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Exploring the use of mobile warehouses in midsized urban and rural regions for last-mile transportation

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Abstract: Efficient last-mile transportation is a continuous difficulty for businesses, particularly in e-commerce, necessitating the development of creative solutions. This thesis investigates the use of mobile warehouses in mid-sized urban and rural areas to help with this problem. The study begins by emphasizing the importance of flawless delivery as well as the role of warehouses in supply chains. Mobile warehouses emerge as a possible solution, addressing constraints related to these regions' low population density, purchasing power, and market dynamics. The methodology includes a review of the literature on mobile warehouse solutions and the introduction of a generalized cost function model for estimating last-mile logistics costs. The model, which is adaptable to different vehicle types, is applied to Dalarna County in Sweden, considering delivery routes and stops. The findings spotlight the efficacy of mobile warehouses, notably mobile trucks, for last-mile delivery in Dalarna County. Interpretation of results from simulation scenarios emphasizes the importance of route optimization. While the study acknowledges its limitations, it underscores the potential benefits of adopting mobile warehouses, both in practical and theoretical terms. These findings resonate as valuable insights for businesses and the logistics industry, especially in the dynamic landscape of e-commerce. The study illuminates the way forward, emphasizing the critical role of adaptive, geography-specific solutions, such as mobile warehouses, in enhancing last-mile delivery efficiency.

Keywords: Mobile Warehouse, Last-Mile Logistics, Supply Chain, Logistics, Distribution
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Chapter 1

1.1 Identifying problem areas.

Businesses, especially those engaged in e-commerce, depend on timely product delivery to customers. Businesses are seeking efficient ways to reduce the cost of their last-mile transportation as consumer demand for quick and dependable delivery keeps growing. The transfer of goods in the final mile is the emphasis of last-mile transport, which can be accomplished using a variety of vehicles, including electric cars, bicycles, tricycles, light goods vehicles, and drones (Olsson, J.et al., 2019).

Warehouses and Distribution Centres (DC) play a crucial role in the supply chain. Distribution centers and warehouses are logistics facilities that store finished goods before they are picked and packed to fulfil customer orders, particularly in terms of expediting and accurately filling customer orders while keeping associated costs low (Higgins, J. K. et al., 2005, Jermsittiparsert, K. et al., 2009). While a whole building can be used as a warehouse, having various components, including rack and storage capacity compartment sets, systems for climate control products, including managing temperature, warehouse software, and inventory control software (Patil et al., 2021). Depending on the demands or structure of the organisation, these centres can be run and managed in various ways. Some retailers, for example, create and maintain their own distribution centers, while others collaborate with Third-Party Logistics (3PL) suppliers.

Warehouse space constraints have become a stumbling factor for supply chain and inventory management in terms of delivery requirements. Choosing the right property in the right location can be critical to a company's success. With customers' preferences changing so quickly and wanting virtually same-day delivery on online purchases, investing in warehouses or distribution centres closer to the end user to reduce delivery costs and timing for the last mile is costly (Johnson, S., 2023). Aside from limited storage capacity, supply chain management must plan for seasonal inventory flex, weather disruptions, pricing volatility, and increased reverse logistics
of inventory. Having a backup plan in place for unanticipated disruptions ensures that items are delivered on time.

Another component in delivering the products to the customer is last-mile delivery. Last-mile delivery represents the last part of the supply chain, which consists of transporting a product from the warehouse or DC to the customer. Last-mile delivery is also one of the most expensive parts of the whole logistics operations (Rosenberg, L.N et al., 2021). The traditional last-mile delivery system, which relies on central warehouses and local delivery vehicles, is not always cost-effective or practical for mid-sized urban and rural regions (Seghezzi, A et al., 2022). The distance from these areas to central warehouses can result in longer transit times, higher transportation costs, and increased environmental impact. The use of mobile warehouses as a solution for last-mile delivery in mid-sized urban and rural regions has the potential to address these challenges.

Using mobile warehouses as a last-mile delivery is one new solution that has drawn attention recently. Mobile warehouses are made to be carried to various sites by trucks, giving businesses that need to store and transport goods to several locations as a flexible and adaptable solution to swiftly and efficiently supply items to consumers (Srivatsa S. et al., 2021). While the concept of mobile warehouses is new, there is limited research on their feasibility and effectiveness in mid-sized urban and rural regions. The use of mobile warehouses presents several challenges, including accurate demand forecasting to respond timely to consumers’ online orders (Mangiaracina R. et al., 2019), limited storage space, route and location optimisation similar to mobile parcel lockers for efficient last-mile distribution (Schwerdfeger, S. et al., 2020) technological requirements for temperature or humidity levels required to store certain items and regulatory compliance (Mohammad et al., 2023). These challenges need to be addressed to ensure the effectiveness of mobile warehouses in last-mile delivery.

The Just-in-time (JIT) is a logistics method that tries to make products arrive precisely when they are needed in the manufacturing process, avoiding the need for excess inventory and waste (Mishra, O. et al., 2013). However, to achieve JIT,
businesses must rely on inventory availability at the right location and right time. Warehouses and Distribution Centres play an important role in this process by providing storage space, order fulfilment, and transportation. These facilities enable firms to stockpile goods and efficiently manage their supply chain, guaranteeing that products are accessible for distribution when and where they are needed.

Furthermore, as a last-mile delivery solution, mobile warehouses can help organisations accomplish JIT by providing flexible and customisable storage space closer to the end consumer. Mobile warehouses can serve as a buffer inventory, allowing firms to respond rapidly to fluctuations in demand, keep a consistent supply of products on hand, and lessen the risk of stockouts. Businesses can build a comprehensive and efficient supply chain that enables JIT inventory management while providing timely and dependable delivery to their customers by combining mobile warehouses with regular warehouses and distribution hubs.

1.2 Research Problem

Mobile warehouses, which are built to be transported to different areas by trucks, provide firms with the flexibility and agility to supply things quickly and efficiently to consumers in several locations. While the concept of mobile warehouses is relatively new, there is limited research on their feasibility and effectiveness in urban and rural regions. Verlinde, S. et al. (2014) explored the utilisation of mobile depots, which are movable warehouses, in an urban setting. These mobile depots were developed to address challenging urban working conditions, including narrow streets, traffic congestion, congestion charges, and environmental zones. They found that implementing mobile depots resulted in increased capacity by reducing the distance travelled per stop from 1.34 km in the Business-As-Usual scenario to 0.52 km in the Mobile-Depot scenario while also enhancing drop density. Consequently, the adoption of mobile depots led to improved efficiency in last-mile delivery and higher profit margins.

Deploying mobile warehouses in mid-sized urban and rural regions would encounter considerable unresolved obstacles regarding last-mile fulfilment. These challenges
arise from factors such as low population density, an older population, sparsely populated areas, limited purchasing power, and the presence of strong local social ties (Sousa, R. et al., 2020). The low population density implies there are fewer customers in a given geographic area, resulting in lower demand and potentially lower efficiency in utilising mobile warehouses. This makes it more challenging to achieve high drop densities and cost-effective last-mile delivery. Socioeconomic and demographic characteristics can further complicate the adoption and effectiveness of mobile warehouses. For instance, an older population may have different shopping habits or preferences that need to be considered. Sparsely populated areas may require longer distances to cover for each delivery, reducing the efficiency of the mobile warehouse solution (Viu-Roig, M. et al., 2020). Low purchasing power can affect the viability of the business model and the affordability of delivery services (Escamilla, R. et al., 2021). Stronger local social ties may impact consumer behaviour and preferences, requiring tailored approaches for effective last-mile delivery.

The low population density in the mid-sized urban/rural market relative to the urban market is a significant impediment, resulting in a smaller market size for Logistics Service Providers (LSP) servicing this region than in the metropolitan market, i.e., market size in terms of population density typically refers to the number of potential customers or consumers within a specific population density range (Sato Y. et al., 2012). Dalarna County, for example, had a population density of 10.3 inhabitants per km² in 2022, compared to 374.6 inhabitants per km² in Stockholm County (Statista, 2023). This suggests a 97.10% fall in population density as compared to Stockholm County. It is worth noting that Stockholm is also the capital city of Sweden and has a larger population than an area like Dalarna. Businesses that analyse market size based on population density can make informed decisions about market entry, expansion, and resource allocation in order to maximise market prospects.
1.2.1 Last-Mile Delivery Cost

The final delivery stage from a distribution centre or warehouse to the end consumer's location is referred to as the supply chain's last mile. A mobile warehouse can be thought of as a last-mile delivery option. Last-mile costs are expenses incurred during the final delivery stage of a product. These costs can vary depending on several circumstances, and they can have a major impact on overall supply chain costs. According to a recent study, last-mile delivery costs are high as a percentage of total shipping costs, accounting for 53% in total (Glanders, C., 2023). Buyers are less likely to pay a delivery price with the increasing prominence of "free shipping," forcing logistics partners to shoulder the cost. As a result, it has become the main strategy for incorporating new technologies and optimising procedures. Here are some common elements that contribute to last-mile costs (Blauwens, G. et al., 2020):

Transportation Costs: This includes expenses related to transporting goods from the warehouse to the customer's location. It involves fuel costs, vehicle maintenance, driver wages, and any tolls or fees associated with the transportation route.

Labour Costs: Last-mile delivery often requires additional labour, such as delivery drivers or couriers, to handle the final leg of the delivery process. Labour costs include benefits, training, and any additional expenses associated with managing delivery personnel.

Vehicle and Equipment Costs: Businesses must invest in suitable vehicles and equipment for last-mile delivery. This can include trucks, vans, bicycles, or even drones, depending on the nature of the business and the delivery requirements. Vehicle acquisition, maintenance, insurance, and equipment upkeep all contribute to last-mile costs.

Route Optimisation: Efficient route planning is essential for minimising last-mile costs. Optimising delivery routes can reduce fuel consumption, travel time, and
vehicle wear and tear. Utilising route optimisation software or algorithms can help businesses streamline their delivery routes and improve cost efficiency.

Customer Service: Providing a positive customer experience often involves additional costs. This includes features such as real-time tracking, customer notifications, flexible delivery options, and reverse logistics management. Ensuring customer satisfaction may require investments in technology, personnel, and operational processes.

Inventory Management: Last-mile costs can be affected by inventory management practices. Maintaining appropriate inventory levels, optimising stock placement, and minimising stockouts or overstocks can impact overall supply chain costs, including the last mile.

Infrastructure and Access: Factors such as urban congestion, road conditions, parking restrictions, and delivery to remote or difficult-to-access areas can increase last-mile costs. Additional time, resources, or alternative delivery methods may be required to overcome these challenges.

1.2.2 How Mobile Warehouses Reduce Last-mile Delivery Costs?

Reducing last-mile costs is a priority for businesses as it can directly impact profitability and customer satisfaction. An innovative solution, such as mobile warehouses, can play a significant role in reducing last-mile costs as a delivery solution. Here are some ways in which mobile warehouses contribute to cost reduction:

Proximity to End Consumers: Mobile warehouses can be strategically positioned closer to the end consumers' locations, reducing the distance and transportation costs associated with the last mile. By bringing the inventory closer to the customer, mobile warehouses minimise the need for long-distance transportation from central warehouses, distribution centres, or retail stores.
Flexibility and Scalability: Mobile warehouses offer flexibility in adapting to changing demand patterns and varying customer locations. They can be easily moved or relocated to different areas based on demand fluctuations, seasonal requirements, or emerging market trends. This adaptability allows businesses to optimise their operations and allocate resources efficiently, reducing unnecessary transportation and inventory holding costs.

Efficient Inventory Management: Mobile warehouses enable businesses to store inventory directly near the target market. By accurately forecasting demand and stocking the mobile warehouse accordingly, businesses can minimise inventory carrying costs and reduce the risk of stockouts or overstocks. The ability to carry a specific range of products based on demand requirements helps optimise inventory levels and reduces the need for excessive stock transfers.

Route Optimisation: Companies may integrate their Mobile warehouses with route optimisation algorithms or software to plan the most efficient delivery routes. By considering factors such as customer locations, traffic conditions, and delivery time windows, businesses can optimise routes to minimise fuel consumption, travel time, and vehicle wear and tear. This optimisation helps reduce transportation costs and improve overall operational efficiency.

Timely and Reliable Delivery: Mobile warehouses enable faster response times to customer orders, especially in areas with low population density or limited access to traditional distribution centres. By positioning mobile warehouses strategically, businesses can ensure timely and reliable delivery, enhancing customer satisfaction and reducing the costs associated with failed or delayed deliveries.

Reduced Infrastructure Dependency: Mobile warehouses offer flexibility without relying heavily on fixed infrastructure. Instead of investing in permanent brick and mortar facilities, businesses can leverage mobile warehouses as a cost-effective alternative. This eliminates the need for maintaining and managing multiple physical locations, reducing operational expenses such as rent, utilities, and property maintenance.
Scalability for Seasonal Demand: Mobile warehouses are particularly beneficial for managing seasonal demand fluctuations. During peak periods, businesses can deploy additional mobile warehouses to handle increased order volumes efficiently. This scalability allows for better resource allocation and cost optimisation, preventing overburdening of existing infrastructure during high-demand periods.

Overall, mobile warehouses provide a versatile and cost-effective last-mile delivery solution by improving proximity to customers, optimising inventory management, reducing transportation costs, and offering scalability. By addressing key cost drivers in the last-mile delivery process, mobile warehouses help businesses enhance their operational efficiency, reduce expenses, and ultimately provide a better customer experience.

1.2.3 Is mobile warehouses useful for large or small businesses?

Mobile warehouses can be beneficial to both large and small businesses because their benefits are not fixed to a specific company size. Large corporations, such as Amazon, frequently must manage complex supply networks and large inventory levels. Mobile warehouses can help them be more flexible and agile in their logistical operations. They can strategically place mobile warehouses in various places to optimise distribution and better fulfil consumer demand. This enables large corporations to improve their last-mile delivery capabilities, cut costs, and boost customer satisfaction.

Consequently, small enterprises may encounter resource and infrastructure constraints. They can save money by using mobile warehouses instead of traditional stationary warehouses or distribution centres. Small businesses might employ mobile warehouses to expand their reach, especially in places where permanent facilities may not be possible or cost-effective. Mobile warehouses allow small firms to modify their operations based on demand swings, allowing them to service customers in different places effectively. Small businesses can eliminate the need for large warehousing infrastructure and associated costs by utilising mobile
warehouses, making it a feasible choice for improving their last-mile delivery capabilities.

While it may appear that using mobile warehouses in numerous locations is more advantageous than using them in a single city, its acceptance would depend on the businesses' individual operational requirements, market conditions, and long-term goals, independent of their size. Such as the geographical spread of the target market or client base and economic considerations in utilising a mobile warehouse, as it may be more cost-effective to collaborate with other LSP.

Overall, the usefulness of mobile warehouses is not limited to the size of the firm or the number of cities they operate in. Both big and small firms can benefit from the flexibility, cost savings, and improved customer service offered by mobile warehouses as a last-mile delivery solution.

### 1.3 Objectives of the Study

The aim of this thesis is to identify the feasibility of using mobile warehouses in mid-sized urban and rural regions for last-mile transportation and to evaluate their last-mile costs.

### 1.4 Research Question

Considering the mentioned challenges faced by logistic providers, this paper aims to explore the feasibility of using mobile warehouses for mid-sized urban/rural regions based on a category of product, such as perishable/non-perishable and the last-mile transportation costs that would keep these retail stores competitive and in business.

As such, the following research questions will be answered:
Research question 1: What are the types of mobile warehouses that are best suitable for the perishable/non-perishable category of products in Dalarna County, Sweden?

Research question 2: What would be the estimated last-mile transportation costs for the mobile warehouses used in Dalarna County, Sweden?

1.5 Contribution of the Study

This study on the use of mobile warehouses for last-mile transportation in mid-sized urban and rural areas presents a unique and useful contribution to the subject. This study fills a gap in the existing literature by examining the problems and opportunities related to mobile warehouses in these specific regions.

The value of this study resides in its ability to provide insights and recommendations for firms, particularly those involved in e-commerce, wanting to optimise their last-mile transportation in mid-sized urban and rural areas. The findings can assist firms in lowering the cost of last-mile delivery, increasing efficiency, and improving customer satisfaction. Furthermore, the study can help with specific issues associated with low population density, socioeconomic conditions, and demographic traits peculiar to these places.

This work adds to the theoretical knowledge of last-mile transportation and supply chain management in the setting of mid-sized urban and rural regions. The study improves the knowledge base on creative solutions for last-mile delivery by studying the role of mobile warehouses in addressing the issues faced in these areas. A theoretical understanding of how mobile warehouses can reduce last-mile delivery costs and improve operational efficiency is enhanced by examining elements such as closeness to end customers, flexibility and scalability, effective inventory management, route optimisation, and timely delivery. The study also investigates the applicability of mobile warehouses to businesses of all sizes, providing insights into their benefits and limitations for both large and small organisations.
In summary, the value of this study rests in its practical implications for firms operating in mid-sized urban and rural areas, providing recommendations on optimising last-mile transportation using mobile warehouses. Furthermore, studying the unique constraints and opportunities in these regions contributes to the theoretical knowledge of last-mile delivery and supply chain management. By solving these issues, the study hopes to promote more efficient and cost-effective last-mile transportation, which will benefit businesses, customers, and the logistics ecosystem as a whole.
Chapter 2. Literature review

Mobile warehouses have gained popularity as a last-mile delivery alternative to help with last-mile delivery due to the explosive rise in e-commerce. Trucks may transport mobile warehouses to multiple locations, giving firms a flexible and adaptive way to distribute goods quickly and effectively to customers (Srivatsa S. et al., 2021). However, using mobile warehouses in mid-sized and rural areas poses several challenges. The market size and customer base in these areas are small, which could affect the demand for goods. With a smaller market size, businesses may face challenges in achieving economies of scale and maximising operational efficiency. Other challenges using mobile warehouses include precise demand forecasting to fulfil online orders from customers promptly (Mangiaracina R. et al., 2019), a lack of storage space, route and location optimisation, technological requirements for the temperature or humidity levels needed to store certain items, and regulatory compliance (Mohammad et al., 2023).

In our literature exploration, we found that there are not many publications that explored mobile warehouses. However, in B2C e-commerce, mobile warehouses have been applied as solutions to improve last-mile delivery efficiency.

2.1 What can be considered a mobile warehouse?

2.1.1 Mobile Trucks

Mobile trucks are sizable, enclosed vehicles that may be driven to various locations (Srivatsa S. et al., 2021). They have ample space to hold a large variety of products. A mobile truck's major function is to provide on-site storage capabilities, allowing for quick inventory access and management. Some vehicles have temperature-controlled systems to ensure proper storage conditions. They are useful as a last-mile delivery option since they provide mobility and flexibility in reaching various locations. A fundamental distinction between mobile trucks and conventional trucks is that a mobile truck concentrates on providing temporary on-site storage, whereas a traditional truck primarily transports items between different places (Srivatsa S. et
al., 2021). It is commonly used to transport goods from a Distribution Centre or Warehouse to retail establishments, enterprises, or end users.

Trucks were used as mobile warehouses in their paper (Srivatsa S. et al., 2021) to solve the problem of getting vaccines to remote and underserved areas, which was helpful. Utilising them increased coverage while reducing waste. One of the major benefits outlined in their paper for using a mobile warehouse was the potential to provide the product needed to the client fast without incurring extra expenditures, as opposed to if it were created from a typical warehouse. Electricity, labour, and rental costs are decreased. The study also gives an analytical model that can be used to determine whether a mobile warehouse can handle deliveries or not. Figure 1 explains how the products are delivered to customers and replenished between mobile warehouses.

![Flowchart](image)

**Figure 1** – B2C e-commerce provider’s operations in the presence of a mobile warehouse (Srivatsa S. et al., 2021)
In addition, (Banker, S., 2020) demonstrated how 'The Amazon Effect' has revolutionised everything in the world of e-commerce. This entails a subscription fee model for guaranteed delivery durations based on a set expenditure level. Customers prefer that pricey items and perishables be delivered within a 2-hour span. This was accomplished by increasing the number of smaller warehouses in large urban areas. These smaller warehouses function as distribution facilities, sorting customer orders by destination zone and consolidating them into trucks for faster delivery.

However, little research has been conducted on the practicality of mobile warehouses in medium-sized and rural areas. Sousa et al., 2020, proposed outsourcing last-mile delivery in rural areas, but they did not consider using mobile warehouses.

2.1.2 Mobile Depot (MD)

The term mobile warehouse can take multiple forms, one of them being mobile depots. Mobile depots are also a concept which provides mobility for delivering finished goods to customers. The paper “Does a mobile depot make urban deliveries faster, more sustainable and more economically viable: Results of a pilot test in Brussels” (Verlinde, S. et al., 2014) discusses the mentioned concept. A Mobile Depot (MD) is a trailer that includes a loading dock, warehousing space, and an office. The trailer is loaded with all deliveries for the day at the start of each business day and driven to a central parking spot in the city. Dispatch riders make the final deliveries from there (Fig. 2).
Essentially, mobile depots are trailers which are used for delivery operations, such as picking up the goods and delivering them, which can be argued that it functions similarly to a mobile warehouse. In the article, the authors have conducted a case study in Brussels, a large urban city that shows great use for the urban regions. However, one limitation of their work is that they have also not considered rural areas in their studies.

Furthermore, additional setup costs are discussed in the article, such as the trailer itself. In this case, the trailer needs to have a loading dock, warehousing facilities, and an office, which would come up with increasing costs of designing such a concept and maintenance for it as well. Therefore, we consider that this logistics solution is not a suitable choice for solving our research questions.

### 2.1.3 Mobile Parcel Lockers (MPL)

This is a different form of mobile warehouse. These parcel lockers are installed on a truck, as opposed to the fixed parcel lockers seen in public settings. See Fig. 3a (Deutsch & Golany, 2017). Figure 3b shows a schematic sketch of a Mobile Parcel Locker. They are adaptable and can switch locations during the day to reach their...
clients based on their location (Schwerdfeger & Boysen, 2020). Customers access their packages by entering a one-time passcode, barcode, or QR code, which is communicated to them via a smartphone app through their mobile phones.

Unlike mid-sized mobile trucks with cargo capacities of 20m$^3$ (Li, A., 2023; Wellpack, 2022), mobile parcel lockers feature multiple compartments and are designed to contain at least 96% of all packages intended to be delivered to the parcel locker (Van Duin, R et al., 2019). For example, Instabox, a logistics firm that provides e-commerce deliveries in Sweden, runs over 1,500 parcel lockers throughout the Nordic region. Their largest box, which fits into the locker, measures 40 x 40 x 60 cm and has a capacity of 0.096 m$^3$ (Instabox, 2023).

In their study (Schwerdfeger & Boysen, 2020), they compared the benefit of using mobile parcel lockers to their stationary counterpart in serving customers, which revealed up to 400% more stationary lockers to serve customers compared to using mobile lockers to cover the area, representing a significant cost saving on setting up stationary parcel lockers. However, obtaining appropriate parking space to offer secure customer access and additional stress on public infrastructure in the form of increased traffic on the streets is a drawback to using this last-mile delivery option. The study focuses on urban regions with limited space and high population density.
as a convenient alternative to home delivery by offering a centralised site for package pick-up. It does not explore its usage in rural areas.

2.2 Benefits and drawbacks of mobile warehouse solutions

In Appendix A, we described the current mobile warehouse solutions that we have reviewed and analysed them by considering their advantages and disadvantages. As a last-mile delivery option in response to the rise of e-commerce, mobile warehouses, such as mobile trucks, provide mobility, flexibility, and storage capacity, making them well-suited for reaching a variety of locations, including remote and underserved areas. They enable speedier delivery, lower operating costs, and can take a wide range of commodities, including those requiring temperature control. Mobile warehouse solutions in mid-sized and rural areas, on the other hand, face challenges such as limited market size, demand forecasting, storage capacity restrictions, route optimization, and regulatory compliance.
Chapter 3. Methodology

This chapter outlines the methodology employed in this thesis research project, which aims to explore the use of mobile warehouses in mid-sized urban and rural regions for last-mile transportation. A literature review will be carried out to investigate our first research question on mobile warehouse solutions used for perishable/non-perishable product categories in Dalarna County. While a mathematical model would be formulated using the generalised cost function based on the work of Gevaers et al. (2014) to estimate the last-mile cost for our second research question.

3.1 Literature Review on Mobile Warehouse Solutions for Perishable/Non-perishable Products

Further literature searches for relevant articles focused on mobile warehouse solutions and their application for delivering perishable and non-perishable products for lastmile deliveries, revealed that the most common solutions were mobile trucks and depots. They were employed in several vehicle routing problem variants when delivering perishable and non-perishable products (Mangiaracina, R. et al., 2019; OrjuelaCastro, J.A. et al., 2019). Multi-temperature trucks and cold packing (Tsang, Y. P. et al., 2020; Yang, C. et al., 2023) were used to monitor the temperature of perishable products using fuzz logic knowledge repository technology. The trucks were also used as innovative last-mile solutions, such as consolidating products (Hagberg & Hulthén, 2022) to meet consumer demand. Furthermore, combining various transportation means for last-mile parcel delivery (Viu-Roig & Alvarez-Palau, 2020; Rashidzadeh, E. et al., 2021; Cano, J. A. et al., 2022), such as drones, due to their limitation of flight time, payload capacity and alternate power sources. As a novel last-mile concept, mobile parcel lockers were the least featured solution (Liu, Y. et al., 2021). It can permit variable delivery to clients' locations and boost customer accessibility depending on the product's kind. Table 2 summarises our review of mobile warehouse solutions based on our literature search.
### Table 1 – Literature review of mobile warehouse solutions

<table>
<thead>
<tr>
<th>Source</th>
<th>Mobile Warehouses</th>
<th>Product Type[^1]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mobile Truck</td>
<td>Mobile Depot</td>
</tr>
<tr>
<td>Bosona, T. (2020)</td>
<td>x</td>
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<tr>
<td>Cano, J. A. et al. (2022)</td>
<td>x</td>
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<tr>
<td>Hagberg &amp; Hulthén (2022)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Liu, Y. et al. (2021)</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Mangiaracina, R. et al. (2019)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Orjuela-Castro, J.A. et al. (2019)</td>
<td>x</td>
<td></td>
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<tr>
<td>Rashidzadeh, E. et al. (2021)</td>
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<td>Romanowski, R. et al. (2022)</td>
<td>x</td>
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<tr>
<td>Silva, V. et al. (2023)</td>
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<tr>
<td>Tsang, Y. P. et al. (2020)</td>
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<td>Viu-Roig &amp; Alvarez-Palau (2020)</td>
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<tr>
<td>Yang, C. et al. (2023)</td>
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</table>

[^1]: P: Perishable, NP: Non-Perishable
3.2 Generalised Cost Function

Gevaers et al. (2014) suggested a generalised cost function that may be used to evaluate and simulate last-mile logistics expenses. It considers different cost factors or features that influence the overall cost of last-mile delivery. These cost drivers include things like consumer service level, security and delivery type, geographical area and market density, vehicle fleet and technology used, and environmental impact. Estimating and analysing the potential cost implications in various circumstances is attainable by adding these factors into the cost function.

Several factors influenced this study’s decision to use the generalised cost function. Firstly, the framework created by Gevaers et al. (2014) is specifically customised to handle B2C last-mile logistics, which is a good fit with the emphasis of this thesis research. Second, the cost function considers a complete collection of cost drivers established by a thorough analysis of the literature and expert interviews. This guarantees that the research includes all the important elements driving last-mile logistics costs in urban and rural areas. Furthermore, the generalised cost function offers a systematic approach to simulating costs per unit delivered, allowing comparison of various scenarios and alterations in last-mile features. It allows for incorporating special variables and coefficients associated with mobile warehouses, which are crucial to this research area. By integrating the mobile warehouse concept into the cost function, we can evaluate its impact on last-mile logistics costs and determine the estimated cost-effectiveness of utilising mobile warehouses in mid-sized urban and rural regions.

3.2.1 Mathematical Model – The Cost Function

The paper "Cost Modelling and Simulation of Last-mile Characteristics in an Innovative B2C Supply Chain Environment with Implications on Urban Areas and Cities” (Gevaers et al., 2014) can answer our research aim and the second research question. The authors start by emphasising that B2C last-mile logistics is “the final leg in a business-to-consumer delivery service whereby the consignment is delivered to the recipient, either at the recipient’s home or at a collection point”.

20
They start by discussing the standard distance and time cost function, which can be seen below:

\[ TC = T \times t + D \times d + Z \]

Where:

- \( TC \) is the total transportation cost.
- \( T \) is the duration/time of the transport
- \( t \) is the time/hour coefficient
- \( D \) is the distance driven/travel for the transport
- \( d \) is the distance coefficient
- \( Z \) is the extra costs not related to distance and/or time

The generalized cost function mathematical model will be employed in this investigation. We will then develop the model using the data we have available and implement the model specified later in this chapter.

### 3.3 Geographical Location

Our thesis research on evaluating last-mile transportation costs for mobile warehouses is centred on Dalarna County, Sweden. This decision is based on data from the region and is also motivated by the fact that the County is in central Sweden northwest of Stockholm and has a varied landscape, ranging from mountains in the north along the Norwegian border to plains with lakes in the centre and south. Paper, pulp, iron, and steel dominate the economy's industrial base. It is also a well-known tourist attraction (Landré, 2012). The context of Dalarna County is essential for understanding the geographical, demographic, and socio-economic characteristics of the region under study.

Dalarna County is located in central Sweden. It is bounded by the counties of Gävleborg, Jämtland, Västmanland, Örebro, and Värmland and consists of fifteen
(15) municipalities, which can be seen in Figure 4. The physical location of the county is conveniently positioned within the country's transportation network (Wikipedia, 2023).

Figure 4 – Municipalities of Dalarna County (Wikipedia, 2023)

In comparison to Stockholm County, Sweden's capital, which has a population of 2.44 million as of 2022, Dalarna County has a population of 288,310, contributing to the county's socioeconomic dynamics and transportation requirements (Statista, 2023).

The population is split between mid-sized urban and rural areas, with various levels of population density between municipalities. The county comprises a large land area with a variety of geographical features. Dalarna County has a total land area of around 28,188.80 km², including various natural landscapes like forests, lakes, and mountains. The population density in Dalarna County varies per municipality. While mid-sized metropolitan regions have higher population densities, rural areas have lower population concentrations. The population density element is critical in assessing the county's market size and demand trends for last-mile logistics.

Dalarna County benefits from a well-developed transportation infrastructure, including road networks and railways. Major highways and arterial roads connect various municipalities and facilitate the movement of goods and people. The
availability and quality of transportation infrastructure influences the efficiency and cost-effectiveness of last-mile transportation operations. There is a diverse range of economic activities and industries which characterise Dalarna County (Nilsson, L., 2014). Traditional sectors such as mining, forestry, and manufacturing coexist with modern sectors like information technology, tourism, and services.

Overall, the population, land mass area, population density, transportation infrastructure, and economic activity of the county serve as the foundation for analysing the region's specific logistical issues and prospects. We can acquire useful insights into optimising last-mile logistics operations in Dalarna County, Sweden, by investigating these characteristics.

3.4 Datasets

For our implementation, we have encountered very few choices of datasets, however, we have decided to adopt one through a mid-size logistics company.

The obtained datasets consist of 2 tables. The first table consists of delivery routes, and the second table consists of delivery stops. The company used mobile phones to monitor and collect GPS (Global Positioning System) or geospatial data from the delivery routes and stops during 2018. The data was collected in Dalarna County, Sweden.

Using an obtained dataset can limit the creation of delivery scenarios. For this, we have decided to create a synthetic dataset, that would replicate the company’s dataset structure, to explore new possibilities of routes and discover new delivery scenarios.

Certain tools were utilized to manipulate the datasets and to explore them. Excel program, which is part of the Microsoft Office Suite, was one of the primary tools used to store the data. The QGIS (QGIS Development Team, 2023) program was used to visualize the data from a geospatial standpoint, with features such as using
real maps as a background cover layer. Based on the original dataset collected from the logistics company, the ArcGIS application platform was also used to generate fresh delivery data. Python was also used to generate the vehicle movement data, as well as for file conversion and the EDA (Exploratory Data Analysis).

Both datasets are presented, in detail below in subchapters 3.4.1 and 3.4.2, respectively.

### 3.4.1 Dataset obtained from the logistic company

As mentioned, the obtained data set consists of two tables, the first one containing delivery route data and the second one containing delivery stops data. These are explored in the upcoming sections.

#### 3.4.1.1 Delivery Routes Table

The delivery routes tables consist of 3 routes, which were conducted by drivers who had to deliver products to certain locations as well as to supply other trucks. The data that we collected was organised into 3 CSV (Comma-Separated Value) files. Table 2 displays the dataset structure of one route, showcasing the variables, their data type and a short description. The same structure is applied to the rest of the delivery route datasets.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Data Type</th>
<th>Short Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>Object</td>
<td>Driver’s Route Name</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Integer</td>
<td>Vehicle’s year</td>
</tr>
<tr>
<td>Date &amp; Time</td>
<td>Object</td>
<td>The recorded date &amp; time</td>
</tr>
<tr>
<td>Latitude</td>
<td>Float</td>
<td>The recorded latitude, used in geographical data</td>
</tr>
<tr>
<td>Longitude</td>
<td>Float</td>
<td>The recorded longitude, used in geographical data</td>
</tr>
</tbody>
</table>

Table 2 – Delivery route dataset structure
Before we proceeded further, certain steps had to be done to make sure that we would deal with an optimal dataset, those steps being:

- Renaming the “Driver” column into “Route” and assign the value of the number of routes for each table, for example “Route_1”.
- Concatenating the 3 CSV files and converting them into a single table as the main dataset
- Dropping the “Vehicle” as its data was not relevant

With the concatenating data, the EDA (Exploratory Data Analysis) was conducted in order to check for missing values, duplicated values or anything else that may influence our further methodology. With a total of 5 variables and 1275 observations, the concatenated dataset had no issues that required correction.

Using the QGIS software, we can visualize the data, as in figure 5.
Figure 5 – Map of the delivery routes, with the first and third route’s data being displayed on QGIS. The red route is the first delivery track, and the green route is the third.

For the other routes we have obtained similar results as in Figure 5.

In table 3 the time that was conducted for each route is shown.

Table 3 – Table of estimated travelled time per route.

<table>
<thead>
<tr>
<th>Delivery Route</th>
<th>Estimated Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1</td>
<td>2 hours and 40 minutes</td>
</tr>
<tr>
<td>Route 2</td>
<td>20 minutes</td>
</tr>
<tr>
<td>Route 3</td>
<td>1 hour and 40 minutes</td>
</tr>
</tbody>
</table>

3.4.1.2 Delivery Stops table

The delivery stops table consists of the stops that were conducted by the drivers from each route. Initially, the table was saved in an SHP (shape) file format, which
could be opened only with the QGIS software. However, a Python library called geopandas, was used to import the data from the SHP file into a geodata frame. Table 4 displays the dataset structure of the stops, showcasing the variables, their data type and a short description.

Table 4 – Delivery Stops dataset structure.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Data Type</th>
<th>Short Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>Object</td>
<td>Driver’s Name</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Integer</td>
<td>Vehicle’s Year</td>
</tr>
<tr>
<td>Date &amp; Time</td>
<td>Object</td>
<td>The recorded date &amp; time</td>
</tr>
<tr>
<td>Latitude</td>
<td>Float</td>
<td>The recorded latitude, used in geographical data</td>
</tr>
<tr>
<td>Longitude</td>
<td>Float</td>
<td>The recorded longitude, used in geographical data</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>Integer</td>
<td>The vehicle’s speed in terms of kilometres per hour, measured at precise time</td>
</tr>
<tr>
<td>Layer</td>
<td>Object</td>
<td>Reference to the Delivery Route</td>
</tr>
<tr>
<td>Date &amp; T_1</td>
<td>Object</td>
<td>Date of the Delivery Stop</td>
</tr>
<tr>
<td>Time</td>
<td>Object</td>
<td>Time of the Delivery Stop</td>
</tr>
<tr>
<td>Field_10</td>
<td>Object</td>
<td>Time zone</td>
</tr>
<tr>
<td>T or F</td>
<td>Object</td>
<td>Boolean value</td>
</tr>
<tr>
<td>Path</td>
<td>Object</td>
<td>File path of the data</td>
</tr>
</tbody>
</table>
Generated by the geopandas library to record the geographical point composed of latitude and longitude values

Before we proceeded further, certain steps had to be done to make sure that we would deal with an optimal dataset, those steps being:

- Removing the following columns: driver, vehicle, field_10, T or F and Path, as we have no use for them in our analysis.
- We assign the values from the “Layer” column into the “Driver” column, as it categorizes the observations by the delivery route
- We dropped the column of “Layer”, shortly after the previous step
- We renamed the “Driver” column into “Route”

With the imported data, the EDA was conducted in order to check for missing values, duplicated values or anything else that may influence our further methodology. With a total of 8 variables and 17 observations (or stops), the dataset had no issues that required correction.

Like in the delivery route dataset, we have been able to display the location of the stops on the QGIS, this can be observed at figure 6.
Furthermore, we decided to combine the 2 tables into a single one as the delivery stops are organized by the delivery routes. For this, we made the decision to rearrange both of the tables to have the same structure.

### 3.4.2 Generated Synthetic Dataset

As previously said, we have decided to replicate the company's dataset structure in order to produce a synthetic dataset that would allow us to investigate alternative delivery scenarios in a variety of contexts or routes.
The synthetic dataset is generated in two stages. First, a delivery stops dataset was established, and then a synthetic delivery route dataset was generated based on the selected stops. The steps are described in the following sections.

### 3.4.2.1 Selection of the delivery stops data

Delivery stops, unlike delivery routes data, which consists of multiple observations that follow a vehicle's journey, can be selected manually using Google Maps or QGIS. Before doing so, two directions were chosen for the delivery possibilities, which are discussed in section 3.5.1. The following stops were chosen depending on the routes that were chosen:

- The first selected route consists of the following key locations: Borlänge, Hede, Romme Alpin, Smedjebacken, Ludvika and Falun. The end of this route is back at Borlänge.
- Second route consists of the following locations: Falun, Boda, Vikarbyn, Rättvik and Laknäs. The end of this route is back at Falun.

As a result, we can see that various sites and directions will be noticed from these two routes, particularly in the southern, south-west, and northward regions of Dalarna, from Borlänge. Unlike the previous dataset, which exclusively explored the westward region from Borlänge, our new dataset addresses the other geographical directions.

The selected stops can be observed in the figure below.
As previously stated, these stops were chosen randomly by hand using Google Maps or QGIS. The manually obtained data comprises of geolocation data (such as latitude and longitude values) and the location's name.
3.4.2.2 Generation of delivery routes data

Following the selection of delivery stops in the preceding stage, the data was loaded into the ArcGIS Network Analyst, an extension or add-in within the ArcGIS software, which is a commercial or proprietary GIS (Geographical Information System) desktop software, used to perform routing analysis (Esri, 2023). The ArcGIS Network Analyst tool was used to perform routing and find the optimal delivery routes between the various manually selected delivery locations or stops. One advantage of employing the aforementioned tool is that it may generate vehicle movement data between the designated stops while taking existing infrastructure into account. In this way, we also highlight one of the key differences between the datasets. The obtained dataset was created by monitoring the driver’s movements, through a GPS mobile app, while in this synthetic dataset, an algorithm was used to determine the best delivery route. The QGIS was also used partly for visualization.

Because two directions were examined in the previous part, two new routes were developed using ArcGIS software. The results are shown in the image below.
Figure 8 – The two new generated routes, using ArcGIS.
3.4.2.3 Tools that were used for creating the dataset

Google Maps, ArcGIS, and the Python programming language were previously discussed. The new dataset was created using ArcGIS and Google Maps, and the movement of a vehicle along each route was generated using Python. The movement in this instance consists of time, distance, and speed. The use of these tools and software in the creation of the dataset will be covered in this section.

As previously mentioned, we started by manually choosing the delivery stops for our new dataset, which consisted of their coordinate values for latitude and longitude. We chose the World Geodetic System (WGS84) as the coordinate system and imported the information into the ArcGIS program. This data was then stored as a SHP file, for easier processing in Python.

Next, we generated the mapped routes based on the locations we had chosen, having already stored the delivery stops. To do this, the ArcGIS Network Analyst tool was used to find the shortest path between each site of the stops. Using ArcGIS to produce the routes has the benefit of accounting for the current infrastructure and producing travel routes appropriately.

Python was used to import the data using the saved SHP files. The code was created to accomplish two goals: it was to determine the total distance travelled and the amount of time spent on each route; also, it was to determine the vehicle's speed for each data point derived from the delivery routes table.

A vehicle's speed was mostly generated using the delivery route data. It should be noted that the delivery route data is arranged into route coordinates, which are separated into latitude and longitude. The code first iterates over the data based on this input, calculating the distance to the next point in the data while employing a random speed that imitates the original dataset. The code also employs spatial data intersection to determine circumstances when a vehicle is approaching an intersection; in this case, the slowing of the speed as one vehicle approaches the respective location is simulated. Acceleration from the previous stop is likewise
simulated. The same idea applies to delivery stops, and the data is kept in a column called "Speed (km/h)" alongside the rest of the route data.

Following the generation of the speed data, several steps were carried out in order to calculate the total distance and time for the synthetic dataset. The geodetic formula Vincenty was used to compute the distance between two places on the Earth's surface, as well as their different latitudes. The formula is based on the WGS-84 ellipsoid, which is a popular approximation for the shape of the Earth. It calculates distances over large distances more accurately than simpler approaches, such as the Haversine formula, which assumes a spherical Earth (Lawhead, J., 2015). The Vincenty formula is a complicated mathematical expression that involves numerous trigonometric functions as well as iterative methods. For the second scenario, as previously stated, numerous delivery stops (or points) were chosen. In our solution, we used the vincenty_distance function from Python's geodesic library to compute the trip time and distance between several delivery points in sequential order.

3.5 Implementation of the model

Based on the literature of Gevaers et al. (2014), the model employed in this work would be the cost function. The cost function will be created using a typical general time and distance transport function, with the data provided by the logistic company as well as the synthetic data set. In the absence of reliable data, data from the literature or funded assumptions will be used.

The costs are the last mile B2C, as indicated in paragraph 3.2.1. Delivery at the recipient's house or other specified place as advised by the recipient for pick-up. The cost will be the total cost of delivery along a specified driver's route, with no consideration given to return parcel flow because this information was not made accessible. We begin with the usual transportation cost function arrangement described by Gevaers et al. (2014).
Where:

\[ TC = \text{Total transportation cost (EUR)} \]
\[ T = \text{time/duration of the transport (Hour)} \]
\[ t = \text{time/hour coefficient (EUR/Hour)} \]
\[ D = \text{distance driven/travel for transport (Km)} \]
\[ d = \text{distance coefficient (EUR/Km)} \]
\[ Z = \text{extra cost not related to distance/time (EUR)} \]

Total time costs are determined by multiplying the driver's total driving time by the time coefficient, and total distance costs are computed by multiplying the driver's total driving distance by the distance coefficient. This, together with any additional fees, will result in the total transportation costs for the last mile. In this function, the two different coefficients are critical. The time (t) and distance (d) coefficients can vary depending on the size and payload of the last-mile delivery truck or van. As our mobile warehouse, we evaluated both mid-sized trucks and delivery vans, which would imply different time and distance coefficients, as shown in Table 5. The logistics supplier assessed an additional fee (Z) of EUR10.90.

Our Total Last Mile Cost (TC) is:

\[ TC = T \times t + D \times d + 10.90 \]

**Table 5 - Time & Distance Coefficients (Source: Adopted from Gevaers et al., 2014)**

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Truck (5 tons)</th>
<th>Van (0.5 tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>23.70</td>
<td>22.26</td>
</tr>
<tr>
<td>d</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>Z</td>
<td>10.90</td>
<td>10.90</td>
</tr>
</tbody>
</table>

From Table 5, it can be observed that a van, being the lightest vehicle option, is faster than a truck, therefore it is able to cover more distance.
3.5.1 Simulation Design

Based on the sample delivery route of the Driver obtained from the logistics provider, we would estimate the cost of last-mile transportation with mobile warehouses located in Dalarna County.

In the obtained dataset, we chose Leksand as the location of our mobile warehouse because there are more delivery stations in the area. Furthermore, it is a remote and sparsely inhabited rural town with a strong road and train network to important municipalities in Dalarna, including Borlange and Falun. Based on the delivery routes, a DC is in Borlange. This decision was made because the municipality has the highest population density in Dalarna County. It is roughly 20 kilometres from Falun, the county's administrative capital. It has a strong train network and easy access to the E16 motorway, which connects metropolitan centres, rural areas, and mountain scenery. At the same time, our traditional warehouse would be located at Skedvi Kyrkby in Sater municipality.

As noted earlier in section 3.4.2.3, to further simulate the use of mobile warehouses in other areas of Dalarna County, we performed a routing analysis to get the best route between the delivery stop locations. The reason for using ArcGIS as opposed to manually defining the route is that this would give an optimized route in terms of distance, and the route would be along existing road infrastructure.

The route was used to constrain the simulation of GPS point data, i.e. to make sure the point falls within the route. Simulation of the point involved random estimation of the speed and time, and this was used to calculate the location of the points in a manner that would mirror actual vehicle travel data. The total time duration and the average velocities within the original data were used to provide the ranges for speed and time of the simulated data. This range was an average speed of 49 Km/h from the original dataset with a deviation of ± 3 Km/h.

The generated synthetic data delivery routes extended southward to facilitate delivery from the DC up to Ludvika, a rural community with industrial and economic significance. The town is home to Hitachi Energy (Hitachi, 2023), a
global business with expertise in automation, robotics, and heavy electrical equipment. Its location in Dalarna makes it a transportation hub within the region. Another route towards north – east, i.e., from Falun, where another mobile warehouse would be situated, distributing to Rättvik and its surroundings. Rättvik is a famous tourist location, particularly during the summer. It's on the banks of Siljan Lake, one of Sweden's largest and most beautiful lakes. Dalhalla, Europe's most spectacular outdoor music venue, is located in this rural location (Dalarna, 2023). People travel from all over Sweden to attend the concerts, which take place primarily between June and early September. Consequently, propelling economic activity during this time. It is accessible by automobile, and it is connected to neighbouring towns and cities via local roads and highways.

3.5.2 Simulation Scenario

We determined that the last mile cost estimate would be simulated using two scenarios. The original delivery routes provided by the logistics company, and two other delivery routes from our generated synthetic data. The synthetic data allows us to investigate a broader range of situations, such as various traffic patterns and road network infrastructure, that may not be present in the original data sets. It also enables us to extrapolate findings beyond the specific routes provided by the logistics company, providing insights that may be applied to a broader range of scenarios or places.

In each scenario, we would use a delivery truck and a mobile warehouse and compare the cost-benefit of employing a mobile warehouse to using only a delivery truck.

Our delivery routes for calculating the total last-mile cost that would be employed in this scenario are as follows:

Scenario 1 (Using Original Dataset): The delivery route covers between Sater municipality to Leksand municipality.
TC\textsubscript{X}1= Covers total cost distributing between Gagnef to Sater municipality by the truck, delivers to the Mobile Warehouse located at Leksand, and returns to the distribution centre (DC) in Borlänge. All of this is performed by one driver.

TC\textsubscript{X}2= Covers total cost distributing within Leksand and its environs with the Mobile Warehouse located at Limsjögården in Leksand municipality. This is performed by a different driver from the previous TC\textsubscript{X}1.

TC\textsubscript{X} = Covers total cost distributed along the whole delivery route from Sater to Leksand municipality by truck, with the traditional warehouse located in Skedvi Kyrkby at Sater municipality. This is performed by one driver only.

Scenario 2 (Using Synthetic Dataset): The delivery route covers between Ludvika and Rättvik municipalities.

TC\textsubscript{Y}1= Covers total cost distributing between Ludvika to Falun municipality by the truck, delivers to the Mobile Warehouse located at Falun, and returns to the distribution centre (DC) in Borlänge. All of this is performed by one driver.

TC\textsubscript{Y}2= Covers total cost distributing from Falun to Rättvik and its environs with the Mobile Warehouse located at Stigaregatan in Falun municipality. This is performed by a different driver from the previous TC\textsubscript{Y}1.

TC\textsubscript{Y} = Covers total cost distributed along the whole delivery route from Ludvika to Rättvik municipality by truck. All of this is performed by one driver.

Google Maps and Excel were used to compute the Generalized Cost Function Model, which would estimate the total cost of last-mile delivery in Scenario 1. Google Maps was used to compute the overall travel distance and time, and Excel was used to perform the calculations of the last mile cost of TC\textsubscript{X} routes. Similarly, in Scenario 2, the Python programming language was used to compute the overall travel distance and time using the Vincenty formula, and Excel was used to perform the calculations of the last mile cost of TC\textsubscript{Y} routes.
Chapter 4. Results and Discussion

The outcomes of the methodology's analysis are presented in this section to address our research questions and will be followed by a discussion.

4.1 Findings on Mobile Warehouse Solutions for Perishable/Non-perishable Products

Our literature search revealed no studies on mobile warehousing solutions for perishable/non-perishable products conducted in the setting of Dalarna County, Sweden. However, based on our review of the available literature, we believe Mobile Trucks best fit the perishable/non-perishable product category in Dalarna County. This is based on its use in other European regions and is simple to put in place. Furthermore, because the region is sparsely inhabited and has a low population density, the mobile truck, as a mobile warehouse solution, provides the benefits of visiting various remote locations with quick delivery and lower operational expenses.

Overall, our analysis of the literature reveals that mobile trucks are the best type of mobile warehouse for last-mile distribution of perishable/non-perishable products in Dalarna County, Sweden. This solves our first study research question and pushes us to employ this mobile storage solution to estimate the cost of last-mile delivery in Dalarna County.

4.2 Interpretation of the results

In this section, we will display the results and interpret them, to answer our second research question.

As stated in Chapter 3, we investigated two scenarios for our simulation to assess the entire estimated cost of a delivery. We used a mid-sized truck to make deliveries on
the TC_X1 route. A truck will also make deliveries on the TC_Y1 route using our synthetic dataset. In both scenarios, delivery vans would function as mobile warehouses on the TC_X2 and TC_Y2 routes, stocked by trucks covering the TC_X1 and TC_Y1 routes, respectively. The simulation is also compared to the TC_X and TC_Y routes to determine the expected cost benefits of using a mobile warehouse along the routes rather than a truck.

The results can be observed in the table below.

**Table 6 – Scenario 1: Simulation results**

<table>
<thead>
<tr>
<th>Model Variables</th>
<th>TC_X</th>
<th>TC_X1</th>
<th>TC_X2</th>
</tr>
</thead>
<tbody>
<tr>
<td>D - Distance (Km)</td>
<td>305.00</td>
<td>246.80</td>
<td>58.60</td>
</tr>
<tr>
<td>d - distance coefficient (EUR/Km)</td>
<td>0.23</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>T - Time (Hr)</td>
<td>5.00</td>
<td>3.05</td>
<td>1.87</td>
</tr>
<tr>
<td>t - time/hour coefficient (EUR/hour)</td>
<td>23.70</td>
<td>23.70</td>
<td>22.26</td>
</tr>
<tr>
<td>Z - Extra Cost</td>
<td>10.90</td>
<td>10.90</td>
<td>10.90</td>
</tr>
<tr>
<td><strong>Total Cost (EUR)</strong></td>
<td><strong>199.55</strong></td>
<td><strong>139.95</strong></td>
<td><strong>61.90</strong></td>
</tr>
</tbody>
</table>

Table 6 demonstrates that adding our mobile warehouse solution to cover the TC_X route increases the total estimated cost of delivery by EUR2.30, or EUR201.85 (TC_X1 + TC_X2), as compared to using a truck on the route, which is EUR199.55.

For the entirety of the TC_X routes in Scenario 1, the logistic company provided the total distance, D, and time, T, of 305.00 km and 5.00 hours, respectively. This information was gathered via the GPS mounted on the vehicle during the delivery routes. We used Google Maps to collect the estimated distance 58.60Km, D, and time 1.87 Hrs., T, along the routes of the delivery stops in order to compute the total estimated last-mile delivery cost by deploying a mobile warehouse on the TC_X2 route. Using the transportation cost model described in Section 3.5 and the appropriate distance and time coefficients, we calculated the total estimated last-mile cost to be EUR61.90. Similar computations and comparisons were performed for the TC_X and TC_X1 routes.
Adding a mobile warehouse solution to the TC\textsubscript{Y} route, on the other hand, reduces the total estimated cost of delivery by EUR5.41, or EUR 246.15 (TC\textsubscript{Y1} + TC\textsubscript{Y2}), as compared to using a truck on the route, which is EUR251.56, as shown in Table 7.

<table>
<thead>
<tr>
<th>Model Variables</th>
<th>TC\textsubscript{Y}</th>
<th>TC\textsubscript{Y1}</th>
<th>TC\textsubscript{Y2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>D - Distance (Km)</td>
<td>309.59</td>
<td>150.02</td>
<td>159.57</td>
</tr>
<tr>
<td>d - distance coefficient (EUR/Km)</td>
<td>0.23</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>T - Time (Hr)</td>
<td>7.15</td>
<td>3.58</td>
<td>3.57</td>
</tr>
<tr>
<td>t - time/hour coefficient (EUR/hour)</td>
<td>23.70</td>
<td>23.70</td>
<td>22.26</td>
</tr>
<tr>
<td>Z - Extra Cost</td>
<td>10.90</td>
<td>10.90</td>
<td>10.90</td>
</tr>
<tr>
<td><strong>Total Cost (EUR)</strong></td>
<td><strong>251.56</strong></td>
<td><strong>130.25</strong></td>
<td><strong>115.90</strong></td>
</tr>
</tbody>
</table>

Unlike Scenario 1, where the routes were developed by GPS based on the driver's intuition, in Scenario 2, routes were generated using the ArcGIS software, which optimized the routes along the delivery stops, based on the current road network only. It did not consider real-time factors such as accidents, obstructions, etc. The Vincenty formula, which calculates the differences in distance between two locations on a spheroid's surface, was used to calculate the estimated last-mile cost of deploying a mobile warehouse on the TC\textsubscript{Y2} route. The estimated distance, D, was 159.57 km, and the estimated time, T, was 3.57 hours, along the optimized routes of the delivery stops using the Python dedicated library. Similarly, we estimated the total last-mile cost to be EUR115.90 using the transportation cost model given in Section 3.5 and the necessary time and distance coefficients. For the TC\textsubscript{Y} and TC\textsubscript{Y1} routes, similar calculations and comparisons were carried out.

The results of both scenarios showed that mobile warehouses in strategic locations such as Leksand in Scenario 1 and Falun in Scenario 2, for last-mile distribution incur the lowest transportation costs but offer the most significant cost benefits overall by lowering the total delivery costs by EUR5.41 when located in Falun to cover distributions to sparsely delivered locations up to Rättvik.
In scenario 1, it's clear that adding a mobile warehouse (TC\(_X\)2) raises the total estimated cost of delivery compared to using a truck (TC\(_X\)). This is counterintuitive, and it's critical to understand why. The TC\(_X\)2 route was based on the logistics provider's actual data, capturing the driver's intuition. In contrast, TC\(_Y\)2 routes were generated using ArcGIS optimization. While adding a mobile warehouse (TC\(_X\)2) has a greater total delivery cost, the broader ramifications must be considered. This path is not only shorter, but also far more efficient in terms of time. When optimized at critical areas, mobile warehouses can significantly cut delivery time, which is especially important for businesses striving to fulfill tight delivery schedules. The distinction between TC\(_X\)2 and TC\(_Y\)2 also suggests that mobile warehouses may be less effective in urban-like environments such as Leksand, where delivery sites are more concentrated, and standard trucks may suffice. Mobile warehouses appear to be most useful in remote or sparsely populated areas, where optimizing routes with them might result in significant cost reductions.

Scenario 2 yields better results for mobile warehouses. TC\(_Y\)2, which employs a movable warehouse, reduces the overall total estimated cost of delivery when compared to TC\(_Y\). This shows that, in some cases, mobile warehouses can be a cost-effective alternative. The use of route optimization tools like ArcGIS and Python's dedicated libraries for route estimation is critical. These tools allow for the creation of efficient routes, which significantly impact costs. It's essential to note that mobile warehouses' effectiveness is highly dependent on route efficiency as well as the weight of the delivery vehicles, which might alter the distance coefficient, as observed in Table 5.

Following our analysis of the results based on the various situations, we can conclude that:

- Mobile warehouses are particularly effective in remote or sparsely populated regions, where route optimization can lead to significant cost savings and

- Mobile warehouses can help meet tight delivery schedules, making them suitable for businesses with time-sensitive deliveries.
However, they also have their drawbacks, which includes:

- Mobile warehouses, particularly trucks, may not be the best solution in densely populated or urban-like areas where delivery points are closely clustered;

- Effective use of mobile warehouses requires route optimization tools to ensure efficient routes and cost savings;

- The success of mobile warehouses is highly dependent on strategic locations. As our scenarios revealed, locating the mobile warehouse at Falun reduced the overall estimated total delivery cost, compared to that located at Leksand, and

- Operating mobile warehouses can be more complicated than traditional delivery methods, with careful planning and administration, especially in terms of additional operating expenditures such as additional drivers and vehicle maintenance.

According to the simulation results, mobile warehouses can be a powerful tool for optimizing last-mile delivery, especially in remote or sparsely populated areas with less efficient routes. However, their success depends on route optimization and the specific characteristics of the delivery area. Employing mobile warehouses should be considered on a case-by-case basis, taking into account the unique logistics needs and challenges of the region in question.

### 4.3 Limitations of the work

The simulation was developed with random delivery locations and assumed consistent distance coefficients (EUR/Km) and time coefficients (EUR/hour) for all routes. In actuality, these coefficients may change based on factors such as road conditions, truck type, traffic, and weather, and may not accurately reflect the intricacies of all delivery scenarios. In addition, the study relied on simulated data, which may not indicate real-world conditions.
Furthermore, while the study primarily focused on cost concerns, other considerations such as environmental impact and other stakeholders such as customer satisfaction, logistics providers, and government may influence the decision to deploy mobile warehousing solutions.

While using the ArcGIS solution to determine and generate the optimum delivery route between the delivery stops, it also requires manual input from the user, especially when dealing with traffic bottlenecks or blocks. This may have an impact on the development of the optimum delivery routes, as the user must be aware of long-term road upgrades and modifications. This can also have an effect when a driver is pursuing a predetermined route but encounters unanticipated traffic jams or roadblocks, rendering the route inefficient for delivery.

Another limitation of using the ArcGIS software is that it does not consider the type of terrain when simulating the delivery routes. Hilly regions can have an impact on the vehicle’s speed, which can affect the overall covered distance.

More studies might be conducted to examine a broader range of scenarios with more thorough breakdowns, such as fuel, labour, maintenance, and mobile warehouse operations, in order to provide insights into cost savings and to use real-world data to improve the accuracy of cost estimations.
Chapter 5. Conclusion

The study investigates the viability of using mobile warehouses as a solution to the complex difficulties of last-mile transportation in mid-sized urban and rural areas. Our research objectives were to evaluate the feasibility and effectiveness of using mobile warehouses, as well as their last-mile costs. The results reported in this conclusion highlight the significance of these goals in improving last-mile delivery efficiency, particularly in the context of the ever-changing e-commerce business.

Our journey began with the establishment of the basic research objectives, which were:

- What types of mobile warehouses are suitable for different product categories in Dalarna County?
- What are the estimated last-mile transportation costs associated with these mobile warehouses?

In response to these questions, our research shows that movable warehouses, particularly mobile trucks, have great promise for last-mile delivery in Dalarna County, Sweden. The applicability of mobile warehouses is determined by the nature of the products being delivered as well as the product life, which might be short or long.

Mobile trucks are an ideal solution for products with a short shelf life, such as fresh produce, dairy, and bakery items. Their mobility and capacity to reach remote places provide consumers with freshness and proximity, answering the special needs of these categories. Non-perishable commodities such as electronics, household appliances, and apparel with longer shelf life, on the other hand, can benefit from mobile warehouses when reaching customers in sparsely inhabited areas. These mobile warehouses can cover larger delivery areas more efficiently and provide proximity to areas with lower population density.
Based on the nature of the items and the geographical parameters of the delivery area, our study shows that different types of mobile warehouses can be ideal for various product categories. Mobile trucks are ideal for perishable items, whilst other forms of mobile warehouses may cater to long-lasting products while optimizing delivery in various regions.

A variety of factors influence last-mile transportation costs, including the choice of mobile warehouse solution, route optimization, and the geographical characteristics of the delivery location. Our modeling results revealed unexpected implications on our scenarios. Contrary to expectations, employing a mobile warehouse for last-mile transportation is slightly more expensive (by EUR2.30) than using a truck across the delivery routes in our Scenario 1. The mobile warehouse reduced total delivery costs by EUR5.41 in Scenario 2. However, the report emphasizes that mobile warehouses significantly reduce delivery costs in rural areas such as Leksand due to shorter transit distances and times with closely clustered delivery points and optimizes delivery routes for longer transit distances and times with sparsely delivered locations such as Rättvik. Overall, our findings indicate that good route planning and mobile warehouse utilization might result in substantial cost savings in some cases.

The practical implications of our research point to the potential benefits that businesses operating in mid-sized urban and rural regions can gain by embracing mobile warehouses. These benefits encompass cost savings, efficient last-mile delivery, and enhanced customer service. We advise cautious planning and the use of route optimization tools to businesses considering the usage of mobile warehouses. These tools are critical for boosting mobile warehouse efficiency and assuring cost-effectiveness. The mobile warehouse solution chosen should be in accordance with the specific characteristics of the product categories being transported as well as the geographical peculiarities of the area served.

While our research provides helpful insights, it is important to recognize its limitations, which include the use of simulated data and assumptions in the cost model. To address these constraints, future studies should include a broader range
of scenarios and broaden the scope of analysis to include aspects other than cost, such as environmental effects and stakeholder considerations.

In conclusion, our study illuminates the potential benefits of overcoming last-mile delivery issues in mid-sized urban and rural areas. Businesses may offer efficient, cost-effective, and customer-centric delivery solutions that adapt to the varying needs of different product categories by embracing mobile warehouses. This work is important beyond the academic realm since it has practical ramifications for businesses and the logistics industry as a whole. The lessons learnt here emphasize the important role of mobile warehouses and efficient last-mile delivery in satisfying the demands of customers in varied geographies as firms traverse the ever-expanding world of e-commerce. To improve delivery efficiency, firms must remain open to new ideas, adapt to unique geographical and product-based needs, and capitalize on the possibilities of mobile warehouses.
References


## Appendix A

Table A1 – Current mobile warehouse solutions

<table>
<thead>
<tr>
<th>Reviewed Solutions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Mobile Trucks      | • Mobility and Flexibility: Mobile trucks can be driven to various locations, allowing for greater reach and adaptability in last-mile delivery operations. They can access diverse places, including remote and underserved areas.  
• Storage Capacity: Mobile trucks offer sufficient room to store a sizable number of different items. They can accommodate a variety of products, including those requiring temperature-controlled conditions, ensuring the integrity of goods during transportation.  
• Fast Delivery: Mobile trucks enable faster delivery to customers, especially in areas where traditional warehouses may be distant. They bring the products closer to the end-users, reducing delivery times and improving customer satisfaction. | • Limited Capacity: While mobile trucks offer storage space, they have limitations on the total capacity they can carry compared to larger stationary warehouses. This may restrict the volume of goods that can be transported in a single trip.  
• Road Restrictions: Mobile trucks are subject to road restrictions and regulations, including weight limits, size restrictions, and access limitations in certain areas. These restrictions can affect the efficiency and flexibility of last-mile delivery operations.  
• Maintenance and Operational Challenges: Mobile trucks require regular maintenance and operational management, including fuelling, vehicle inspections, driver scheduling, and route planning. Managing a fleet of mobile trucks can be complex and may require additional resources. |
| Mobile Depot | • Cost Savings: Using a mobile warehouse in the form of a truck can help reduce operational costs compared to traditional warehousing. Expenses such as electricity, labour, and rental costs may be decreased or eliminated, leading to cost savings for businesses. |
| Mobile Depot | • Space Constraints: Mobile trucks may have space constraints depending on their size and configuration. This can limit the types of products that can be transported and the overall storage capacity available. |
| Mobile Depot | • Mobility and Flexibility: Mobile depots, in the form of trailers, offer mobility in delivering finished goods to customers. They can be transported to different locations, allowing for flexibility in reaching diverse areas within an urban region. |
| Mobile Depot | • Efficient Urban Deliveries: The case study conducted in Brussels (Verlinde et al., 2014) highlights the effectiveness of mobile depots for urban regions. They can help improve the efficiency of last-mile delivery operations in densely populated areas where traditional warehouses may be limited or inaccessible. |
| Mobile Depot | • Limited Scope: Mobile depots are primarily suitable for urban regions and may not be as viable or effective in rural areas. The case study mentioned in the article focuses on urban deliveries, and the authors have not considered the application of mobile depots in rural settings. |
| Mobile Depot | • Setup Costs: Implementing a mobile depot requires additional setup costs, such as designing and equipping the trailer with a loading dock, warehousing facilities, and an office. These setup costs can be significant and may impact the economic viability of using mobile depots as a last-mile delivery option. |
| Mobile Depot | • Potential Sustainability Benefits: Mobile depots can contribute to sustainability by... |
| **Mobile Parcel Lockers** | **Mobility and Adaptability:** Mobile parcel lockers installed on trucks offer mobility and adaptability in reaching customers based on their location. The lockers can switch locations during the day to serve different areas, increasing convenience and accessibility.  
**Cost Savings:** The study by Schwerdfeger and Boysen (2020) highlights cost savings in using mobile parcel lockers compared to stationary lockers. It revealed that a smaller number of mobile lockers could cover the same area as a significantly larger number of stationary lockers, resulting in cost savings on setting up and  
| **Maintenance and Operational Complexity:** Mobile depots require regular maintenance and operational management, including the need for trained personnel, monitoring storage conditions, and ensuring proper inventory management. The complexity of managing a mobile depot system adds to the logistical challenges  
| **Parking Space Requirement:** One drawback of using mobile parcel lockers is the need for appropriate parking space to accommodate the truck and provide secure customer access. Finding suitable parking locations can be challenging, especially in urban areas with limited space and high population density.  
**Increased Traffic and Infrastructure Stress:** The presence of mobile parcel locker trucks on the streets can contribute to increased traffic and put additional stress on public infrastructure. This can have implications for road congestion and the overall functioning of the transportation system. |
| Maintaining stationary locker infrastructure. | Limited Application in Rural Areas: The study focuses on urban regions as a convenient alternative to home delivery. It does not explore the usage of mobile parcel lockers in rural areas, where the infrastructure and population density may differ, potentially limiting their applicability. |
| Convenient and Secure Package Pickup: Mobile parcel lockers provide a centralised site for package pick-up, offering convenience to customers. Customers can access their packages using a one-time passcode, barcode, or QR code, ensuring secure retrieval of their items. |