being at home when the parcel arrives. Failed home deliveries contribute to both costs and environmental impacts, as the LSP must make repeated visits to the same customer [9].

For the LSPs, parcel lockers enable consolidated deliveries, fewer stops, and reduced driving distances, ultimately enhancing the efficiency of last-mile operations [10]. Deliveries to parcel lockers can occur around the clock, independent of the consumer's availability [11], resulting in more successful first-attempt deliveries [12,13]. Parcel lockers may also serve as collecting points for returning products [14].

Challenges associated with parcel lockers are tied to location and installation, influenced by factors such as acceptance for installation and consumers' willingness to travel [15]. Other issues are the parcel lockers' maximum per-parcel volume and weight capacity. This requires an up-to-date technological verification system at the terminal to only select parcels within these constraints [11].

Increased demand for home deliveries affects the distribution system. Therefore, there is a need for more efficient last-mile delivery solutions. On the one hand, there is a scale advantage for the LSP to deliver more parcels in a limited geographic area; on the other hand, these present challenges for delivery capacity. Parcel lockers are a capacity-expanding measure, and the main question is whether these will replace home deliveries or pick-up points in stores, and how it affects the economy and the environment.

This paper aims to study how parcel lockers can contribute to a more efficient and sustainable e-commerce, focusing on the cost and environmental effects compared to pick-up points and home deliveries. Our main research question is: *How can parcel lockers contribute to a more economical and environmentally friendly e-commerce?*

Literature review

Last mile logistics

Last-mile logistics refers to the final leg of the delivery process in the supply chain, which "involves a series of activities and processes necessary for the delivery process from the last transit point to the final destination of the delivery chain" [16]. Last-mile logistics is known as the least efficient stage of the supply chain, as it is time-consuming and costly for the LSP [17]. The cost linked to the last mile can equate to half of the logistics costs [18]. As well as being costly, an essential concern with last-mile services is the environmental footprint [19]. The distribution of parcels in urban areas is analyzed by [20,21]. They measured the cost of various service levels related to; delivery time window, lead time, frequency, and return of goods. Their findings indicated that the level of customer service had a significant impact on the overall cost. They explored the cost disparity between urban and rural deliveries and examined how delivery density influenced overall costs. While they didn't analyze parcel lockers, their findings revealed that an increased number of parcels led to reduced delivery costs per drop. The estimated cost for one parcel per stop was 2.91 Euro, decreasing to 1.16 Euro when the number of parcels increased to 2.5 per stop.

Economies of scale describe how the average cost per unit of distribution decreases as the LSP's output increases [22]. This occurs as fixed costs are distributed over a higher volume, subsequently reducing variable costs [23]. This concept is particularly crucial for large service providers in the last mile, where significant investments in automatic sorting terminals require handling large parcel volumes, and vice versa

Parcel lockers as an alternative to home deliveries

The economic and environmental effects of reusing locked newspaper kiosks as parcel lockers in an urban city in Spain were analyzed by [21]. They found that replacing home deliveries with parcel lockers had a significant potential for distance reduction, with as much as 90 %, and an environmental impact reduction of 93 %.

A route planning optimization program was used by [24] in Shushan District in Hefei City in China to calculate the cost and environmental effects of replacing home deliveries with parcel lockers and found that total costs and carbon emissions could be reduced by up to 51 %. Another study [25] found that the average cost for home and parcel locker deliveries differed by approximately 59 % in favor of parcel lockers.

Challenges are also linked to the turnover rate of available capacity within the parcel lockers, as consumers may collect their parcels. Parcel lockers also require an investment cost when acquiring them, and there is a trade-off regarding numbers to install versus consumer coverage per parcel locker [26].

Taking advantage of the parcel lockers, drivers could drop off multiple parcels at each locker, leading to a more consolidated delivery instead of delivering at each location or doorstep [27]. Other findings suggested that if consumers were more flexible or indifferent regarding selecting parcel locker locations, it might be possible for the service provider to optimize even more efficient and effective routes [28]. Parcel lockers may also reduce environmental impact and delivery time [29]. Also, two other studies [30,31] found that replacing home deliveries with parcel lockers could reduce emissions from the last mile by almost two-thirds. However, both noted that the impact was highly dependent on the delivery area. Extra-urban areas showed both higher emissions (91 %) and a greater potential for emission reduction when substituting home deliveries with parcel locker deliveries, compared to urban areas. However, as argued by [13], the environmental gains depend on how consumers choose to pick up parcels. An analysis of a centrally located waste solution compared to individual bins per household [32], found that people with car access would use a car instead of walking when distances exceed approximately one kilometer.

A case study on parcel lockers in Szczecin, Poland [15] reported positive results when comparing last-mile distribution using parcel lockers to traditional home deliveries. In terms of efficiency, the parcel lockers outperformed other last-mile courier services on average, excelling in aspects such as the total number of delivered parcels per day, reduced kilometers traveled, and ultimately, decreased fuel consumption and CO_2 emissions.

A comparison of home delivery and parcel lockers in Poland shows a significant reduction in daily distance per driver, changing from 150 kms for home delivery to 70 kms for parcel lockers, and a corresponding reduction in CO_2 emission from 300 gs to 14 gs per parcel [33].

Customer's final leg

A main difference between home deliveries and deliveries to parcel lockers is the final leg [14], which in the case of parcel lockers is transferred from the LSP to the consumer. When consumers use self-service technology, they create the service and become a service receiver [34]. However, an underlying assumption is that consumers are willing to accept these self-service terms, which means that success depends on their willingness to use them [35]. Regarding parcel lockers, consumers have individual ways of viewing and perceiving value created, where consumers have functionality, sociality, emotional, or financial differences [14]. A similar study found that the leading indicator for using parcel lockers was how consumers perceived its main advantage, meaning that complexity, compatibility, and trialability only indirectly influenced their attitude towards using the lockers [10].

Summarising and contribution

Extensive literature has analyzed the efficiency of substituting home deliveries with parcel lockers, primarily focusing on distributor costs and environmental impacts. Our analysis expands on this by considering pick-up points at stores as an additional delivery option, alongside attended and unattended home deliveries, and parcel lockers. Additionally, the assessment includes the evaluation of operating costs for both battery-electric trucks and vans, as well as biogas-fueled trucks, incorporating the environmental footprints resulting from consumers' mode choices for the final leg. Utilizing real data from an LSP in the Oslo region, a densely populated area with approximately 1.1 million inhabitants, our study allows for an assessment of cost and environmental trade-offs among the four distinct delivery concepts and different powertrains in distribution.

Methodology and data

Delivery alternatives

There are four last-mile delivery alternatives for parcels to consumers, analyzed in this paper. These are:

i. Pick-up in stores (here referred to as pick-up points)

ii. Unattended home deliveries (LSP deliver the parcel without meeting the customer)

iii. Attended home deliveries (customer must be home to confirm the delivery)

iv. Pick-up from parcel lockers

Fig. 3.1 illustrates the primary principles and distinctions in the distribution chain, including the mode of transport, for the LSP.

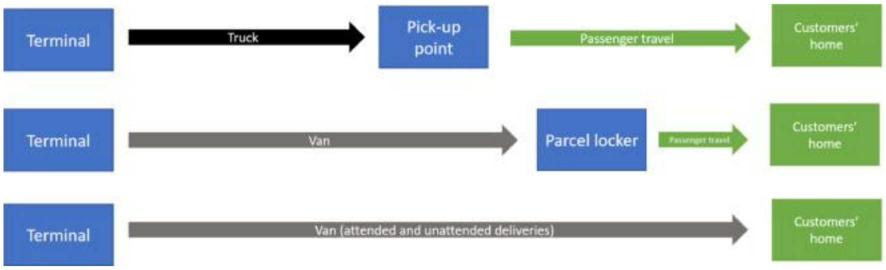

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Fig. 3.1. Illustration of the primary principles in the four analyzed delivery options.

These four delivery solutions incur different costs for the LSP and trigger varying degrees of collection travel for recipients. Parcel distribution to pick-up points involves delivery to stores by trucks, performed as consolidated parcels in roller cages. The LSP pays a fee per parcel to the stores, covering tasks such as registering, storing, and physically handing over parcels to customers. For the remaining three delivery solutions, parcel distribution is carried out using vans from the terminal. Home deliveries can be either attended or unattended. The key distinction lies in the time window, with attended deliveries having a more restricted timeframe as recipients must be at home to confirm parcel receipt. Attended deliveries are often used for high-value or large and heavy parcels, requiring driver assistance in carrying them into customers' homes. Unattended deliveries can be left outside the customer's door or in a mailbox, eliminating the need for receivement confirmation. Both home delivery solutions are more time-consuming per parcel delivered, as each customer must be visited, resulting in one stop per parcel. For attended deliveries, there's also a risk of the recipient not being home. For distribution to parcel lockers, more than one parcel can be delivered per stop, resulting in reductions in both driving distance and time consumption per parcel delivered compared to home deliveries. However, a longer stop time is needed per parcel compared to deliveries to pick-up points, as the driver must register each parcel before placing it in the locker.

Cost model and variables

To analyze the cost and environmental effects of the four different delivery solutions, a Decision Support Tool (DST) is developed. The DST is built bottom-up and categorizes costs into three main categories: fixed, variable, and salary costs. The model specification makes it suitable for analyzing how changes in parameters and assumptions affect costs and emissions. Similar tools have been developed for the analysis of food distribution [36] and distribution of Waste from Electrical and Electronic Equipment (WEEE) [37].

Transport costs are calculated from a total cost of ownership (TCO) perspective for a representative truck and van, both assumed to have diesel engines. The TCO encompasses all costs incurred in owning and operating a vehicle throughout its seven-year depreciation period. The cost parameters in the TCO are categorized into fixed and distance-dependent costs, as specified in Table 3.1. The analysis also considers the need for increased vehicle capacity as the number of parcels increases.

Table 3.1. Cost components and assumption categories included in the TCO model.

Fixed costs	Distance dependent costs
Capital costs (investment costs, depreciation period, interest rate, vehicle residual value)	Energy costs (energy consumption, energy/fuel price, and applicable taxes and fees)
Motor insurance tax (vans), annual weight fee (trucks)	Road toll fees
Insurance and administration	Maintenance, repairs, and operation (MRO)
	Wash, tires, requisites

Investment costs and energy consumption for three different propulsion technologies (diesel, battery-electric, and liquid (bio) gas) for trucks were acquired through interviews with four different truck providers in Norway. Enova, a state-owned company, offers a subsidy covering up to 40 % of the additional investment costs for battery-electric trucks compared to diesel trucks. Price lists for new vans, along with fees and taxes, are publicly available from the Norwegian tax authorities. Road toll fees are obtained from the toll company, Fjellinjen↗. Battery-electric trucks and vans, as well as trucks fueled with compressed or liquid biogas, are exempt from road tolls in the Oslo region.

The TCO models serve as inputs to the Decision Support Tool (DST), which considers various elements in the last-mile operation. Distribution costs are calculated for each delivery product separately, with a key principle being the determination of how many parcels can be delivered during a maximum 8-hour working shift. Time spent on each operation and distance per parcel delivered are treated as exogenous variables, while the number of shipments and daily driven kilometers per delivery product and vehicle are endogenous variables in the model.

Operational efficiency, in terms of time spent on each operation in the working process and the number of parcels delivered on each trip is essential in the calculations. Operational time is divided into all activities related to distribution and deliveries, such as loading parcels into the vehicle at the terminal, driving, deliveries to customers' homes, parcel lockers, and pick-up points, which are key elements. To compare the efficiency of the different delivery solutions, separate cost models are specified for each solution. However, in actual operations, there may be a co-distribution of various solutions, especially in rural areas.

Input parameters are based on (real) shipment data from an LSP operator in Norway, encompassing information about vehicles used in last-mile operations, including payload capacity and average fuel consumption. Time processes are partly inferred from parcel tracking timestamps and partly measured by the LSP.

Details about driving distance and time usage concerning truck deliveries rely on GPS tracking data, utilizing the Haversine formula to calculate distances between consecutive vehicle observations. Identifying stops, utilizing the same methodology as [38], introducing a 50-meter radius buffer for inner-city areas to prevent the merging of stops. Standard driving times are estimated based on observed speeds, adjusted for exit time from the stop radius to avoid dwell time overestimation.

Driven distance is divided by the average number of parcels delivered per pickup point. Vehicle stop time is relatively unaffected by the number of parcels, but stop time per parcel decreases with an increasing number of parcels per stop.

The LSP procures last-mile distribution services by van without insight into the total operational costs. Due to a lack of information on actual driving distances for vans, optimized distance and driving time are calculated using the commercial route-planning tool, Spider Solution, for each delivery product based on deliveries for a representative day [39,40]. Different analysis scenarios provided a basis for estimating how the average distance per parcel delivered to parcel lockers changes with an increase in total parcel numbers and per stop. Estimated distribution distance is divided by the number of routes and the average number of parcels per route. It's worth noting that the transport distance per parcel is shorter for attended than unattended home deliveries, mainly because there are more attended deliveries compared to unattended in the dataset. Since deliveries to parcel lockers were in a pilot phase during this optimization, several expansion scenarios were simulated, including parcel lockers in all housing cooperatives, grocery store locations, and combinations of such locations in the region [39]. This provided a basis for estimating how the distance driven per parcel varies when both the locker network is expanded and the number of parcel deliveries increases.

Other input factors in the model are derived from 1) Operational data from the LSP, including the delivered number of parcels per stop, time of deliveries per stop and per parcel, average fuel consumption, vehicle payload capacity in m^3, and maximum payload utilization). 2) Optimised distance and driving time per parcel delivered. 3) Input data from the cost models in a National freight transport model in Norway, encompassing insurance, tires, administration, and MRO (maintenance, repairs, and operation) [41]. 4) CO2 intensity in diesel, scaling parameters for mandatory bio blending in diesel in Norway, and scaling for CO_2 contents in biogas.

Major input parameters in the cost model, along with their sources, are summarized in Table 3.2, while Table 3.3 provides an overview of major time and distance components in the last-mile operations.

Table 3.2. Overview of major cost components in the model (SN = Statistics Norway).

Input	**Unit**	**Delivery solution**					**Source**
		Pickup point	**Un-attended**	**Attended**	**Parcel locker**		
Vehicle type (and model)		*Truck*	*Van -VW Crafter*			*MB Sprinter Cabinet*	
Investment costs diesel vehicle	EUR	123 737	43 555			92 654	Interviews and The Norwegian Tax-authority
Investment costs BE vehicle	% / EUR	+ 155 %	56 919			121,082	
Public grant in % of added costs BEVs	%	35%					Enova↗
Vehicle loading capacity	m3	31	14	14	14	22	LSP

Input	Unit	Delivery solution					Source
		Pickup point	Un-attended	Attended	Parcel locker		
Payload utilisation	%	80 %	80 %	80 %	80 %	80 %	
Fuel consumption (diesel)	liter/km	0.24	0.08	0.08	0.08	0.12	
Fuel consumption (biogas)	kg/km	0.22					
Energy consumption (electricity)	kWh/km	0.89	0.30	0.30	0.30	0.44	
Lifetime	Years	7	7	7	7	7	Assumptions
Rest value	EUR	0	0	0	0	0	
Interest	P.A.	4 %	4 %	4 %	4 %	4 %	
Tires	EUR	1 980	990	990	990	1 237	Grønland (2022)
Insurance	EUR/year	2 772	1 782	1 782	1 782	2 178	
Administration	EUR/year	332	304				
MRO	EUR/km	0.10	0.08				
Road tolls	EUR/year	9 978	4 989				Fjellinjen↗
Fuel price (diesel)	EUR/liter	1.64	1.64				SN Table 09,654↗
Energy price (electricity)	EUR/kWh	0.16	0.16				SN Table 09,364 ± tax
Fuel price (liquid biogas)	EUR/kg	2.32					Fuel prices | Circle K↗
Driver salary incl. social costs	EUR/hour	35.30	32.33				SN Table 11,418↗
Working shifts per day	#	1	1				Assumptions
Working days per year	Days	250	250				
Irregularity supplement (07:00PM-01:00AM)	%	25 %	25 %				Yrkestrafikkforbundet↗
CO_2 intensity	kg/litre diesel	2.67	2.67				Fridstrøm (2022)
-Scaling mandatory bio blending	%	88 %	88 %				
-Scaling biogas	%	20 %					Circle K↗
Endogenous in the model:							
Distance per working shifts per day	Km/shift/day	126	84	58	122		
Distance per year per working shifts	Km/year/shift	31 463	21 005	14 559	30,541		
Road toll/km	EUR/km	0.32	0.24	0.34	0.16		

Table 3.3. Overview of major time and distance components in the last mile operations.

Variables:	Unit	Source*	Pickup point	Un-attended	Attended	Parcel locker	Scenarios parcel lockers					
Max duration distribution route	Hours	Fixed	8	8	8	8						
Average parcel size	Dm^3	A	6.0	6.7	48.6	9.1						
Loading time per trip in the terminal	Min.	A	45	30	30	30						
Number of parcels per pickup point/parcel locker	Parcels	A	50	1	1	5	1	10	15	20	25	30
Distance per parcel	Km	A/O	0.15	1.33	0.93	0.93	1.06	0.76	0.60	0.44	0.28	0.11
The probability that the recipient is at home	%	E	100 %	100 %	70 %	100 %						
Speed	Km/h	A/O	40	17.2	17.5	23.1						
Parking, including handling of tailor lift (per stop)	*Sec*	*E*	*420*	*15*	*30*	*30*						

Variables:	Unit	Source*	Pickup point	Un-attended	Attended	Parcel locker	Scenarios parcel lockers					
Time for organizing parcels in a vehicle (per stop)	*Sec*	*E*	*180*	*10*	*10*	*18*						
Walking time to delivery (per stop)	*Sec*	*E*	*60*	*10*	*25*	*10*						
Delivery time per parcel	*Sec*	*E*	*2*	*50*	*100*	*30*	*31*	*28*	*26*	*25*	*23*	*21*
Preparation for the next stop	*Sec*	*E*	*120*	*60*	*60*	*90*						
Total time per stop	Min.	Sum	14.7	2.4	3.8	5.0	*3.0*	*7.2*	*9.1*	*20.0*	*25.0*	*30.0*

***A = Generic Average, C = Calculation, *E*= Estimates from operational data from the LSP.

The vehicle's stop time per parcel delivered to a parcel locker is higher than for deliveries to pick-up points. At a pick-up point, the driver delivers the parcels in one or more roller cages, which is time-efficient for large parcel volumes. For deliveries to parcel lockers, each parcel must be registered by the driver when placed in the locker.

Emission factors

CO_2 is one of the most significant greenhouse gases contributing to global warming, making it a priority to reduce CO_2 emissions. Local emissions, such as particles and nitrogen oxides, primarily affect air quality at a local level. While addressing local emissions is crucial for public health and the environment, the emphasis on CO_2 emissions may arise from the desire to tackle global climate challenges. Our study is limited to calculating CO_2 emissions; however, the percentage changes for local emissions will likely be lower than those for CO_2 emissions. This is because shifting to battery-electric vehicles will reduce CO_2 emissions to zero, but there will still be some local emissions related to brake dust and tire wear.

CO_2 emissions are calculated as a function of average fuel consumption per liter of diesel, kilometers driven, and constants for CO_2 per liter of fossil diesel (2.67 kg/liter [42][2]), adjusted for mandatory biofuel blending: Norwegian legislation mandates a biofuel blend-in of at least 17 % for liquid fuels in road traffic, with specific sub-requirements including 12.5 % advanced biofuels and a double-counting provision. A minimum of 4 % of total fuel sales for petrol-driven vehicles should be biofuels. These requirements are dynamic and vary for different fuel types, creating a 'moving target.' Actual blend-in rates, estimated by [43], [44], [45], average 13.7 % for diesel in 2021, and 12.2 % for 2022 and 2023, accounting for energy shares of approximately 12.4 % and 11.1 %, respectively. Biofuels are considered zero-emission from a climate accounting perspective [43], [44], [45].

Also, emissions for the final leg of transport, managed by parcel receivers, are included in the analysis. These emission factors are derived from fuel consumption for an average passenger car and bus in 2022, adjusted for mandatory biofuel blending in Norway. Passenger car emissions are based on averages from [46]: 188 gs CO_2/km for exhaust cars and 0 gs CO_2/km for Battery Electric Vehicles (BEVs), considering Norway's renewable electricity production. For public transport, an assumption of 42.5 gs of CO_2 per passenger-kilometer is made, based on city bus fuel consumption data from [46] and an average of 20 passengers. This assumption is conservative, considering the presence of electric trams and metros with minimal CO_2 emissions, as well as the expansive transition to battery-electric buses in the Oslo region by the end of 2023.

Results and discussion

Cost analysis

The cost analysis is based on the DST, categorizing cost components as fixed, variable, and salary costs. Cost estimates per trip, *per* stop, and parcel are summarized in Table 4.1 for the *four* different delivery solutions.

Table 4.1. Summarised cost estimates per delivery solution in EUR.

	Pick-up point	Unattended	Attended	Parcel locker
Cost per trip	520	355	344	364
Cost per stop	32			14
Cost per parcel	0.65	5.64	7.68	2.80
Number of shipments per trip	839	63	45	132
Average parcel size (dm^3)	23.4	27.7	78.1	27.3
Vehicle utilization in %	79 %	16 %	32 %	33 %

As indicated in Table 4.1, the cost per trip is highest for deliveries to pick-up points, while the other three solutions exhibit a more comparable cost level per trip. This discrepancy results from the use of different vehicles (trucks for pick-up points, vans for others). Therefore, both vehicle and salary costs per time unit are higher for deliveries to pick-up points compared to parcel lockers. When breaking costs down per stop, pick-up points incur over twice the cost of parcel lockers (EUR 32 vs. EUR 14).

Analyzing costs per parcel underscores the economy of scale, with pick-up points standing out as the most cost-effective (EUR 0.65), followed by parcel lockers (EUR 2.80). Unattended home deliveries incur a cost of EUR 5.64, while attended home deliveries emerge as the most expensive option at EUR 7.69. Despite the shorter distribution distance per stop, attended home deliveries are more expensive than unattended home deliveries due to the probability of the recipient not being at home, necessitating multiple visits.

The delivered number of parcels per stop is essential to reduce these costs. Deliveries to parcel lockers are still in an early phase, so the number of parcels per locker is currently quite low, with five parcels delivered per locker on average. It is expected that this number will increase, and the analysis in this paper simulates different scenarios for the use of parcel lockers. The results illustrate that both attended and unattended home deliveries will always be the most expensive alternatives, while unit costs for deliveries to pick-up points and parcel lockers depend on the average number of parcels at each stop.

Table 4.2 illustrates the cost shares and economies of scale for various delivery solutions, breaking down costs into fixed, variable, and salary costs for each solution.

Table 4.2. Cost in EUR per delivered parcel per delivery solution, broken down into fixed, variable, and salary costs, with cost shares in parenthesis.

	Pick-up point	Unattended	Attended	Parcel locker
Fixed costs	0.17 (26 %)	0.91 (16 %)	1.28 (17 %)	0.39 (16 %)
Variable costs	0.14 (21 %)	0.66 (12 %)	0.81 (11 %)	0.34 (14 %)
Salaries	0.34 (53 %)	4.07 (72 %)	5.60 (73 %)	1.78 (71 %)
Sum	***0.65 (100 %)***	***5.64 (100 %)***	***7.69 (100 %)***	***2.51 (100 %)***

The main cost drivers are the time spent on various sub-tasks in the delivery process and salary costs, constituting 53–73 % of total costs, followed by fixed (16–26 %) and variable costs (11–21 %). Therefore, the number of parcels delivered per stop is essential to reduce these costs. Total costs and the number of parcels delivered during an eight-hour day shift are calculated as a result of the distribution operations.

Despite significant differences in cost per parcel, the pattern remains consistent. Salary costs per delivered parcel are nearly 40 % higher for attended compared to unattended home deliveries and almost three times the level for parcel locker deliveries. Surpassing the cost level for deliveries to pick-up points by more than 10 times, highlighting the considerable expense of home deliveries, especially attended ones, for the LSP. The higher cost efficiency in transportation for deliveries to pick-up points compared to delivery to parcel lockers underpins that parcel lockers are, most of all, an alternative to home deliveries. However, the costs of installing the parcel lockers and the costs the LSP is paying to the pick-up point's shops for handling the parcels are not part of this analysis but should be taken into consideration. The difference between these two cost components should be compared to the difference in transport costs (EUR 2.51 – EUR 0.65 = EUR 1.86). However, these two components are sensitive both for the LSP and the other actors involved.

The average number of parcels per delivery to a locker is currently only five, and the cost per parcel is estimated at EUR 2.80. In comparison, deliveries to a pick-up point cost EUR 0.65 per parcel. As operational experiences from the pilot phase accumulate, the utilization of parcel lockers is expected to increase. The cost reduction per parcel delivered to a parcel locker is most significant for a small number of deliveries and flattens out when the number exceeds 25 per locker. This triggers the need for a van with a higher payload capacity.

CO_2 emissions

As mentioned in paragraph 3.3, CO_2 emissions are calculated as a function of the average fuel consumption per liter of diesel, kilometers driven for each delivery solution, and constants for CO_2 per liter of fossil diesel, adjusted for mandatory biofuel blending. Table 4.3 summarizes CO_2 emissions related to the four different distribution solutions, broken down by trip, stop, and parcel, assuming that the vehicles are running on diesel.

Table 4.3. CO_2 emission for different delivery solutions, concerning trip, stop, and parcel.

	Pick-up point	Unattended	Attended	Parcel locker
Kg per trip	70.54	15.70	10.88	22.82

	Pick-up point	Unattended	Attended	Parcel locker
Kg per stop	4.41			0.88
Kg per parcel	0.09	0.25	0.24	0.18

The analysis illustrates that the last mile CO_2 emissions per trip are almost seven times higher for deliveries to pick-up points than for attended home deliveries, four times higher compared to unattended home deliveries, and 2–3 times higher than for deliveries to the parcel lockers. The primary explanation for these differences lies in the vehicle size used for each delivery solution, along with the total trip distance influencing CO_2 emissions across routes. However, measuring CO_2 emissions in kg per parcel reverses the scenario: Attended and unattended home deliveries have the highest but nearly equal CO_2 emissions per parcel (0.24 and 0.25 kg each). Deliveries to pick-up points have the lowest (0.09 kg), while CO_2 emissions per parcel for deliveries to parcel lockers fall in between (0.18 kg).

Scenario analysis

Costs

Illustrating the impact of stop time on the cost per parcel delivered, a sensitivity analysis was conducted with equal percental changes in total time per stop for all delivery solutions. This is summarised in Fig. 4.1.

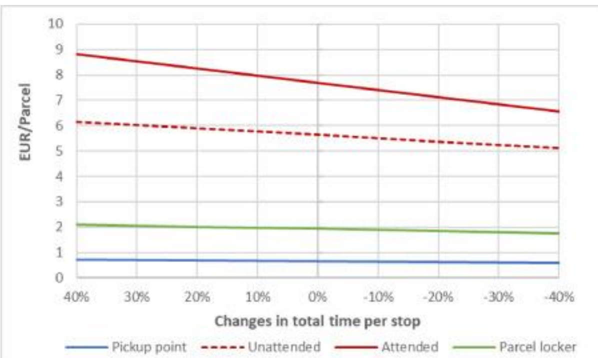

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Fig. 4.1. Analysis of how percental changes in total time per stop affect costs per parcel for each delivery solution.

Although the same percentage changes in total time per stop are basis, the effect in terms of the slope of the cost curves is very different for the four different solutions. This must be seen in connection with the cost level as it appears from Table 4.2: While changes in total stop time affect the cost level for attended home deliveries most, it can hardly be seen that it affects the cost level of deliveries to pick-up points. This is because labor costs make up a smaller part of deliveries to pick-up points than for the other delivery solutions and, not least, stop time per parcel is very low for this delivery solution.

Parcel lockers are still in an early phase, and the average number of parcels delivered per parcel locker on a trip was only five on average in 2022 but varied throughout the year: Most parcels were delivered in the period before Christmas (with 7–8 on average per locker) and the fewest in summer (3–4 on average). Fig. 4.3 summarizes a sensitivity analysis of how various numbers of parcels delivered to each parcel locker on a trip affect the costs per parcel, compared to the cost level of the other delivery solutions (where the assumptions for these are kept constant). In the figure, the cost of using a battery electric van in the last mile for parcel locker deliveries is also included, as well as a curve representing the vehicle's payload utilization, for the vans used in distribution to parcel lockers.

Even in a situation where only one parcel is delivered per parcel locker, the related unit cost is lower than for both types of home delivery. This is because the LSP does not have to drive to each customer's home but can deliver to a more centrally located locker. Unit costs decrease as the number of deliveries per trip and parcel locker increase, and cost reduction is most significant from a small number of deliveries. When number of parcels per locker surpasses 25, there is a need to change to a larger van for capacity reasons; however, this change hardly affects the unit costs per parcel. The per-unit cost curve for parcel locker deliveries crosses the costs for pick-up points at the level of 30 parcels delivered on average per locker.

The average storage time per parcel is measured at 36 h from the time it is placed in the locker until it is picked up by the customer [47]. Considering that one single locker cabinet has on average 14 individual lockers, and a maximum of 22 individual lockers (with only small hatches), it emphasizes that several cabinets per location are required to have sufficient capacity. Several cabinets are area demanding, and it is also important to keep in mind the trade-off between the LSP's efficiency and the location's distance to the customer base because the distance to customers affects their mode choice on the final leg.

As seen in Fig. 4.2, operating a battery electric van to parcel lockers is slightly cheaper than a van with an Internal Combustion Engine (ICE), given the assumptions that emerge from Table 3.1, where an exemption from road tolls is a main factor that makes the calculation favorable. A critical factor, however, is whether the van needs to be charged during the working day. The range for this van is stated at 160 km (city driving), which is hardly sufficient for the longest route intended for the parcel lockers. However, there are electric vans with longer ranges on the market, so this is not a critical factor, but fast charging during the day is both expensive and entails a shorter time for operation during the day. The costs of operating the truck with either battery-electric or biogas (not presented in the figure) were analyzed. It was found that battery-electric operation is slightly cheaper, while biogas operation is slightly more expensive than operating a diesel truck (EUR 0.61 per parcel for battery-electric operation versus 0.65 for diesel and 0.67 for biogas).

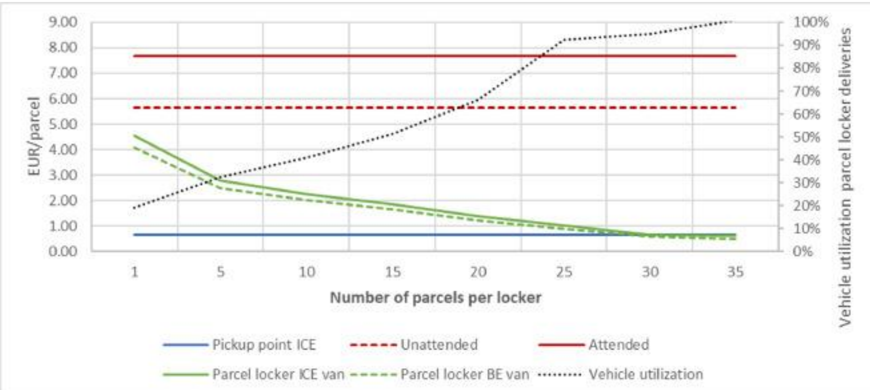

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Fig. 4.2. Analysis of how changes in the delivered number of parcels per locker affect the costs per parcel, compared to the other delivery solutions, and payload utilization for vans used in parcel locker distribution.

Deliveries to parcel lockers will from a cost perspective initially replace attended home deliveries of parcels. However, customers may hesitate to receive valuable goods in the parcel lockers until trust is established that the lockers are a safe delivery method. For the LSP, it will also be favorable to replace unattended home deliveries with deliveries to parcel lockers. It is less likely that the LSP would replace deliveries to pick-up points from a transport cost perspective. In that case, it will depend on how much the pick-up points charge for each parcel they deliver and how feasible it is to establish enough parcel lockers to meet this capacity. However, during peak periods, it is likely that the LSP will use parcel lockers as an alternative to pick-up points from a capacity perspective. Furthermore, the costs of installing the parcel lockers and the costs to the pick-up point's shops for handling the parcels are not part of this analysis but should be taken into consideration. The difference in cost between these two alternatives should be compared to the transport cost difference (EUR 2.80 – EUR 0.65 = EUR 2.15). However, this information is sensitive for both the LSP and the other actors involved.

CO_2 emission

Fig. 4.4 summarises a sensitivity analysis of how changes in the delivered number of parcels per locker affect the CO_2 emission per parcel, compared to the other delivery solutions, where the number of deliveries is constant. It is also taken into account that it is necessary to change to a heavy van when the number of parcels delivered per locker exceeds 25. Since CO_2 emissions per parcel are almost equal for both home delivery products (from Table 4.3), only one curve represents home deliveries in Fig. 4.3.

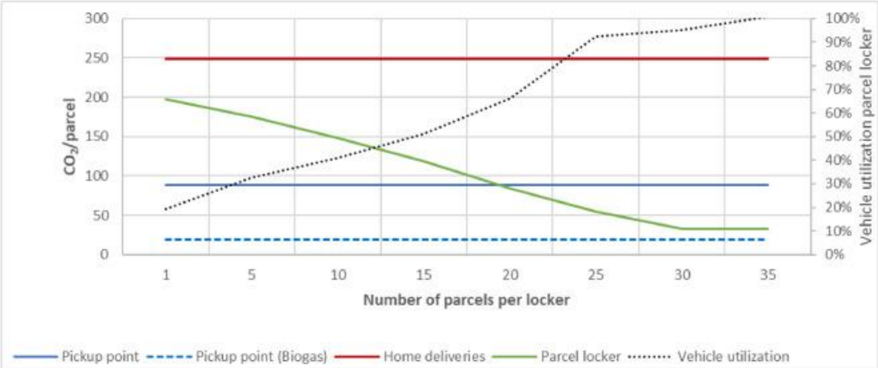

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Fig. 4.3. Analysis of how changes in the delivered number of parcels per locker affect CO_2 emissions per parcel, compared to the other delivery solutions.

The figure demonstrates that the environmental impact of parcel lockers, compared to other delivery solutions, is significantly influenced by the average number of parcels per locker. According to the model presented, CO_2 emissions per parcel delivered to parcel lockers are lower than deliveries to pick-up points when the number of parcels delivered per parcel locker exceeds 20. This holds only if the operation is with a diesel truck. If the operation is with a biogas-fueled truck, the CO_2 emissions per parcel delivered with the truck will decrease by 80 %, while if the operation is with battery-electric vehicles (trucks and vans), the delivery will be CO_2-free.

Beyond the emissions associated with the LSP's last mile, total emissions also depend on the final leg, where consumers pick up the parcel and transport it home. If this final leg is done by walking, cycling, or with an electric vehicle, there will be no additional emissions. Traveling by bus adds emissions, which increase further if the final leg is performed with a passenger exhaust car. This footprint is added to the emissions from the LSP's last mile, considering various assumptions about the distance for the customer's last leg (Fig. 4.4).

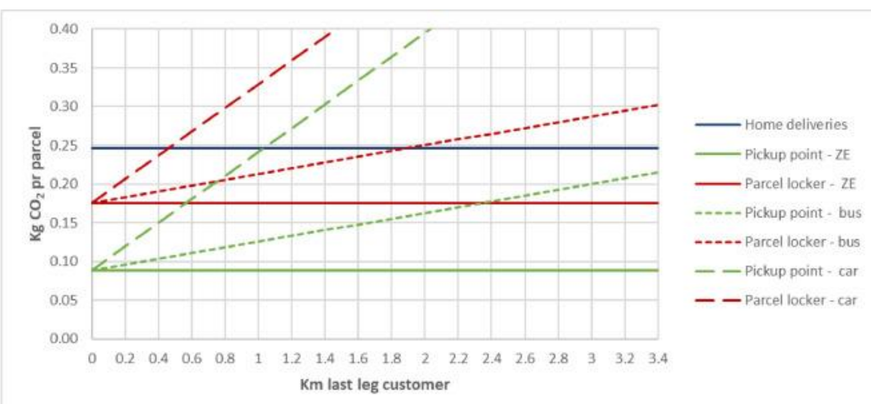

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Fig. 4.4. CO_2 emissions: Different delivery solutions and customers' mode of transport on the final leg (ZE = final leg is performed with zero emission).

Fig. 4.4 reveals that the footprint ranking of different delivery solutions depends on how consumers complete their final leg. If consumers take a bus, parcel lockers become less eco-friendly than home deliveries after a 2 km round trip, while pick-up points follow at approximately 3.5 km. Yet, if consumers use a car, these distances shrink significantly to 0.5 km (round trip) for parcel lockers and 1.1 km for pick-up points. With an increase in the average number of parcels per locker, the CO_2 emission per delivered parcel decreases, potentially placing this curve below the pick-up points curve, allowing longer pick-up distances with exhaust cars before home deliveries become more environmentally friendly.

Certainly, the environmental impact of the last leg is influenced by whether the consumer's trip is solely for parcel pick-up or if it's combined with other activities. In cases where the pick-up trip is part of a larger errand, the entire footprint of the final leg may not need to be added, except for any potential detour it causes. Variations in travel behavior and mode choice can arise from factors like access to public transport, car ownership, socio-economic characteristics, and more. An analysis conducted by [48], based on data from a large national travel survey

(NTS) in Norway from 2018/2019, the last regular pre-pandemic years, includes detailed information on travel behavior within the population. In this analysis, the Oslo region (capital area) was divided into eight geographical areas. Relevant to the current study is the information on modal choice, additionally broken down by trip length (<1 km, 1–2.9 km, etc.). The main findings from this analysis are that 69 % of people in Inner Oslo (Oslo CBD) are either walking or cycling on distances between 1 and 2,9 km, 21 % use public transport (also including tram and metro), while only 8 % use a passenger car on such distances. However, car use is increasing rapidly in the outer parts of the city, with a further increase in the outskirts of the city (34–40% and 52–59% respectively.

In another Norwegian sample survey among receivers of parcels to pick-up points and parcel lockers [49], recipients were asked if their journey solely served the purpose of picking up the parcel, or if it also included other errands. They found that a significant portion of those who drive a car to pick up their parcel from a locker do so on their way to or from other errands. Although cars are the preferred mode choice when picking up parcels in combination with other errands, there are still 42 % of car journeys made solely for parcel retrieval. The distribution was relatively similar for parcel retrieval either the picking up was from lockers or pick-up points. The exception was parcel retrieval from lockers using a car, where the share of people combining parcel retrieval with other errands was approximately 10 percentage points higher than for the other alternatives and constituted 58 % of the pick-ups by car. This demonstrates that there is a potential to reduce car travel, either by encouraging consumers to retrieve parcels as part of another trip or by encouraging them to switch to alternative modes of transportation.

This finding also figures out another main finding, which is at least as important, that it matters where the lockers are located. Ideally, the lockers should be located as close to the customers as possible, so the locations do not trigger a need to use a car on the pick-up journey. However, [39] found that there is a point of saturation for how many parcel locker locations there can be before it affects the distributor's efficiency. The distributor's trade-off is, on the one hand, to have so many locations that they are attractive to the customer, but on the other hand, they cannot have so high density that it reduces their distribution efficiency. Since there is time connected to each stop regardless of the number of parcels delivered, each stop should therefore involve more than a marginal number of delivered packages.

In the years to come, the overall footprint will also change because of the ongoing phasing-in of electric vehicles. This applies to both customers (passenger cars and city buses) and the distribution, which will soon be performed with electric vehicles or vehicles fueled by biogas (vans and trucks). However, CO_2 emission is not the only negative externality in transport. This is especially true in urban and residential areas, where accidents, noise, queues, and local pollution are important externalities from all traffic. Therefore, both the last mile must be carried out as efficiently as possible, but also that the customers' final leg does not generate a new car trip.

Conclusions

The purpose of this paper was to study how parcel lockers can contribute to more efficient and sustainable e-commerce. While parcel lockers have been rolled out in urban areas throughout Norway in recent years, pick-up points, followed by attended and unattended home deliveries, remain the most common delivery options. The analysis calculates the costs and CO_2 footprints of four different distribution solutions for parcel deliveries to the consumer market, considering three different powertrains for trucks and two for vans.

The cost analysis presented here underscores the significance of the economy of scale in various delivery solutions. The number of parcels delivered per stop is crucial in determining the most profitable alternatives. Both attended and unattended home deliveries will always be the most expensive options, while the unit costs for deliveries to pick-up points and parcel lockers depend on the average number of parcels at each stop.

The average cost per parcel delivered to a parcel locker was estimated at EUR 2.80. In comparison, costs related to deliveries to pick-up points were estimated at EUR 0.65 per parcel. As operational experiences from the pilot phase accumulate, the utilization of parcel lockers is expected to increase. The scenario analysis illustrates that the cost reduction per parcel delivered to a parcel locker will be most significant for a small number of parcels and flattens out when the number exceeds 25 per locker, triggering the need for a van with a higher payload capacity.

The CO_2 footprint connected to the LSP's last mile distribution for different delivery solutions illustrates that home delivery has a much higher footprint than deliveries to pick-up points and parcel lockers. For deliveries to pick-up points and parcel lockers, the footprints are considered in two ways. First, there is a classical CO_2 calculation depending on the fuel consumption during distribution, which is dependent on the operator's driving distance, fuel consumption, and CO_2 intensity per liter of fuel. The CO_2 footprint has a trade-off of 20 parcels to a locker: If more than 20 parcels are delivered per parcel locker, parcel lockers stand out as more environmentally friendly than deliveries to pick-up points, given the assumptions upon which this analysis is based.

Our main findings align with former studies. Table 5–1 compiles our findings along with those of previous studies from the literature study, examining the potential for cost and CO_2 reductions when replacing home deliveries with deliveries to parcel lockers.

Table 5–1. Compiling our findings with those of former studies concerning the potential of cost and CO_2 reductions of replacing home deliveries with deliveries to parcel lockers.

Reference number	Cost reduction	CO_2 reduction
Our analysis	19 - 89 % vs. unattended 41–92 % vs attended	21–87 %
[21]	90 % (Distance reduction)	93 %
[24]	51 %	51 %
[25]	59 %	59 %
[30]	N.A.	67 %–91 %
[33]	53 % (Distance reduction)	95 %

While most of the former studies provide a single estimate for the potential of both costs and CO_2 reductions, our analysis visualizes a broader range of potentials depending on the assumptions the analysis is based on. We find that the cost reduction potential heavily depends on the number of deliveries per parcel locker. Our analysis also demonstrates that battery-electric operation can be profitable, applying to both trucks and vans. However, the operation with a biogas-fuelled truck is slightly more expensive than for a diesel truck. This finding is contingent on these vehicles being exempt from toll fees in the Oslo region, as well as the state company Enova covering up to 40 % of the additional costs for battery-electric trucks.

Our analysis also includes various scenarios where the environmental footprint was examined based on how customers pick up their parcels. When parcels are collected using an exhaust car or bus, there is an additional footprint in the consumer's last mile that must be considered. Conversely, if the receiver walks, cycles, or drives an electric car, there will be no additional environmental footprint from the last leg. When customers travel by public transport, the additional footprint can range from zero to something in between zero and the emissions of an exhaust car. The distance to the pick-up point and locker is crucial to this decision, and data confirming this picture are highly heterogeneous, depending on the distance from home to the locker or passing by on their everyday travel.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Chat GPT as a tool for proofreading some of the paragraphs. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Inger Beate Hovi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Eirill Bø:** Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors report that there are no conflicts of interest to declare.

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Data availability

The main data underlying this research (individual detailed parcel data) cannot be made publicly available, as this information is proprietary and business-sensitive for the LSP.

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2 According to the European Standard NEN-EN 16258, 1 kg of fossil diesel contents 3,21 kg CO_2 in a Tank to Whell perspective, while 1 litre of fossil diesel weights 0,832 kg. This results in a CO_2 content per liter of fossil diesel of 2.67 kg/liter.