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On the way to the electric transition of road and air transport

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On the way to the electric transition of road and air transport

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Travail de fin d'études présenté par
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en vue de l'obtention du diplôme de
Master en sciences de gestion à finalité spécialisée en management général

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ABSTRACT

Global warming due to human activity is starting to cause concern. A multitude of endeavours are being actively pursued to mitigate the release of greenhouse gases, with the overarching objective of attaining carbon neutrality by 2050, in alignment with the European Commission's Green Deal initiative. These endeavours predominantly target sectors that make substantial contributions to greenhouse gas emissions, among them is the transport sector. In response, a range of technological solutions are viable. Among these, a particularly promising avenue is the shift from conventional heat engines to electric motors. The field being vast, only road and air transport is studied in the frame of express deliveries. However, for this initiative to attract investors and develop faster, this transition to electric technologies must have a financial advantage compared to the current situation. This leads to the first research question of this thesis: Does transitioning to electric technology in the domain of express delivery, both for air and road transport, yield significant financial benefits?

In parallel, as the reliability of autopilot systems continues to improve and ensure robust flight safety, airlines are becoming increasingly inclined to explore opportunities for reducing or even eliminating onboard pilots as a cost-saving measure. Hence, the second research question explored in this thesis aims to quantify the potential advantages that could arise from such crew reduction strategies. This inquiry encompasses scenarios ranging from transitioning from two pilots to one, and in the extreme case, the full implementation of autonomous flight. In the same idea, the feasibility of eliminating drivers in the context of road transport is also being investigated.

Keywords: Electrification, air & road transport, Vehicle Routing Problem, Optimisation

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NOMENCLATURE

API Application Programming Interface

ATAG Air Transport Action Group

CVRP Capacited VRP

DCVRP Distance-Constrained VRP

DP Dynamic programming

EU European Union

FDP Flight Duty Periods

FTL Flight and Duty Time Limitations

GHG Greenhouse Gas

GTR Giant-Tour Representation

MCVRP Multiple compartment VRP

MMA Maximum Authorised Weight

TRL Technology Readiness Level

TSP Travelling Salesman Problem

TWVRP Time Windows VRP

VRP Vehicle Routing problem

VRPPD VRP with Pickup and Delivery

1

INTRODUCTION

1.1 Motivation & Aim

Global warming and the increase in greenhouse gases have become major concerns for the planet, with the potential to cause irreversible damage to the environment and human society. Being mainly caused by the development of economies and the rising consumer society, it is very likely that the latter will continue to grow in the coming years. Indeed, from energy production to agriculture and livestock through transportation, in all these areas the demand is growing leading to increase the supply of them. As a result, more and more grassroots activism and global politics tend to react to global warming caused by human activity. In particular, aviation has been identified as a major contributor after the Paris Agreement on climate. Indeed, the latter is responsible for 2.6% of greenhouse gas emissions in the world in 2018. In addition, its fuel combustion alone corresponds to approximately 1 billion tonnes of CO_2 per year, i.e. in order of magnitude the equivalent of Japan's emissions, which is far from being insignificant (Stéphane Amant, 2022).

In October 2021, ATAG (Air Transport Action Group) set itself the goal of achieving carbon neutrality by 2050[1]. This objective is compatible with the Paris Agreement on climate aiming to maintain the increase in global temperature of 1.5°C by the end of the century compared to pre-industrial temperatures (Safran, 2021). To this end, aircraft and engines manufacturers are looking into several promising technologies, such as the development of engines that can use biofuels or even hydrogen (that should emerge around 2035) or secondly, the electrification of the latter. Although electric aviation has so far only been intended for very small aircraft with small payloads and short distances, the latter is gradually growing in size, payloads and range thanks to improvements in electric motors and, above all, in batteries.

Eviation is one of the pioneer manufacturers in the challenge of aviation electrification to offer an aircraft, called *Alice* (Fig. 1.1) that can carry up to 9 passengers or a cargo capacity of up to approximately one ton. Moreover, the range is about 450 km which is adequate for regional transport with zero carbon footprint. Hence, this is starting to make sense for small cargo carriers or small private jets. Actually, civil transport companies such as Cap Air or DHL for freight transport have already placed orders to receive and use them around 2027.

From experience an electric engine is more efficient and less expensive in maintenance than a thermal engine. Then, it is believed that this is the factor that could reduce the cost of air transportation. Nevertheless, the weight of the batteries is the limiting part on flight autonomy, the loading capacity and requires a lot of time to recharge. It is therefore of interest

1 Carbon neutrality is defined as the state where the production of CO_2 generated by human activity does not exceed the capacity of the atmosphere to absorb CO_2 and through carbon capture actions.

to see quantitatively with today's means if electric planes can be economically profitable or not compared to thermal engines ones.

Figure 1.1: Eviation Alice.

The subject of study being vast, this thesis will focus only on the case of cargo transport. In the field of logistics, air transport is considered to be a rather luxurious means of transport compared to others (road, river, or rail). However, over long distances, it proves to be an efficient way to serve customers more quickly. In reality, to respond to the explosion of online retail, large logistics companies plan to increase the transport of air freight (Stéphane Amant, 2022). Consequently, the aim of this thesis is to study the installation of an express cargo distribution network using electric aviation.

Secondly, nowadays, with the existence of very reliable and efficient autopilots, airline companies are pushing to legalise one-pilot cockpits instead of two to save costs on their high salaries. Towards the end of the decade, the first commercial flights could begin with a one-pilot cockpit (Hughes, 2022). Nonetheless, these flights will first have to be tested on cargo flights since fewer civilians are in danger. This thesis will analyse the impact that it can have on the costs of reducing the crew or even making it completely autonomous. Therefore, see if this is a real advantage and how much is it compared to current flights with two-pilots cockpits.

Finally, given the extensive use of road transport in logistics as well as the environmental efforts to transition towards electrification, a similar profitability study to that of electric aviation is carried out. As a result, the analysis will reveal whether it is cost-worthy to electrify road transportation. Then, again as in the case of aviation, the impact of the reduction in driver staff is studied by making the vehicles autonomous this time.

1.2 Covered topics

The next chapter will focus on the state of the art for this study i.e. on solving the so-called Vehicle Routing Problem (VRP) known in logistics to find optimal paths from warehouses containing a group of vehicles in order to dispatch all customers. First, the VRP will consider the European regulations concerning the maximum number of flight hours and daily working hours for pilots (referred to as flight duty periods). Subsequently, equivalent European regulations for drivers will be examined and integrated into the VRP.

During this work, electric aviation will be constantly compared to aviation with thermal engines. In order to answer the question of whether the cost of air transport can be reduced by electric aviation, two similar airplanes in size and payloads are chosen. In Chapter 3, the airplanes considered for the analyses will be presented with its technical specifications. Then, the rest of the chapter is devoted to the modelling of the VRP i.e. the cities, opening/closing hours of the customers and the different costs taken into account and injected into the VRP.

In Chapter 4, the results of various simulations will be presented. As previously stated, the analysis will commence with a comparison between electric-powered vehicles and their thermal-engine counterparts. Subsequently, the study will explore the impact of different cockpit/divers configurations, including two pilots/drivers (applicable to planes only), one pilot/driver, or autonomous systems.

Finally, conclusions will be drawn on whether electric-powered transport does indeed have an economic advantage in addition to being environmentally friendly compared to the heat-powered one. However, before closing this first introductory chapter and get to the heart of the matter, a PESTEL analysis is carried out.

1.3 PESTEL ANALYSIS OF THE ELECTRIC TRANSITION OF AVIATION

While electric road transport has made significant progress for light and medium-weight vehicles, this is less the case for the aviation. The PESTEL analysis will primarily concentrate on the shift towards electric aerial transport. The issue of reducing the number of crew members is not addressed, as it closely resembles the PESTEL analysis conducted in Volvert's thesis (Volvert, 2020). The latter focused on studying the various effects that a shift from conventional trucks to autonomous trucks, meaning without pilots, could potentially bring about in road transport.

Politic factors: To complete the electric transition of air transport, the private sector needs public authorities to put in place fair and effective regulations around CO_2 emissions from air transport (Safran, 2021). With the European Council establishing the the European Green Deal aiming to reduce the greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, and achieve climate neutrality by 2050, the European climate law has been introduced. To accomplish these ambitious goals, EU member states must implement specific measures to decrease emissions and transition to a low-carbon economy. As a result, the implementation of new rules and updates to existing EU legislation are essential to make the green transition a tangible and achievable reality (European Council, 2023).

On December 9, 2022, Clément Baune, the Minister of Transport in France, unveiled a funding initiative aimed at supporting the decarbonisation of the air transport industry, quoting *"The decarbonisation of aviation is not an option, it is an obligation"*. Hence, the French government has allocated 435 million euros from 2023 to invest in measures to reduce carbon emissions within the air transport sector (Gouvernement, 2022).

The ”Clean Sky” public-private partnership was established in 2008 as a collaborative technological endeavour funded by the European Commission and industry, with a budget of 1.6 billion euros allocated over seven years, reaching 4 billion euros in 2014. This expansive research initiative unites over 900 entities from 27 countries with the primary goal of developing advanced technologies to limit CO_2 emissions, air pollution, and noise generated by the aeronautics sector (Safran, 2021).

Therefore, among these two non-exhaustive examples, it is clear that a reaction is being made gradually on the part of the public authorities to fight against CO2 emissions.

Economic factors: As introduced in the Policy factors, more and more funding and budget is allocated to the development of greener technologies in order to decarbonise the aviation. In addition, the aviation sector expects a return to pre-COVID conditions of 2019 in 2025 with a number of 11.1 million flights during that year i.e. an increase of 2 million flights compared to 2022 (Eurocontrol, 2022).

Then, the International Air Transport Association (IATA) anticipates a rise in the profitability of the airline industry. Here are some expectations (IATA, 2023):

- The projected net profits for the airline industry in 2023 are anticipated to reach 9.8 billion dollars, with a net profit margin of 1.2%, which is more than double the previous forecast of 4.7 billion dollars made in December 2022.
- Cargo volumes are expected to reach 57.8 million tons.
- Total revenues are projected to experience a year-over-year growth of 9.7%, reaching 803 billion dollars. This will mark the first time the industry’s revenues have surpassed the 800 billion dollars milestone since 2019 when they amounted to 838 billion dollars. Moreover, expense growth is expected to be limited, with an annual increase of 8.1%.

In addition to these forecasts, it can be said that the electrification of aviation will allow savings in operating costs. Indeed, electric aircraft has lower operating costs in comparison to traditional fossil fuel-powered aircraft. The reason lies in the fact that electricity is generally cheaper than aviation fuel, resulting in reduced fuel expenses for airlines and lower costs for air travel. Moreover, in the coming years, with the deployment of renewable means of electricity production, the price of the latter could decrease while that of fuel oil would tend to increase. Furthermore, electric aircraft typically have fewer moving parts and simpler propulsion systems than conventional aircraft. This simplicity translates to lower maintenance costs, as electric motors generally require less maintenance and have longer lifespans than internal combustion engines. During a conversation with a technical representative from Eviation at the International Aeronautics and Space Show in Le Bourget, it was estimated that there could be a significant reduction of approximately 30% in maintenance costs.

Finally, as with any innovation, electric aviation could create new job opportunities, particularly in research and development. Then, given its shorter range and lower noise level, electric aviation could allow reaching destinations less visited by air and increase regional connectivity. The latter could therefore help boost local tourism and stimulate economic growth in these regions. To a lesser extent, Environmental and Health Cost Savings as electric aviation would pollute the air less. Thus, potentially reducing air pollution-related healthcare costs.

Social factors: From a social point of view, electric aviation can be beneficial in several ways. First of all, the engines of the electric plane are much less noisy than those with combustion. A flight in an electric plane will therefore be much more comfortable for passengers. At the same time, local residents located near airports will be much less disturbed by the noise pollution generated mainly by the aircraft's engines.

In addition, as the electric plane does not emit persistent contrails and cirrus clouds behind it, this will give a direct visual impact for some that the electric plane is much cleaner than fuel-powered planes. This has already been observed in the automotive sector where an electric car seems much less polluting when in use compared to a fuel-powered car, just because it is silent and does not emit smoke through the exhaust pipe. However, it should not be forgotten that certainly electric transport does not emit CO_2 during its use, but during the manufacture of batteries and the generation of electricity, a significant amount of CO_2 is emitted.

Technological factors: Within the aerospace industry, the standard practice for assessing the maturity of a technology involves using the Technology Readiness Level (TRL). This level is illustrated in the Fig. 1.2.

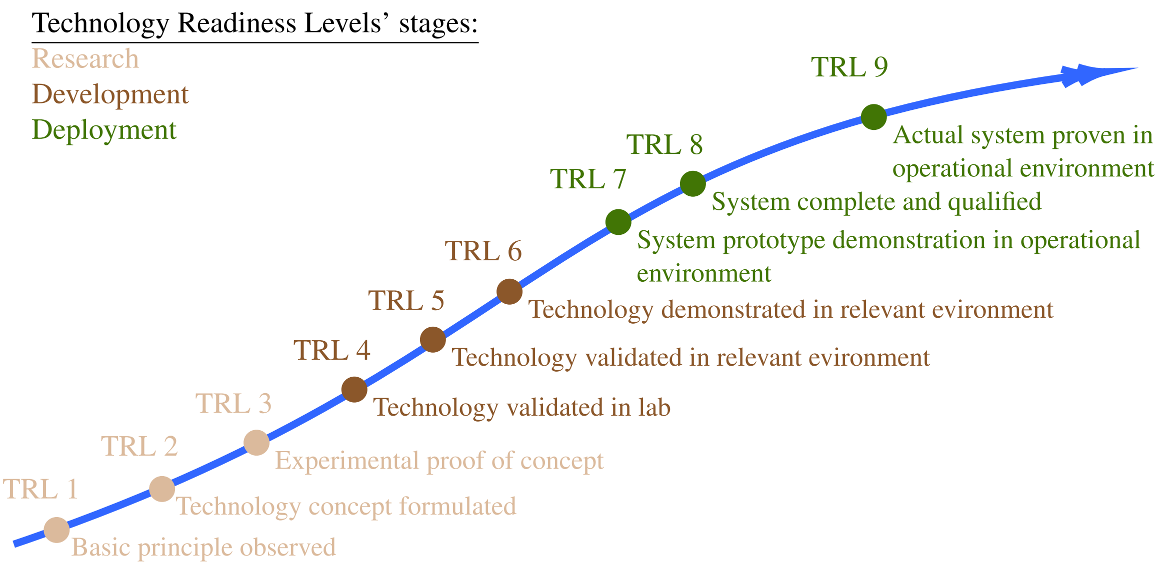


Figure 1.2: Technology Readiness Levels in aerospace industry

As depicted, the scale used for assessing technology readiness is a 9-step continuum, ranging from 1 to 9, where a TRL of 9 indicates full maturity and successful validation. In the electric aviation domain, small aircraft with one to two seats and limited payload capacity have already reached the deployment stage. However, medium and large aircraft in this sector are still in earlier stages and necessitate further research and development. As shown in Fig. 1.3, NASA's recent report on electric propulsion reveals that electric propulsion technology is currently at TRL 5-6, indicating that now and until 2025, the final stages of the development phase will be addressed, and if everything progresses as planned, the transition to deployment will follow soon after.

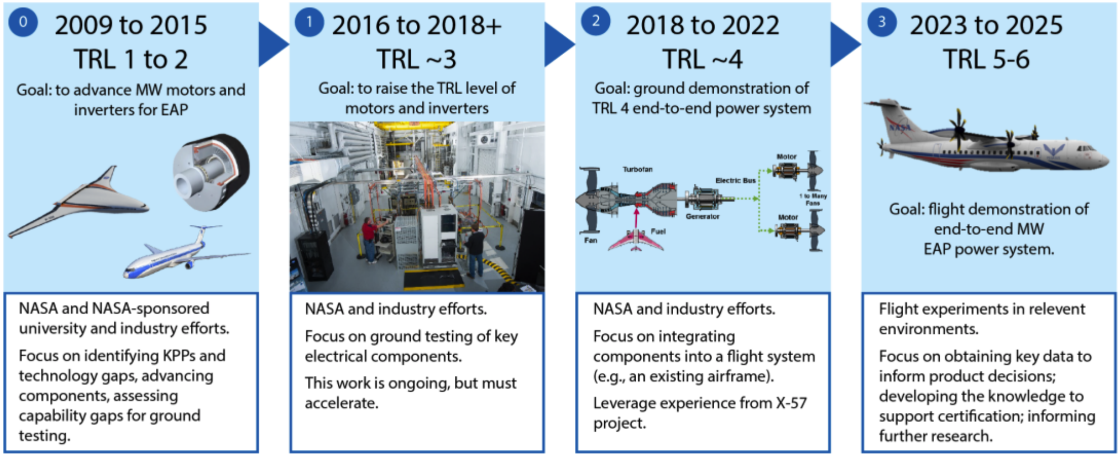


Figure 1.3: NASA's Electrified Powertrain Advancement through Flight Demonstration as of January 2023 (NASA, 2023)

From a technological standpoint, electric propulsion for larger aircraft engines has reached a level of maturity that makes its implementation in the near future feasible. As for the autonomy of these aircraft, advancements in energy storage, particularly batteries, will be essential. Notably, a significant breakthrough is anticipated with the emergence of solid-state batteries, expected towards the end of this decade, which should have the potential to double the energy storage mass capacity (Xia, Wu, Zhang, Cui, & Liu, 2018).

Environmental factors: At the environmental level, as illustrated in Fig. 1.4 the transport sector accounted for 23.2% of greenhouse gas emissions in Europe in 2020, closely following energy industries at 23.3%. Among all sectors emitting greenhouse gases, 74% is attributed to fuel combustion. It is therefore crucial to prioritise the replacement of fuel usage in sectors where it is possible with other energy sources that produce little to no greenhouse gas emissions. This is precisely the objective of the European Green Deal initiative introduced by the European Commission, aiming to achieve greenhouse gas neutrality in Europe by 2050. Fortunately, as previously mentioned, renewable technologies are in a relatively advanced state, and continuous improvements in efficiency are expected in the coming years, providing a promising outlook for the success of the Green Deal, particularly in the transport sector, encompassing both aviation and road transport.

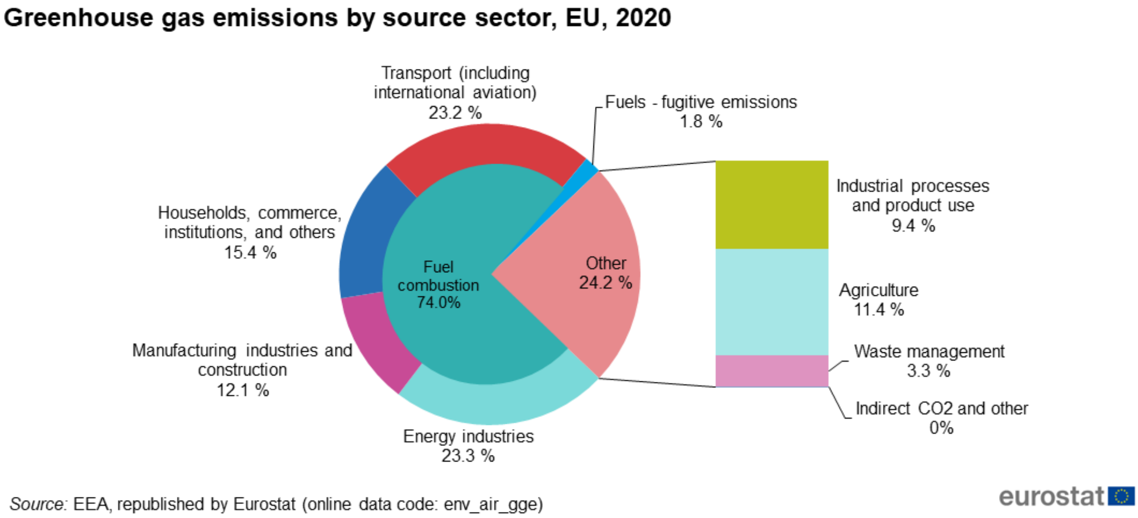


Figure 1.4: Greenhouse gas emissions by source sector in the European Union in 2020 (Eurostat, 2020)

Legal factors: Initially, most legal factors affecting electric aviation are likely to be already addressed by those governing traditional fuel-based aviation. However, if any alterations occur in the legal framework, they are expected to favour electric aviation, given the substantial efforts being invested by political and private entities in transitioning the aviation sector to emit fewer CO_2 emissions. On the other hand, potential challenges for electric aviation may arise in the area of regulation and certification of these novel aircraft. Ensuring safety and airworthiness may lead to considerable costs in the event of modifications to certification standards.

2

STATE OF THE ART

In order to test the efficiency and cost-effectiveness of electric aviation compared to thermal aviation in the logistics field, nothing better than a practical situation where customers have to be served. At the same time, it is also interesting to be able to compare the cost savings that can be achieved by reducing the number of pilots in the cockpit. As mentioned in the introduction, the state of the art on which this thesis is based is the solution of the Vehicle Routing Problem (VRP).

Programs using this method have already been developed and sold to logistics companies to best dispatch to their customers. According to the vendors of these VRP routing tools, these can offer cost savings between 5% and 30% (Geir Hasle, 2007). This chapter will present the mathematical models used to solve this problem with the assumptions made regarding legislation that can be filled with exceptions and which some of them will be omitted for simplification.

2.1 Mathematical modelling

The Vehicle Routing Problem (VRP) is an extension of the Traveling Salesman Problem (TSP), which is a classic optimisation problem aiming to find the shortest route that visits each city exactly once and returns to the starting point. However, the TSP assumes there is only one vehicle available for the entire trip.

In the case studied in this thesis, there are several vehicles available, and the goal is to determine the most efficient combination of routes for a fleet of vehicles to reach a set of customers for deliveries. This is where the VRP method becomes more relevant because it allows for finding the best routes for multiple vehicles, optimising the entire delivery process.

In this section, the theories presented are mainly derived from the following references: (Toth & Vigo, 2002), (Van Hoorn, 2016). Additionally, it is important to mention that since Volvert's thesis (Volvert, 2020) was also centred on the state-of-the-art of the VRP, this subsection 2.1 on mathematical modeling may be redundant to his thesis.

Both the TSP and the VRP are optimisation problems that fall under the category of NP-hard problems[1], meaning that there are no algorithms capable of providing a solution in polynomial time (Van Hoorn, 2016). To solve this problem it is possible to test all the

1 Optimization problems can be divided into two main categories: Polynomially solvable problems and NP-Hard problems. In the case of polynomially solvable problems, the time complexity for solving them can be expressed as a polynomial function of the input size. On the other hand, NP-Hard problems do not have an algorithm that can represent their time complexity as a polynomial.

possibilities and to find the optimal solution. However, this naive approach called *"brute force"* sees its time complexity increasing tremendously when the number of customers rises. Indeed, the latter is of order $\mathcal{O}((n\text{-}1)!)$ or $\mathcal{O}(((n\text{-}1)/2)!)$ if the distance matrix between all cities is symmetric (which will be the case in this study). Fortunately, advancements in algorithm design have led to the development of more efficient approaches, categorised into two main classes:

- Exact algorithm: which strives to find the best possible solution to a problem, ensuring optimality. However, they might not always exhibit a favourable time complexity, making them potentially computationally expensive;
- Heuristic algorithm: which aims to find a good and feasible solution that is considered as "good enough" for practical purposes but does not guarantee the optimality.

In the case of the resolution of the VRP (also of the TSP), many algorithms have already been developed. These can be rewritten using two different techniques: linear programming and dynamic programming. Each with their advantages and disadvantages, these two techniques are explained in more detail in the following subsections.

2.1.1 Linear programming

As said before, the basic principle is to have a fleet of m vehicles available. Each vehicle $v_i \in V$ belonging to its original depot $o_i \in O$ must visit destinations $d_i \in D$. Note that the depot might not be necessarily unique. Depending on the need and the desired constraints, many variants of the VRP already exist. Among them, here are the most recurrent (Toth & Vigo, 2002):

- Capacited VRP (CVRP): each customer has a need for a quantity q_i as well as the vehicles have a maximum loading capacity of Q_i.
- Distance-Constrained VRP (DCVRP): is a variant of CVRP where for each route the capacity constraint is replaced by a length constraint. This is especially the case for electric-powered vehicles given their more limited autonomy.
- Time Windows VRP (TWVRP): is another extension of the CVRP where each client i must be delivered within a specific time interval. This variant is useful when it is desired to impose delivery during the customer's opening hours. Or in general when a maximum delivery time is set, such as in express deliveries where, for example, the latter must be made within 48 hours.
- VRP with Pickup and Delivery (VRPPD): each customer i is related with two quantities d_i and p_i, representing mixed service of homogeneous goods to be delivered and picked up at customer i, respectively.
- Multiple compartment VRP (MCVRP): the deliveries of each customer are not homogeneous and they need a certain quantity of several types of products.

In this thesis, it will be essentially the attributes of DCVRP and TWVRP that will be implemented to model the case study. However, to show the mathematical formulation of the VRP, the CVRP will be taken as an example since it is the most basic version and the other variants are often extensions of the latter by adding specific constraints. To do this, several modeling approaches are possible, the one presented in this thesis is the one called *"vehicle flow formulation"*[2] which is the most used in the basic versions of the VRP. Note that all the equations presented in this subsection come from Toth & Vigo's book (Toth & Vigo, 2002).

Considering a set N of n nodes representing the location of customers (cities) and whose node 0 represents the unique depot taken into account in this formulation[3] i.e. point of departure and arrival of each vehicle. Each of these nodes are connected by edges $e_{ij} \in E$, thus forming a complete graph $G(N, E)$. Each edge e_{ij} is assigned to a cost c_{ij} which can be either a distance d_{ij} or a time t_{ij}. The variable x is binary, that is to say that if the arc[4] $(i, j) \in E$ representing the route from node i to j is part of the optimal path the latter will be equal to 1 in the other cases it will be equal to 0. The cost minimisation equation can be expressed according to Eq. 2.1.

$$\min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}, \tag{2.1}$$

which is subject to the following constraints:

$$\sum_{i \in N} x_{ij} = 1 \quad \forall j \in N \backslash \{0\} \tag{2.2}$$

$$\sum_{j \in N} x_{ij} = 1 \quad \forall i \in N \backslash \{0\} \tag{2.3}$$

$$\sum_{i \in N} x_{i0} = K \tag{2.4}$$

$$\sum_{j \in N} x_{0j} = K \tag{2.5}$$

$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S) \quad \forall S \subseteq N \backslash \{0\}, S \neq \emptyset \tag{2.6}$$

$$x_{ij} \in \{0, 1\} \quad \forall i, j \in N \tag{2.7}$$

The first two constraints, as indicated in equations Eq. 2.2 and Eq. 2.3, guarantee that each node is limited to just two connections, namely the node that comes before it and the node that follows it. Moreover, these two constraints also show that only one vehicle can serve a single customer. Then, constraints in Eq. 2.4 and Eq. 2.5 fix the number K of vehicles available starting from the depot (Eq. 2.4) and returning to the depot at the end of the cycle (Eq. 2.5). On the other hand, Eq. 2.6 is an additional equation ensuring the connectivity of the solution as well as the loading capacity of the vehicles. Indeed, this expresses the requirement is that every cut $(V \backslash S, S)$, where S is a customer set, must be intersected by at least $r(S)$ arcs, which corresponds to the minimum number of vehicles required to serve set S. Eq. 2.6 can be reformulated differently according to the objectives and the contexts such as eliminating the subtours based on the constraints proposed by Miller, Tucker, and Zemlin

2 Two other models are also available: *"commodity flow formulation"* and the *"Set-Partitioning Problem"* for more information see (Toth & Vigo, 2002).

3 The case with multiple depot is considered as an extension of the case with a unique one. It's formulation can be found in Toth & Vigo's book (Toth & Vigo, 2002).

4 An arc is simply called in graph theory as an edge directed between two nodes or otherwise called an arrow.

in the solution of the TSP (Toth & Vigo, 2002). In addition, since this formulation represents the CVRP, the constraint of Eq. 2.6 depending on the context can change and express other physical values than the loading capacity of the vehicle. Finally, the last constraint Eq. 2.7, imposes the variable x_{ij} to be binary. It is important to mention that various exact and heuristic algorithms are available and can be utilised for solving this system of equations[5].

This formulation proves to be straightforward to apply when the solution cost can be represented as the sum of costs linked to the arcs, and the constraints are directly defined as *flows* between the clients (nodes) of the graph G. However, as these constraints can only be expressed as equality or inequality, which may not always be possible, this formulation becomes tedious when more complex additional constraints need to be added.

Note that the presented VRP formulation Eq. 2.2 - Eq. 2.7 is the extension of TSP Dantzig, Fulkerson and Johnson (Toth & Vigo, 2002). Indeed, the formulation of the TSP can be found by setting the number of vehicles available $K = 1$.

2.1.2 Dynamic programming

Dynamic programming is a problem-solving technique that recursively decomposes a problem into sub-problems, known as states, and computes the optimal solution based on the optimal solutions of these sub-problems. The approach works particularly well for problems where the solution can be represented as a sequence of nodes, and the objective is to find the best sequence. As said before without dynamic programming, evaluating all sequences using *brute force* would result in an algorithm of $\mathcal{O}((n-1)!)$ regarding time complexity, which is inefficient. However, dynamic programming reduces this effort by evaluating one partial sequence per subset, resulting in an exponential decrease in the effort required to evaluate all sequences compared to a full enumeration approach. To perform the dynamic programming two ways are possible:

- Forward algorithm: which is an approach to solving a problem by starting with the smallest trivial sub-problems and expanding these to solutions for larger sub-problems, until finally arriving at the optimal solution of the whole problem. This approach is based on the principle of optimality, which states that if an optimal solution to a problem can be found using the optimal solutions of its sub-problems, then it is also optimal for the original problem.
- Backward algorithm: is an approach to solving a problem by starting with the whole problem and recursively breaking it down into smaller sub-problems, until the sub-problems become trivial. This approach is also based on the principle of optimality, but in contrast to the forward algorithm, it starts from the larger problem and works its way down to the smallest sub-problems.

Both forward and backward algorithms can be used to solve problems using dynamic programming, and the choice of approach depends on the problem at hand and the preferences of the user. In this thesis, forward algorithm has been chosen i.e. the smallest trivial sub-problems are tackled first, then their solutions are used to solve increasingly larger sub-problems until the complete problem is solved.

5 In matlab, the *solve* package can be used or *SciPy* in Python.

Hence, this subsection will focus on explaining dynamic programming using the forward algorithm. Most of the explanations, definitions and algorithms come straight out of the book *"Dynamic Programming for routing and Scheduling: Optimizing Sequences of Decisions"* by Van Hoorn (Van Hoorn, 2016). Before going into more detail, some definitions and notations are presented :

Definition 2.1 *A sub-problem, or state, is defined by ξ_ϕ. The subscript ϕ defines the specifics of the sub-problem.*

Definition 2.2 *Let ς denote a solution. With ς_ϕ we define a solution to the sub-problem, or state, ξ_ϕ. By $\check{\xi}_\phi$ we denote an optimal solution to state ξ_ϕ.*

Definition 2.3 *By $\varsigma \rightsquigarrow i$ we denote an expansion in the forward DP algorithm from solution ς with i. This is a new solution of a larger sub-problem. The definition of i depends on the specific problem.*

When solving routing problems such as TSP or VRP, it is crucial to determine a set of nodes N, in this case called customer requests that need to be visited, and a smaller subset $S \subseteq N$. The aim of the algorithm is to find the best solution $\varsigma_N = \check{\xi}_N$ for the state ξ_N that includes a sequence of all the visited nodes. To accomplish this, the problem is broken down into smaller sub-problems, ξ_S, which have an optimal solution $\varsigma_S = \check{\xi}_S$ as previously mentioned.

This time, unlike linear programming, the initial formulation of the algorithm is primarily focused on solving the TSP. Subsequently, specific extensions required for addressing the VRP will be incorporated based on this foundation.

2.1.2.1 Travelling Salesman Problem: algorithm using DP

In the TSP, after finding the optimal solution $\varsigma_S = \check{\xi}_S$ for a particular sub-problem ξ_S, the solution must be expanded to the next node $i \in N \backslash S$. In order to accomplish this, it is necessary to remember the last node l visited within the subset S to calculate the cost c_{li}. Then, the state is updated by adding l as a subscript and the current cost c of the subset as $\xi_{S,l,c}$. As in the previous subsection of linear programming, the starting node s is not included in the subset S because it is common to all possible paths, but the ending node s is included. Thus, the starting point for expanding and resolving the problem is $\xi_{\emptyset,s,0}$, while the end point, which involves returning to the node s, is $\xi_{N,s,c_{total}}$. Therefore, these explanations provided lead to Alg. 1.

Algorithm 1 Forward DP algorithm for the TSP (Van Hoorn, 2016)

Input: An instance of the TSP defined by a complete graph $G = (N, E)$ and a cost c_{ij} (i.e. distance in this case) for all edges $e_{ij} \in E$
Output: A sequence ς associated with an optimal route for the TSP

$\check{\xi}_{\emptyset,s} = \varsigma_{\emptyset,s,0} = \langle\rangle$

for $L = 0$ ***to*** $|N| - 1$ **do**
  for *all* $S \subset N$ ***such that*** $|S| = L$ **do**
    $S' = S$
    if $S = \emptyset$ **then**
      $S' = \{s\}$ `// Ensure` $\check{\xi}_{\emptyset,s}$ `is expanded`
    for *all* $i \in S'$ ***such that*** $\check{\xi}_{S,i} \neq \emptyset$ **do**
      for *all* $j \in N \backslash S$ **do**
        if $j \neq s$ ***or*** $N \backslash S = \{s\}$ **then** `// Feasibility: ensure we finish in` s
          if $\check{\xi}_{S\cup\{j\},j} = \emptyset$ ***or*** $C\left(\check{\xi}_{S,i}\right) + c_{ij} < C(\check{\xi}_{S\cup\{j\},j})$ **then**
            $\check{\xi}_{S\cup\{j\},j} = \check{\xi}_{S,i} \rightsquigarrow j$ `// =`$\langle\check{\xi}_{S,i}, j\rangle$
return $\check{\xi}_{N,s}$

Assuming that feasibility is checked and compared with the current best state during each expansion, the computational complexity of the DP algorithm over sets is $\mathcal{O}(n^2 2^n)$. This is a significant improvement compared to the $\mathcal{O}((n-1)!)$ complexity that would result from evaluating all possible node sequences, as there are $(n-1)!$ such sequences. Nevertheless, it is worth noting that the DP algorithm over sets also incurs exponential memory requirements. Therefore, the more nodes (clients) there are, the larger the memory size will be needed. Since at least two stages need to be kept in memory, the memory requirement is $\mathcal{O}(n2^n)$.

2.1.2.2 Vehicle Routing Problem: algorithm using DP

The VRP involves finding the optimal routes for a set of m vehicles V in order to visit a set of customer requests $r \in R$ while as before each edge $e_{ij} \in E$ is assigned to a cost c_{ij} which once again can be either a travel time t_{ij} or a distance d_{ij}. This time, multiple depot can simply be taken into account leading to add the origins $o_i \in O$ with the destinations d_i [6]$\in D$ to the set N that contained originally only the customers requests r_i. Hence, obtaining the graph $G = (N, E)$ where $N = R \cup O \cup D$. The goal is to discover paths for each vehicle $v \in V$, beginning at their point of origin and concluding at their destination, while visiting a set of customer requests $r \in R$, denoted as $R_{vi} \subseteq R$, such that the total cost is minimised, and each customer request is attended by only one vehicle. Mathematically the latter is expressed as follows: $\bigcup_{v_i \in V} R_{v_i} = R$ and $R_{v_i} \cap R_{v_j} = \emptyset$ for $i \neq j$.

To solve the VRP using Dynamic Programming, the following approach is followed. The procedure involves representing the origin and destination of all vehicles as vertices, connecting all the routes together, and treating it as a single TSP. This approach is known as the Giant-Tour Representation (GTR) of a VRP solution, which was introduced by Funke,

6 In this notation the origin means the departure of the i^{th} vehicle from the depot and d_i means the return to the depot of this same i^{th} vehicle.

Grünert, and Irnich (Funke, Grünert, & Irnich, 2005). In the GTR, if the routes of all m vehicles of a VRP solution are arranged, then it forms a cycle in the graph G where each destination d_i of a vehicle i is connected to the origin o_{i+1} of the next vehicle $i+1$. The last vehicle's destination d_m is connected to the first vehicle's origin o_1 to complete the cycle. In Fig. 2.1 is illustrated an instance of a GTR solution for a VRP that involves a fleet of $m = 3$ vehicles and $n = 10$ clients (customer requests r). By utilising this approach, a VRP can be transformed into a TSP of size $n + 2m$, which results in a computational complexity of $\mathcal{O}\left((n+2m)^2 2^{n+2m}\right)$.

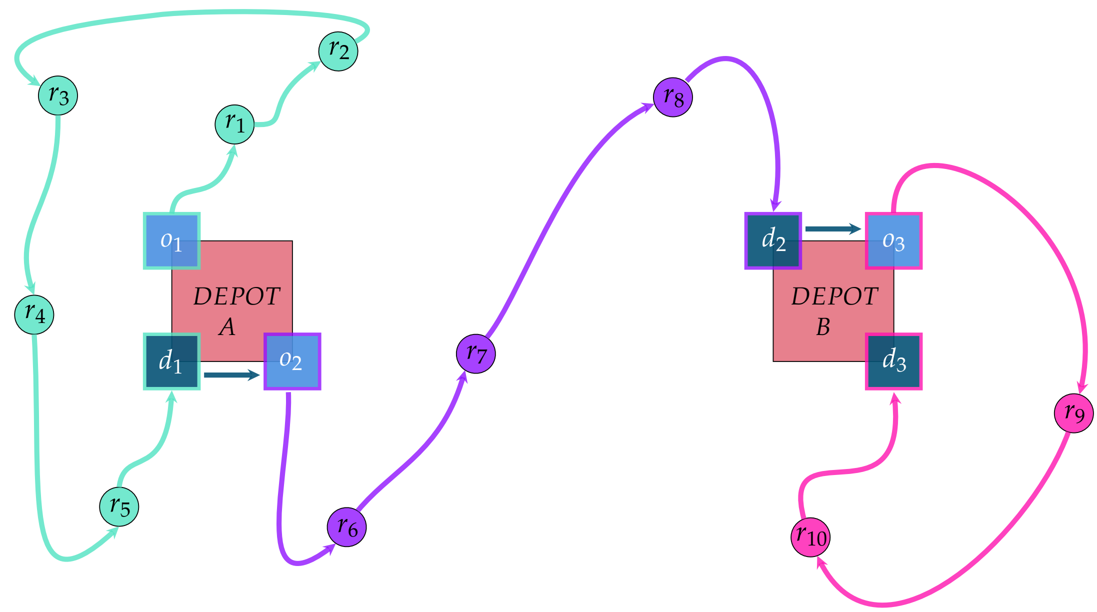


Figure 2.1: GTR depiction of the VRP solution for a fleet of 3 vehicles and 10 customers

This time the mathematical solution logic is as follows. As all the depot are part of the of nodes N appearing in the graph G, a first idea to avoid two depot to be directly connected would be to impose an infinite distance between them. Enforcing constraints on TSP solutions to be a GTR of a VRP solution by adjusting distances in the graph is technically correct. However, in practice, it is often more feasible to ensure such constraints through feasibility checks. Hence, two feasibility checks are incorporated into the DP algorithm during the forward algorithm of the TSP over $G(R \cup O \cup D, E)$ by choosing the destination vertex of the last vehicle d_m as the starting point and initiating the DP algorithm with $\check{\xi}_{\emptyset,d_m}$. At first, the expansion of any solution $\varsigma_{S,i,c}$ to an origin vertex $o \in O$ is only possible if and only if the preceding node i is a destination vertex, i.e., $i \in D$. Secondly, expanding a solution $\varsigma_{S,i,c}$ to a destination vertex $d_k \in D$ is only possible if the corresponding origin vertex $o_k \in S$ has been visited previously. These two constraints result in Alg. 2.

Algorithm 2 Forward DP algorithm for the VRP (Van Hoorn, 2016)

Input: An instance of the VRP defined by a set of customer requests R, and a set vehicles V with for each vehicle $v_i \in V$ an origin $o_i \in O$ and destination $d_i \in D$. A Graph $G = (N, E)$, with $N = R \cup O \cup D$ and a distance c_{ij} for all edges $e_{ij} \in E$

Output: A sequence ς associated which is the GTR an optimal solution for the VRP

```
ξ̌_{∅,d_m} = ς_{∅,d_m,0} = ⟨⟩

for L = 0 to |N| − 1 do
    for all S ⊂ N such that |S| = L do
        S′ = S
        if S = ∅ then
            S′ = {d_m} // Ensure ξ̌_{∅,d_m} is expanded
        for all i ∈ S′ such that ξ̌_{S,i} ≠ ∅ do
            for all j ∈ N\S do
                if j = d_m and N\S ≠ {d_m} then
                    continue // Feasibility: ensure we finish in d_m
                if i ∈ D xor j ∈ O then
                    continue // Feasibility: each origin follows directly
                        a destination
                if i = d_k ∈ D and o_k ∉ S then
                    continue // Feasibility: Allow only destination of
                        current vehicle
                if ξ̌_{S∪{j},j} = ∅ or C(ξ̌_{S,i}) + c_ij < C(ξ̌_{S∪{j},j}) then
                    ξ̌_{S∪{j},j} = ξ̌_{S,i} ⇝ m // ⟨ξ̌_{S,i}, j⟩
return ξ̌_{N,d_m}
```

Using a DP algorithm provides the flexibility to modify the cost function, as per the requirements of the routing problem being addressed, in contrast to a fixed cost function in linear programming. For instance, a new variable can be incorporated into the system to capture the arrival time at each customer. An other, in the case of road transport, enables accounting for traffic congestion when the vehicle travels during peak hours (Volvert, 2020). Consequently, the cost c_{ij} can be modified to reflect this. Additional constraints such as European regulations on driving, which mandate resting breaks for drivers, can also be included. These attributes have been taken in to account when solving the VRP for vans. On the other hand, flight duty periods which are similar regulations in the air transport industry, have been integrated when studying the VRP for airplanes. The next section will delve into these regulations. Because of its ability to accommodate diverse constraints and regulations, Dynamic Programming (DP) has been chosen as a suitable approach for addressing routing problems in this thesis. The implementation was carried out using *Matlab R2020a* to generate the results.

2.2 European legislation: fight duty periods, driving and working hours

The European Union has established common legislation for fight duty periods (FDP) (Parliament & Council, 2014), driving (Parliament & Council, 2006) and working (Parliament & Council, 2002) hours in all member countries. The aim of this common regulation is to achieve the following main objectives:

1. Promote safety on both air and land routes by ensuring that drivers/pilots are not fatigued while working, which can increase the risk of accidents.
2. Protecting the health and safety of drivers/pilots by ensuring that they have adequate rest periods
3. Preventing unfair competition: by ensuring that all drivers and transport companies comply with the same rules regarding working and driving hours and FDP. This helps to prevent companies from gaining a competitive advantage by exploiting their drivers or ignoring safety regulations.

In this section, regulations relating to flight duty periods, driving and working hours from the European Commission will be set out. Then, it will be explained how the latter were taken into account in the forward DP algorithm for the solution of the different VRP situations. As a reminder, the goal will be to first compare electric aviation to the traditional one with thermal engines. Then, for each plane, the number of crew members will be varied from two to zero (autonomous). Finally, it will also be interesting if it is also efficient to electrify road logistics transport.

2.2.1 Regulation (EU) No 83/2014 on flight duty periods

The regulations on *"Flight and Duty Time Limitations and Rest Requirenments"* (FTL) are set out in Annex II of Regulation (EU) No 83/2014 (Parliament & Council, 2014). Depending on the local time of the location where the duty starts versus the local time where the next duty starts, the FTLs differ. In this thesis, given the distance limited to a maximum of 800km around Brussels, the crew members are considered as acclimatised[7]. In this case the limitations of the FDPs are summarised in Tab. 2.1.

7 The term "acclimatised" refers to a condition where the circadian biological clock of a crew member is adjusted to the time zone in which they are located. To be considered acclimatised, a crew member must be synchronised with a 2-hour time zone around the local time at the point of departure.

Start of FDP at reference time	1-2 Sectors	3 Sectors	4 Sectors	5 Sectors	6 Sectors	7 Sectors	8 Sectors	9 Sectors	10 Sectors
06:00 - 12:29	13:00	12:30	12:00	11:30	11:00	10:30	10:00	09:30	09:00
13:30 - 13:59	12:45	12:15	11:45	11:15	10:45	10:15	09:45	09:15	09:00
14:00 - 14:29	12:30	12:00	11:30	11:00	10:30	10:00	09:30	09:00	09:00
14:30 - 14:59	12:15	11:45	11:15	10:45	10:15	09:45	09:15	09:00	09:00
15:00 - 15:29	12:00	11:30	11:00	10:30	10:00	09:30	09:00	09:00	09:00
15:30 - 15:59	11:45	11:15	10:45	10:15	09:45	09:15	09:00	09:00	09:00
16:00 - 16:29	11:30	11:00	10:30	10:00	09:30	09:00	09:00	09:00	09:00
16:30 - 16:59	11:15	10:45	10:15	09:45	09:15	09:00	09:00	09:00	09:00
17:00 - 04:59	11:00	10:30	10:00	09:30	09:00	09:00	09:00	09:00	09:00
05:00 - 05:14	12:00	11:30	11:00	10:30	10:00	09:30	09:00	09:00	09:00
05:15 - 05:29	12:15	11:45	11:15	10:45	10:15	09:45	09:15	09:00	09:00
05:30 - 05:44	12:30	12:00	11:30	11:00	10:30	10:00	09:30	09:00	09:00
05:45 - 05:59	12:45	12:15	11:45	11:15	10:45	10:15	09:45	09:15	09:00

Table 2.1: Maximum daily FDP — Acclimatised crew members

As can be seen from Tab. 2.1, depending on the reference (local) time of the start of the FDP and the number of sectors[8] visited per day, the number of hours of the FDP varies. In fact, the higher the number of sectors visited, the shorter the FDP. Indeed, if the departure of the FDP is at the beginning of the day (between 6:00 a.m. and 12:29 a.m.), the latter can vary from maximum 13 hours in the case where 1-2 sectors are visited up to a maximum of 9 hours in the case where 10 sectors are visited. Besides, the more the reference departure time of the FDP is conducive to flights, the longer the duration. This explains why when a single sector is visited, and when the FDP starts at the beginning of the day (between 6:00 a.m. and 12:29 a.m.) the FDP can last until 13 hours. Whereas if the latter starts later in the evening or at night (between 5:00 p.m. and 4:49 a.m.) the FDP can only last a maximum of 11 hours.

Concerning flight times and duty periods spread over a longer period of time than just one day, these are listed in item ORO.FTL.210 ”Flight times and duty periods” (Parliament & Council, 2014):

(a) *”The total duty periods to which a crew member may be assigned shall not exceed:*
   (1) *60 duty hours in any 7 consecutive days;*
   (2) *110 duty hours in any 14 consecutive days; and*
   (3) *190 duty hours in any 28 consecutive days, spread as evenly as practicable throughout that period.*

(b) *The total flight time of the sectors on which an individual crew member is assigned as an operating crew member shall not exceed:*
   (1) *100 hours of flight time in any 28 consecutive days;*
   (2) *900 hours of flight time in any calendar year; and*
   (3) *1000 hours of flight time in any 12 consecutive calendar months.*

(c) *Post-flight duty shall count as duty period. The operator shall specify in its operations manual the minimum time period for post-flight duties.”*

8 The term ”sector” refers to the part of a flight duty period (FDP) that begins when the aircraft starts moving for takeoff and ends when it stops at the designated parking spot after landing.

Regarding the rest periods, points (1) and (2) of the item ORO.FTL.235 ”Rest periods” have been considered (Parliament & Council, 2014). These are the following:

(a) *”Minimum rest period at home base.*

(1) *The minimum rest period provided before undertaking an FDP starting at home base shall be at least as long as the preceding duty period, or 12 hours, whichever is greater.*

(2) *By way of derogation from point (1), the minimum rest provided under point (b) applies if the operator provides suitable accommodation to the crew member at home base.*

(b) *Minimum rest period away from home base.*

The minimum rest period provided before undertaking an FDP starting away from home base shall be at least as long as the preceding duty period, or 10 hours, whichever is greater. This period shall include an 8-hour sleep opportunity in addition to the time for travelling and physiological needs.

(c) *[...]”*

The other points of this item ORO.FTL.235 are derogations or exceptions from these first two points.

Finally, concerning the other items, the latter, although very important to respect, are not included here since they affect less the problem concerning the VRP.

2.2.2 Regulation (EC) No 561/2006 on driving hours

The legislation governing driving hours (road transport) is set out in Regulation EC No 561/2006 (Parliament & Council, 2006). The details of this legislation are presented below:

- Daily driving time: Drivers are not allowed to exceed a maximum daily driving time of 9 hours, which can be extended to 10 hours no more than twice per week.
- Weekly driving time: Drivers are not allowed to exceed a maximum weekly driving time of 56 hours.
- Total accumulated driving time: Drivers are not allowed to accumulate more than 90 hours of driving time during any 2 consecutive weeks.
- Breaks: After driving for 4.5 hours, drivers must take an uninterrupted break of at least 45 minutes, unless they take a rest period.
- Daily rest: Drivers are required to take a minimum daily rest period of 11 hours, which can be reduced to 9 hours, but no more than three times between any 2 weekly rest periods.
- Weekly rest: Drivers are required to take a regular weekly rest period of at least 45 hours, and a reduced weekly rest period of at least 24 hours.

Regulation EC No 561/2006 pertains to the transportation of goods by road using vehicles with a total mass over 3.5 tonnes, as well as the transportation of passengers by road using vehicles designed to accommodate more than nine individuals. Nonetheless, it is important to note that starting from July 1st, 2026, Regulation EC No 561/2006 will be applicable to the transportation of goods through international or cabotage operations by vehicles (including any attached trailer or semi-trailer) that has a total mass over 2.5 tonnes (Parliament & Council, 2022).

2.2.3 Directive 2002/15/EC on working hours

In addition to being submitted to Regulation (EC) No 561/2006, persons performing mobile road transport activities are subject to the following Directive 2002/15/EC on working hours (Parliament & Council, 2002):

- Definitions that must be set: working time, periods of availability, place of work, mobile worker, self-employed driver, week, night time, and night work.
- Maximum working week: The maximum working week is set at 48 hours, although this can be extended to 60 hours provided that an average of 48 hours per week is not exceeded over a 4-month period.
- Breaks: Workers are entitled to at least 30 minutes of break time after working for more than 6 consecutive hours, although employers should ensure that workers do not work more than 6 hours without a break.
- Rest time: The provisions of Regulation (EC) 561/2006 are maintained, which sets out the requirements for daily and weekly rest periods for drivers of commercial vehicles.
- Night work: When performing a night shift, workers are not allowed to work more than 10 hours in any 24-hour period.

2.2.4 Rules taken into account in VRPs

Now that the regulations have been presented, they must be implemented in the VRP algorithm for all the different situations that will be studied. In this subsection, for reasons of ease of reading, the algorithms are not explicitly written, however the logic of the legislations with the hypotheses carried out is shown.

2.2.4.1 Thermal engines & Electric-powered airplane: Two pilots

To start with, simplifications and assumptions have been made in the VRP legislation model. In the case where two pilots are present in the cockpit the following assumptions have been made:

- From Tab. 2.1 simplifications are made by considering only one value of maximum daily FDP. As highlighted in blue in Tab. 2.1, the value of maximum FDP chosen is 9 hours to be conservative in the simplification. Indeed, 9 hours of daily FDP corresponds to the minimum value in Tab. 2.1, the rest of the values present are higher. As the case study presents the express delivery field, this assumption can often prove to be penalising (by seeing all the higher values not highlighted in blue). Hence, the fact of considering the simplification as conservative.

- As the time frame limit considered is maximum 48 hours, item ORO.FTL.210 ”Flight times and duty periods” is not considered. However, if the case study were to study deliveries over a longer period of time, the latter must of course be considered.
- Point (b) of the ORO.FTL.235 ”Rest periods” has been taken into account by considering that the minimum rest period is 10 hours.
- In the FDP, the time s for loading and unloading goods from the aircraft when it is at destination i is considered. In this thesis, s is considered to equal 30 minutes.
- The autonomy of the vehicles is considered to be 100% charged at each take off.
- The recharging time of fuel-powered planes has been neglected given their long autonomy and short time to refuel. On the other hand, that of eclectic-powered planes, the autonomy being quite short as well as the recharging time being able to be long, the latter has been taken into account. Hence, the autonomy of the electric vehicle is either 463 km or 815 km with a recharge time of 70 minutes to go from 0 to 100% of batteries (FutureFlight, 2023).

Now that the assumptions have been presented the logic of the algorithm can be stated. The latter has 8 main steps and are summarised in Alg. 3.

Algorithm 3 Implementation of the regulation for Thermal engines & Electric-powered Airplane with two pilots

Step 1: At destination i. From the previous destination a distance as the crow flies $d_{i-1,i}$ between $i-1$ and i has been traveled. The fuel/electricity autonomy has decreased by $\Delta E_{i-1,i}$. To take off with full energy (as stated in the assumptions), it is therefore necessary to recharge $\Delta E_{i-1,i}$.

Step 2: Since the loading/unloading of goods from the aircraft lasts a period of time s, if the recharging $\Delta E_{i-1,i}$ takes longer than s, in this case the unloading time s must be exceeded and wait for the plane to fully charge (this will especially be the case for long journeys in an electric plane). After that, a potential first takeoff time of i is obtained.

Step 3: Check if the range of the plane allows to go to the next destination $i+1$:

- If yes: The destination $i+1$ is possible. Go to Step 4.
- If not: impossible to go to destination $i+1$, another destination $i+1$ must be chosen.

Step 4: Check if the maximum daily FDP will not be exceeded to get to $i+1$ in addition to the load/unload time of goods s:

- If yes: in this case, the takeoff has to be done the next day on time to arrive at the customer's opening or once the 10 hours of mandatory breaks have been completed.
- If not: it is possible to takeoff at the time obtained in Step 2.

Step 5: From the result of Step 4, check if on arrival at destination $i+1$, the client is open:

- If yes: then the takeoff time in Step 4 can be kept.
- If not: It must be modified as follows:
  a. If the customer is not yet open then the takeoff has to be done later to arrive at the opening.
  b. If the customer has already closed then it will be necessary to leave destination i the next day at the necessary time to arrive at the opening time of customer $i+1$.

Step 6: Check if the route made by the aircraft does not exceed the time limit given to make all the deliveries:

- If the time limit is exceeded then:
  a. Change destination $i+1$ (other destination remaining from the list of destinations that have not been visited yet).
  b. Add a vehicle.
- If the time limit is not exceeded then it leads to the next Step.

Step 7: Remove the value $\Delta E_{i,i+1}$ from the range of the aircraft, due to the displacement of i to $i+1$.

Step 8: The number of vehicles considered makes it possible to go to the destination $i+1$ within the time limit granted. At this last step, the time of takeoff from i and landing at $i+1$ is known. Also, the autonomy remaining in $i+1$, the number of hours accumulated since the beginning of the trip and the day are saved for future destinations.

2.2.4.2 Thermal engines & Electric-powered airplane: One pilots

Concerning the case where only one pilot is present in the cockpit, it is not authorized for him to execute the same FDP schedule as when there are two pilots present in a cockpit. Indeed, when there are two of them, one of them can afford to take a break or even sleep for a while (this is called a *"power nap"*) while the other is piloting the plane. Hence, the fact that in these cases they can perform long FDP without taking breaks on land. In the case of the single-pilot cockpit, even with the presence of very reliable autopilots these days, the pilot is prohibited from taking breaks or naps while flying. As the legislation for single-pilots has not yet been fully enacted, assumptions based on working hours of Directive 2002/15/EC have been taken. Indeed, during a working day the pilot will have to take a break on land of 45 minutes every 6 hours of work. As for the maximum FDP, the same value was considered as in the previous case i.e. 9 hours. Since everything else is the same, it is expected in this case to have a slower delivery time than in the case of the cockpit with pilots due to forced rest on land.

Regarding the algorithm logic, the Alg. 3 seen previously for the case of two pilots can be resumed with some additional conditions in Step 4. Indeed, this time it is not only enough to check if the flight time does not exceed the maximum daily FDP. It is also necessary to impose a break of 45 minutes every 6 hours of work. Hence, a variable must be added taking into account the number of hours worked and which cannot exceed 6 hours. In the case this variable exceeds 6 hours to get to $i+1$, then the 45-minute break must be taken in i.

2.2.4.3 Thermal engines & Electric-powered airplane: Autonomous

Finally, in the case of the aircraft completely guided by the autopilot i.e. autonomous, the latter will not be subject to any legislation concerning working time and breaks since no human is driving. The plane will therefore be able to supply customers 24 hours a day without taking breaks as long as the customers are open.

Once again Alg. 3 can be resumed but this time it can completely do without Step 4, as no regulations related to working hours have to be checked. The other Steps can remain as they are.

2.2.4.4 Thermal engines & Electric-powered Van: Driver

In the case of road transport, in the same way as in aviation, the schedule of drivers is governed by legislation. However, as mentioned in subsection 2.2.2, nowadays the regulations are only valid for heavy goods vehicles exceeding 3.5 tons. In the study case of this thesis, the land vehicles chosen have a loading capacity of one ton so that this loading capacity is comparable to the model aircraft chosen (i.e. the Alice aircraft from Eviation which has a capacity of about a ton). Vans with the chosen loading capacity are available in diesel and electric versions such that each of them is designed so as not to exceed 3.5 tons. Today, drivers of these vehicles are not subject to Regulation (EC) No 561/2006. Nonetheless, as mentioned in subsection 2.2.2 from July 1, 2026, these will also be under Regulation (EC) No 561/2006. As the present study tries to project a maximum towards the end of this decade (i.e. when the Alice aircraft should begin to make its first commercial uses) Regulation (EC) No 561/2006 is well taken into account.

In addition to being subject to Regulation (EC) No 561/2006 on driving hours, drivers must also comply with Directive 2002/15/EC on working hours. Therefore, it is necessary to implement rules in the VRP model that require the driver to comply with both legislations. For this purpose, references have already been made in both linear programming (Kopfer & Meyer, 2009) and dynamic programming (Kok, Meyer, Kopfer, & Schutten, 2010). As the modelling of VRP uses dynamic programming in this thesis, the second reference is chosen (which is the same reference used in Volvert's thesis (Volvert, 2020)). Their algorithm for scheduling breaks and working hours is designed to cover a typical week of both driving and working. It is divided into two parts: the first part, called the *Basic break scheduling method*, covers the fundamental rules for working and driving hours under the relevant legislation. The second part of the algorithm, called the *Extended break scheduling method*, takes into account all the modified rules and exceptions of the legislation. In the current study, only the first part of the algorithm is considered, without considering all the exceptions, to keep things simple. As it was for aviation, the case study tackles express delivery over a maximum time period of 48 hours. This therefore leads to not taking into account the maximum weekly working time of 60 hours of Directive 2002/15/EC and the 56 hours of maximum weekly driving time of Regulation (EC) No 561/2006. The regulations retained and imposed in the VRP model are then as follows:

- The time limit to serve all customers is a maximum of 48 hours.
- The maximum duration of driving per day is 9 hours, which must be divided into two equal parts. A break of 45 minutes must be taken between these two parts.
- A minimum of 11 hours is required for the daily rest period.
- A break of 30 minutes should be taken after a maximum of 6 hours of daily work. If the daily working period exceeds 9 hours, a break of at least 45 minutes is required.
- The time s for loading/unloading goods from the van is considered as working hours and not driving hours. In this thesis, s is considered to equal 30 minutes.
- The recharging time of diesel-powered vans has been neglected given their long autonomy and short time to refuel. On the other hand, that of eclectic-powered vans, the autonomy being quite short as well as the recharging time being able to be long, the latter has been taken into account. Hence, the autonomy of the electric vehicle considered is 120 km and the recharge time from 0 to 100% is 40 minutes (Mercedes-Benz, 2023a).

Having presented all the assumptions, it is now possible to outline the logic of the algorithm employed in the VRP model. The latter has 4 main steps and are summarised in Alg. 4.

Algorithm 4 Implementation of the regulation for Thermal engines & Electric-powered Vans

Step 1a: At destination i, the departure time of i is known. Moreover, the distance $d_{i,i+1}$ as well as the time needed to get from i to $i+1$ is also known. This first step consists in calculating the number of breaks that the driver will have to make to get to $i+1$. It is therefore also necessary to provide variables retaining the hours of work and driving carried out since the last break. These are constantly checked and reset to zero once the pause is made.

Step 1b: This step only concerns electric vehicles. When the van is driving from destination i to $i+1$, the battery levels must be monitored during the journey. Thus, forced breaks to recharge the vehicle must be made. If the recharging time exceeds 45 minutes (compulsory break after 6 hours of work) then, the counter on working hours is reset to zero.

Note: this time unlike the case of aviation, breaks, refuel and battery charging can be done on the way to get between i and $i+1$ and not only at the destination point i before heading to $i+1$ (this assumes that (fast) charging stations in the study for the electric version are easily accessible on all the roads used).

Step 2: From the result of Step 1, once arrived at destination $i+1$, it is necessary to check if the customer is open (or if it is still open after loading/unloading the goods since it takes a certain time s):

- If yes: then the goods can be loaded/unloaded for a time s.
- If not: then the driver must wait for the customer to open.
  a. If the driver is too early in the day then he has to wait for the opening of the customer to load/unload.
  b. If the driver is too late then he has to spend the night at destination $i+1$ and wait until the opening of the next day to load/unload.

  Note: If the wait for the opening lasts longer than 45 min then the working hours counter for a short break of 45 min is reset. If it exceeds 11 hours then the long pause counter due to driving hours is reset.

Step 3: Check if the route made by the van does not exceed the time limit given to make all the deliveries:

- If the time limit is exceeded then:
  a. Change destination $i+1$ (other destination remaining from the list of destinations that have not been visited yet).
  b. Add a vehicle.
- If the time limit is not exceeded then it leads to the next Step.

Step 4: The number of vehicles considered makes it possible to go to the destination $i+1$ within the time limit granted. At this last step, the time of departure from i and of arrival at $i+1$ is known. Also, the remaining autonomy in $i+1$, the number of hours of work and driving accumulated since the start of the trip and the day are saved for future destinations.

It should be noted that in Alg. 4, an additional verification step must be done in Step 1 (Step 1b), controlling the vehicle battery level as well as the charging time. As the autonomy of current vehicles is quite small and the charging time long, it is possible that in some cases the variable counting the number of working hours is reset before having actually reached 6 hours of work. Indeed, this is due to the fact that charging times exceeding 45 minutes are considered as a mandatory break caused after 6 hours of work.

2.2.4.5 Thermal engines & Electric-powered Van: Autonomous

In the case of the autonomous van, as in the case of the autonomous aircraft, it is not subject to any legislation since no human is driving. The van can therefore drive without taking breaks and serve customers 24 hours a day as long as they are open.

The Alg. 4 can be retaken by removing Step 1a which consists in enforcing the legislations. On the other hand, in the case of electric-powered vans, Step 1b must be kept because it imposes breaks to recharge the van.

3

VRP MODELLING: AIRPLANES & VANS IN ALL PILOT/DRIVER'S CONDITIONS

In the preceding chapter, the mathematical formulation of the VRP model was outlined, and the corresponding European regulations for each case study were integrated. This chapter will delve more in detail into the specific scenarios that will be simulated by the VRP. These scenarios aim to reflect practical and possible conditions in the world of dispatching. Subsequently, the methods used and the assumptions taken to generate the inputs for the VRP model will be elaborated upon. These inputs predominantly encompass an assessment of the distinct sub-costs that contribute to the overall cost of the final delivery round, once the VRP simulation is concluded.

3.1 Case scenarios studied

It's recognised that the autonomy of electric vehicles is comparatively more restricted when compared to their internal combustion engine counterparts. Consequently, the distance covered to reach customers from the depot holds considerable influence in assessing the efficiency of electric vehicles. In pursuit of this analysis, three separate case studies are undertaken, all centred around a singular depot. Each case study involves a set of customers located within three distinct perimeter sizes. Similar to the legislative framework, these case studies will be conducted within the geographical confines of the European continent.

As mentioned in the introduction, the chosen cities are those where airports are situated, facilitating access to air transportation. To simulate a practical scenario, a delivery company operating from a single depot is under consideration. The company's clientele, spread across various European cities, will be served based on differing perimeters aligned with the specific scenarios under examination. In this thesis, the central depot is situated in Zaventem, located a few kilometres from the Belgian capital, Brussels. Moreover, it is in Zaventem that the largest airport in Belgium is located. For the other cities, the selection process is based on the following three perimeter criteria:

1. Benelux
2. 400 kilometres around Brussels not including the UK
3. 800 kilometres around Brussels not including the UK.

The simulations consist of choosing n destinations from a list of 30 to 40 possible destinations according to the perimeters considered by the different scenarios. The list of these is presented in Tab. 3.1 and for information the airports corresponding to the cities with their geographical coordinates are presented in Annex A in Tab. A.1, A.2 & A.2. For each of the scenarios, a large number of simulations is run, each time randomly selecting the n destinations from the lists present in Tab. 3.1. This enables the attainment of a broader outcome by conducting statistical analysis across all simulations for each scenario. As mentioned before, a time limit is imposed depending on the case study to clearly mark the express aspect of the deliveries considered. At the end of the simulations, it is interesting to compare each time if a delivery using the electric engine version is more interesting than the heat engine one.

As can be seen in the chosen perimeters, the United Kingdom has been excluded from the possible destinations although it can be reached by plane from Brussels. The reason behind this is that, in the VRP analysis, it is preferred to utilise a single mode of transportation while delivering to customers. In the case of land transport, the United Kingdom can be reached via the *Eurotunnel*, which is an underground train allowing land vehicles to cross the Channel. As a consequence, during a section of a length of about fifty kilometres the land vehicles use another mode of transport.

3.1.1 Scenario 1: Benelux

This first case study is focused solely on examining customers situated within the geographical region known as Benelux. The latter is a politico-economic union bringing together the following three countries: Belgium, the Netherlands and Luxembourg. Given the small area that this represents, a one-day deadline has been imposed to serve all customers. In addition, the opening time of the customers taken into account is between 8 a.m. and 5 p.m., therefore leaving a time frame of 9 hours to supply everyone. If one vehicle is not enough to serve all the customers in that time frame, then another is added until it is possible to supply everyone on time. As part of this study, it is considered that the logistics company has in its possession enough vehicles necessary to deliver to all customers. Hence, there is no limit on the number of vehicles that can be used. However, improperly optimising the number of vehicles used risks greatly increasing the total cost of the delivery round for the logistics company. Thus, the importance of finding the right number of these to deliver everyone on time.

It should be noted that it is possible to make the simulation even more realistic by taking into account the real working times of the destinations. Indeed, these chosen destinations represent real existing airports, their opening and closing times can be known. In large airports such as Zaventem, the latter work 24 hours a day, while small aerodromes such as in Cerfontaine are open between 9 a.m. and 6 p.m.. Since each of them contains different opening hours, these opening hours could be implemented in the VRP for each customer. Nevertheless, in all three scenarios under study, to maintain simplicity, identical time constraints are enforced for all destinations, based on the particular scenario.

3.1.2 Scenario 2: 400 km

The second scenario, which is called *"400 km"*, takes into account, as mentioned before, destinations located at a maximum of 400 kilometres as the crow flies around Brussels. This limit was chosen taking into consideration the current range of 463 km revealed by Eviation for its future Alice aircraft. Increasing the perimeter of destinations consequently facilitates the inclusion of cities situated in the western part of Germany and the northern regions of France. Here, the time frame left to deliver all customers is 48 hours. If the driver cannot complete their route within a single day and requires an overnight stay away from home,

N°	Benelux	400 km	800 km
1	Zaventem	Zaventem	Zaventem
2	Haren	Ostende/Bruges	Ostende/Bruges
3	Ostende/Bruges	Liège	Liège
4	Wevelgem	Gosselies	Luxembourg City
5	Deurne	Luxembourg City	Rotterdam
6	Weelde	Rotterdam	Haarlemmermeer
7	Brustem	Haarlemmermeer	Eelde
8	Liège	Eelde	Dortmund
9	Spa	Eindhoven	Hamburg
10	Gosselies	Enschede	Frankfurt
11	Cerfontaine	Hoeven	Stuttgart
12	Saint-Hubert	Spa	Munich
13	Jehonville	Bremen	Dresden
14	Zwartberg	Hanover	Berlin
15	Luxembourg City	Dortmund	Kassel
16	Texel	Düsseldorf	Düsseldorf
17	Rotterdam	Kassel	Leipzig
18	Haarlemmermeer	Frankfurt	Nuremberg
19	Eindhoven	Stuttgart	Innsbruck
20	Eelde	Münster	Salzburg
21	Aix-la-Chapelle	Cologne	Prague
22	Deventer	Bielefeld	Copenhagen
23	Weert	Saarbrücken	Aalborg
24	Lelystad	Mannheim	Malmö
25	Hoogeveen	Koblenz	Zürich
26	Middelbourg	Bitburg	Geneva
27	Hoeven	Amiens	Milan
28	Enschede	Paris	Turin
29	Soesterberg	Strasbourg	Amiens
30	Leyde	Dijon	Limoges
31		Caen	Lyon
32		Reims	Bordeaux
33		Nancy	Nantes
34		Orléans	Paris
35		Le Mans	Bourges
36		Rouen	Brest
37		Lille	Strasbourg
38		Calais	Dijon
39		Troyes	Caen
40		Colmar	Reims

Table 3.1: Visited cities for the three scenarios

compensation is provided to them. Regarding customer working times, as the aerodromes considered are generally larger, the latter has been increased to 2 working shifts of 8 hours i.e. from 6 a.m. to 2 p.m. and from 2 p.m. to 10 p.m.. Customers will therefore all be accessible between 6 a.m. and 10 p.m. during the 48 hour time frame. Similar to the previous scenario, the VRP simulation is responsible for determining the ideal number of vehicles needed to cater to all customers within the specified time limit while minimising the total cost of the trip.

3.1.3 Scenario 3: 800 km

The final scenario, referred to as the *"800 km"* scenario, involves destinations situated within a maximum radius of 800 kilometres from Brussels. This limit corresponds to the first range estimated by Eviation for Alice, which was 815 kilometres. This case is also studied to see the influence of electric vehicles over longer distances since the battery will drain faster than internal combustion vehicles and the recharging time is much longer. This time, the scope of activity makes it possible to reach much more distant destinations such as Malmö in Sweden or Turin in Italy. Regarding the time frame once again, 48 hours are granted to deliver everyone. Considering the presence of several major hubs that operate round the clock from the list of destinations, the customers' availability to receive deliveries is also imposed to 24 hours a day, i.e., between 0 a.m. and 12 p.m. Finally, as in the first two cases, the logistics company has no maximum constraint on the number of vehicles available to serve all customers and the VRP model is responsible for finding the appropriate number to minimise costs of the round while ensuring that all customers are delivered on time.

3.1.4 Additional assumptions for scenarios

When a vehicle reaches a destination, it is supposed to unload its delivery (or if necessary load depending on the context). As discussed in the preceding chapter, a time interval of s was taken into account. For every vehicle type, whether it is an airplane or a van, or whether it is powered by an electricity or a combustion engine, the chosen time interval s is 30 minutes. A nuance nevertheless arises in the case of the electric plane where the recharging is obliged to be done at the place of unloading i.e. at the aerodrome. To save time in the various operations, recharging is launched in parallel with the unloading operation. It is also imposed that the aircraft must take off with its battery 100% charged. The time taken to achieve a full battery recharge can surpass the 30-minute unload time by an amount greater than s, based on the initial battery level at the commencement of recharge. In this case, the unloading will be finished but the aircraft will not take off to the next destination until the battery is fully charged.

An additional assumption made is that, as all vehicles possess a similar load capacity of around one ton, the VRP model in this thesis does not incorporate any capacity constraints, unlike the CVRP model discussed in the preceding chapter. Thus, the quantities requested by customers are automatically satisfied by each vehicle.

3.2 Time and distance between destinations

Now that the conditions of the different scenarios have been presented and that all the destinations have been determined, it is time to link all these cities together by a notion of distance and time. Depending on the transport mode, the computation of distance and time between two destinations is different. The following two subsections explain the assumptions used in the case of air transport and then that of road transport.

3.2.1 Air tansport

For air transport, the distance as the crow flies can be a good approximation of the actual distance travelled by the plane to get from one city to another. To do this, the Harvesine formula is used. The latter makes it possible to obtain the distance as the crow flies $d_{i,j}$ between two destinations i and j by taking into account the radius of curvature of the planet. It is therefore sufficient for each calculated distance to provide the latitude ϕ and the longitude ψ of these two destinations as well as the radius r of the Earth. The formula is as follows:

$$d_{ij} = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_j - \phi_i}{2}\right) + \cos(\phi_i)\cos(\phi_j)\sin^2\left(\frac{\psi_j - \psi_i}{2}\right)}\right) \tag{3.1}$$

Then, from this distance $d_{i,j}$, the time $t_{i,j}$ necessary to get from point i to j can be determined if a constant cruising speed v is assumed. Thus, the expression of this travel time between points i and j is expressed as follows $t_{i,j} = d_{i,j}/v$.

Furthermore, it is worth mentioning that the assumption of maintaining a constant speed v throughout the delivery route simplifies the calculation of the motors' energy consumption, in terms of fuel or electricity required to cover the necessary distance. This will be discussed in more detail in section 3.3.

The operation of calculating distances $d_{i,j}$ and times $t_{i,j}$ can therefore be done between the n cities appearing in the VRP. Thus, all destinations are interconnected in distance and time according to a matrix of size $n \times n$ symmetric[1] which is used as input in the VRP model.

3.2.2 Road transport

When it comes to road transportation, it is advisable to consider the actual route based on roads instead of as the craw-flies distance. Indeed, the study has already been carried out in Volvert's thesis and showed a non-negligible difference of about 20% on average according to several cases of VRP (Volvert, 2020). Popular applications such as *Google Maps* or *Waze* not only make it possible to determine the shortest or fastest route by taking into account the speed limits of the paths used. These applications also make it possible to impose constraints such as avoiding highways or maritime transport (if possible) but also to adapt their proposed routes according to traffic during the day.

1 This means that the distance and time required to get from i to j is the same as going in the opposite direction from j to i.

In the case of this thesis, given the fairly high number of cities taken into account, it is preferable to find an automatic way to recover the data containing the time, the distance as well as the real paths used to get from the destination i to j. This can be done via an Application Programming Interface (API). The latter is a set of protocols, tools, and standards that enables communication between software applications. Thus, it is possible to link the results offered by the GPS navigation apps with the VRP code built on *Matlab*. As in the case of air transport, these results are in the form of $n \times n$ matrices and injected as input into the VRP model.

Many APIs are available, but unfortunately the majority are not free and can cost up to several thousand euros per year. Among them are *Google Maps* and *Waze*. However, another API offered by *GrpahHopper* offering a two-week free trial period has been selected. During this period a limited number of simulations is granted but sufficient for the present work. To be independent of the API after this test period, the data is saved[2] i.e. the matrices of distances, times with the routes used between each destination present in Tab 3.1.

The *GrpahHopper* API is quite easy to use with programming languages. Simply by reading the URL that directs to the API service, the latter provides a JSON file with essential data, including the distance, time, and points (geographical coordinates) of all the routes that the vehicle covers to reach from destination i to destination j. In *Matlab* all this is taken care of by the *webread* function so all the necessary VRP data coming from the API is obtained and saved. Each time the URL is named, the latter has the following structure:

https://graphhopper.com/api/1/[API SERVICE]?[PARAMETERS]&key=[API KEY]

In this URL, three sections can be distinguished and are highlighted in blue.

- [API SERVICE]: *GraphHopper* API offers multiple services and features tailored to meet users' specific requirements. To determine the time and distance between two points, *Routing API* and *Matrix API* functionalities need to be employed. For this study, these two features are exclusively utilised, and their detailed usage is presented later in this subsection.

  It is worth noting that the *Route Optimization API* tool offers VRP optimisation as well. However, it cannot be utilised due to its inability to incorporate specific constraints like driver legislation or electric vehicle charging times. Additionally, several other useful but less pertinent functionalities for the present work are accessible on the official website of *GraphHopper* (GrpahHopper, 2023).

- [PARAMETERS]: The segment begins by entering the geographical coordinates of both the starting and ending points. Additional parameters can be added to represent the case study situation as faithfully as possible. The following are the most significant:
  - `vehicle`: The default mode of transportation considered by *GraphHopper* is `car`, but there are several other modes available, ranging from walking to truck. For the purposes of this study, since delivery vans are being used, the `small_truck_delivery` keyword is utilised.

2 The matrices are saved as *.mat* file which is a format readable by *Matlab*.

  - `snap_prevention`: this parameter is used when certain roads must be avoided such as bridges, fords, tunnels or highways. In the case of this study, only ferries were avoided to ensure a single means of transport throughout the delivery round.
  - `weigthing`: This parameter enables the API to identify the optimal route based on whether the objective is to minimise travel time or distance. In this study, the focus is on express delivery, hence the `fastest` option is chosen.

  In certain cases, selected services may have incompatible parameters, such as in the case of the *Matrix API*, which only considers the vehicle's option.

- [API KEY]: this last keyword consists of tracking the number of requests executed by each user and checking whether the daily or monthly quota has not been exceeded.

Here is an example of use between Zaventem and Zürich favouring the *Routing API* mode given that the latter takes into account all the specific parameters listed above and therefore best reflects the conditions of the case study.

https://graphhopper.com/api/1/route?point=50.901389,4.484444&point=47.464722,8.549167
&vehicle=small_truck_delivery&calc_points=true&points_encoded=false&weighting=fastest
&key=xxxxxxxx-xxxx-xxxx-xxxx-xxxxxxxxxxxx;

As can be seen above, the decimal geographical coordinates of Zaventem (50.901389, 4.484444) are first written then that of Zürich (47.464722, 8.549167). The vehicle being a delivery van, the keyword `small_truck_delivery` is used by imposing the `fastest` route. This results in a distance of 632,737 m and a time of 24,490,800 ms. In addition, 4603 coordinates of nodes are given representing the intermediate points through which the vehicle passes to go from Zaventem to Zürich. Thus, the path used can be traced and is shown in Fig. 3.1.

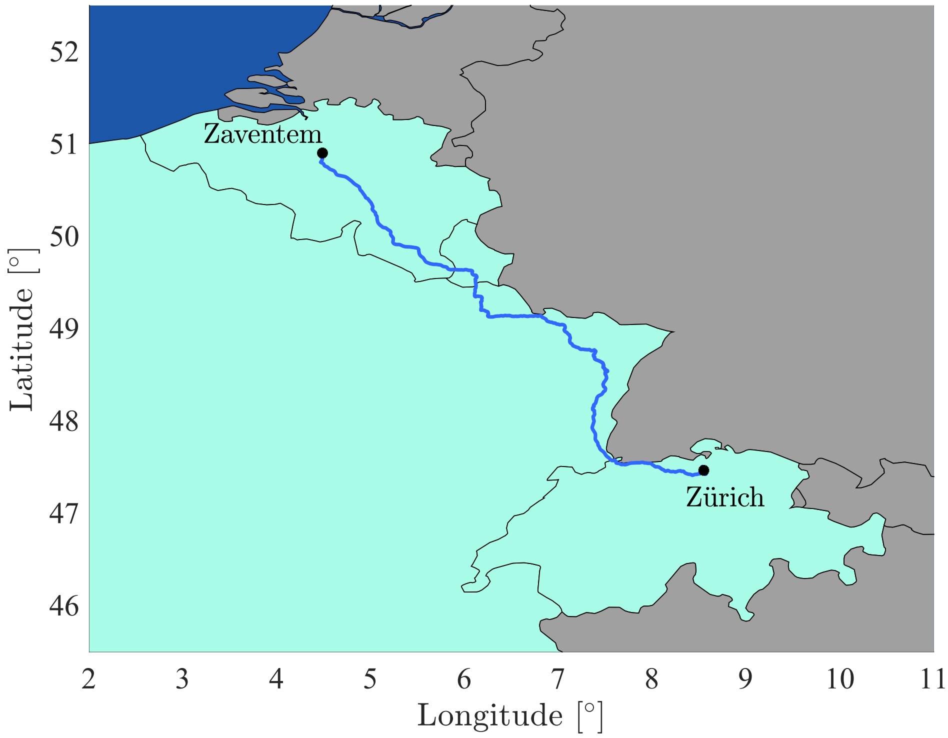


Figure 3.1: Example of using *Routing API* from *GraphHopper* with a delivery van between Zaventem and Zürich using the fastest route

By reproducing this process for all the cities listed in Tab. 3.1, the distance and time matrices required for the VRP can be obtained.

As previously mentioned, priority is given to using the *Routing API* service over the *Matrix API*. Indeed, the latter is especially effective for quickly calculating a large quantity of paths connecting a large list of cities. The input list of n cities is used by the *Matrix API* service to directly compute the $n \times n$ matrices of time and distance. Not taking into account all the parameters as in *Routing API*, it is therefore not known if the given result is the fastest or the shortest path or even a mix of both. Moreover, this mode does not return the vector of points through which the vehicle passes. Thus, it is not feasible to reconstruct the precise route taken except by drawing a straight line between the starting and ending points. Nevertheless, for certain destinations, the *Routing API* service is unable to provide a result and generates an error message where no action can be taken. In such cases, the only option is to use *Matrix API*, which functions reliably all the time.

3.3 Electricity & Fuel consumptions of airplanes and vans

Regarding the energy consumption of each vehicle considered, it is obvious that the latter is not constant per kilometre travelled. Depending on the transport mode, the main factors determining energy consumption per kilometre are:

- For air transport: energy consumption is much higher during the taxi phase or during take-off than when once in cruise mode. Indeed, during the take-off the engines must generally be activated at practically 100% of its power, while in the cruise phase the engines generally operate between 50% and 60% of their maximum power.

- For road transportation, it is well-known that the speed of travel is not constant and can vary depending on factors such as road conditions and traffic. Additionally, the energy consumption of a vehicle per kilometre is affected by its driving speed. Furthermore, differences in elevation between two destinations can lead to significant variations in energy consumption during the journey.

It is therefore quite complicated to build an accurate model of the energy consumption of vehicles during their delivery rounds. A simplified model has nevertheless been constructed for each type of vehicle, considering a fixed average fuel consumption throughout the tour.

3.3.1 Internal combustion engine vehicle

In this subsection are presented the different consumptions of the various heat engine vehicles taken into account in this thesis namely the plane *Pilatus PC-12* and the van *Mercedes Sprinter*. In addition, a comment on the quantities of greenhouse gas (GHG) emissions will also be provided. The consumption values and other data are derived directly from the technical specifications of the selected models.

3.3.1.1 Airplane: Pilatus PC-12

Beginning with the *Pilatus PC-12*, the aircraft is equipped with a single-turboprop Pratt & Whitney Canada PT6A-67P engine that is powered by kerosene and generates 890 kW of power. Typically, the *Pilatus PC-12* aircraft has a cruising speed of 528 km/h and consumes approximately 240 litres of kerosene per hour of flight, which is equivalent to 63 gallons per hour (Chase, 2013). Assuming a constant speed during the delivery round, a speed of around 400 km/h was taken into account to factor in the phases where the aircraft flies slower than its cruising speed. Dividing the kerosene consumption per flight hour by the average speed considered yields a fuel consumption of **0.5927 l/km**.

Burning one litre of Jet A1 Europe kerosene produces 2.545 kg of GHG, in addition to 0.53 kg of emissions from the upstream processes such as extraction, transport, and refining, resulting in a total emission factor of 3.075 kg of GHG per litre of kerosene. Regarding the composition of GHG, more than 99% is made up of CO_2, the rest being nitrous oxide N_2O and methane CH_4 but in negligible quantities (DGAC/DTA, n.d.). Therefore, this thesis assumes that GHG and CO_2 emissions are equivalent and only the CO_2 emissions produced during combustion is considered. Consequently, the *Pilatus PC-12* emits **1.5085 kg/km** of CO_2. It is important to note that in aviation, CO_2 emissions are not the sole factors contributing to environmental pollution. The formation of persistent contrails and cirrus (ice clouds) can occur when a mass of cold and humid air is present at high altitude. This results in an increased retention of terrestrial radiation in the Earth's atmosphere, leading to a warming effect on the climate (Stéphane Amant, 2022).

3.3.1.2 Van: Mercedes Sprinter

Regarding the *Mercedes Sprinter*, it is equipped with a diesel engine that provides 84 kW of power. The average consumption and emissions data can be found in the sales catalogue (Mercedes-Benz, 2023b). Its diesel consumption per kilometre is **9.3 l/100 km**, and its total CO_2 emission is **244 g/km**. This translates to a total CO_2 emission that is around 6 times lower than that of the airplane.

3.3.2 Electric-powered vehicles

Similar to the previous subsection, this subsection details the energy consumption of vehicles equipped with electric motors. Specifically, the two vehicles considered are the *Alice* aircraft by Eviation and the *Mercedes eSprinter* van.

3.3.2.1 Airplane: Eviation Alice

Based on recent sources, the *Alice* aircraft reportedly possesses a battery capacity of 820 kWh. The aircraft is powered by two magniX 650 Electrical Power Unit motors, each offering 700 kW, making a total of 1400 kW. Similar to the *Pilatus PC-12*, an average speed of approximately 400 km/h (equivalent to 50% of the engine power) was considered. Assuming that all the energy stored in the battery is directed solely to the engine and without any intermediate losses, the energy consumption and range of the aircraft can be determined. The formula for calculating range is as follows:

$$\text{Range [km]} = \frac{\text{Capacity [kWh]} \times \text{Cruise speed [km/h]}}{\text{Engine use \% [-]} \times \text{Total Engine Power [kW]}}. \tag{3.2}$$

This results in the range of the *Alice* which is 463 km. If the battery capacity is divided by the range, the motor's electricity consumption per kilometre is known and is equal to **1,768 kWh/km**.

In the third analysis that covers a perimeter of 800 kilometres, the *Alice* aircraft under consideration is the one of preliminary estimates of technical specifications. The battery capacity of that version of *Alice* is reported to be 920 kWh, and it has three motors each rated at 260 kW, resulting in a total power output of 780 kW. Assuming an average speed of 400 km/h (i.e., about 64% of the engine power), the range of this aircraft is estimated to be 815 km, with an electricity consumption of **1,128 kWh/km**.

3.3.2.2 Van: Mercedes eSprinter

The electricity consumption of the *Mercedes eSprinter* is provided in the catalogue and is recorded at 38.5 kWh/100 km, equivalent to **0.385 kWh/km**. It should be noted that the electric motor's consumption is much more dependent on the vehicle's speed than combustion engines. Hence, the consumption and autonomy of the vehicle can vary up to 50% depending on whether it's travelling at 80 km/h or 120 km/h (Mercedes-Benz, 2023a). However, for this study, the autonomy and electricity consumption considered is based on the catalogue's information, regardless of the vehicle's speed.

3.3.2.3 Note on $C0_2$ emissions

The absence of CO_2 emissions during the operation of electric motors is evident in terms of CO_2 emissions, resulting in zero emissions for the two electric vehicles under consideration. Nonetheless, it is important to note that the environmental friendliness of electric vehicles depends on the source of electricity production. If the electricity production source is natural gas, coal or oil, it is not necessarily environmentally friendly. Furthermore, batteries are currently highly polluting due to the use of precious metals like lithium during production, harmful liquid products, and issues with recycling at the end of their lifespan.

Unlike heat engines where emissions are directly visible at the exhaust, emissions from electric vehicles are not seen directly during use but are produced upstream. This could lead to the false belief that the electrification of transportation is a perfect green solution without any emissions. Nevertheless, with the development of new means of electricity production that make better use of natural resources such as hydropower or wind power, this factor could give electric vehicles a considerable advantage in the future. In terms of batteries, solid batteries are expected to be introduced by the end of the decade. This could be a revolution because they would be much cleaner for the environment and have an increased capacity per kilo by almost a factor of two, going from approximately 250 Wh/kg for the current liquid batteries to 500 Wh/kg for future solid batteries (Xia et al., 2018). Since this thesis only considers the CO_2 emissions produced during the vehicle use and does not take into account upstream processing, the CO_2 emissions are kept at **zero**. A more complete analysis of CO_2 emissions taking into account all the factors involved in the operation of an electric motor can be the subject of a future study.

3.4 Costs of the studied vehicles

The final section discusses the last assumptions and inputs required for the VRP simulations, which include the evaluation of the overall delivery costs. The latter can be divided into three categories:

- Variable costs: which refer to the expenses that vary directly with the level of activity;
- Fixed costs: which remain constant regardless of changes in the volume of activity;
- Salary costs.

For each vehicle studied, an evaluation of these three costs is evaluated and detailed in the following.

It is worth mentioning that some of the cost assumptions for vans especially are derived from previous analyses conducted on autonomous transport trucks in Volvert's thesis (Volvert, 2020) who himself was inspired by (Lambert, 2019).

3.4.1 Cost of the Eviation Alice & Pilatus PC-12

First, the expenses related to the aircraft are examined, but as the *Alice* plane is still not in operation, limited cost information is currently available. Thus, most of the costs are derived from the *Pilatus PC-12* with some modifications and adjustments.

3.4.1.1 Variable costs

The first variable cost analysed is the fuel or the electricity needed by the engine. The cost of the vehicle is determined by various factors including the current price of fuel or electricity, the vehicle's consumption rate, the distance traveled, and the number of customers to be visited. For the *Pilatus PC-12* using kerosene, as fuel prices fluctuate constantly, a European price[3] of 0.674€/l was selected on February 3rd, 2023 (IATA, 2023). Regarding the consumption per kilometre, it has already been determined in section 3.3 and is 0.59274 l/km. By combining these last two data, a consumption price per kilometre can be obtained and is worth **0.3995€/km**.

For the *Alice* plane, it is the price of electricity that must be determined. While a kerosene price is considered even for the entire European continent, this cannot be done for the electricity price. Indeed, the price per kilowatt-hour in February 2023 could vary from 0.131€ in Luxembourg to 0.425€ in Germany (GlobalPterolPrices, 2023). Thus, to try to take this effect into account without complicating things too much, an average value is chosen between all the countries involved in each scenario. As a result, according to each scenario the average price of electricity is different and are listed in Tab. 3.2:

Scenario	Price [€/kWh]	Tax (21%) [€/kWh]	Deduced Price [€/kWh]	Consumption Price [€/km]
Benelux	0.2287	0.04802	0.1675	0.2961
400 km	0.2552	0.053592	0.1884	0.3331
800 km	0.2803	0.05887	0.2083	0.2349

Table 3.2: Electricity price, deduced price & consumption price depending on the scenario

Since the company uses this electricity as part of its economic activity to deliver goods or provide services, the latter may deduct the taxes and excise duties present in the costs shown above. For excise duties, a single value was considered, which is 13.189€/MWh, i.e. 0.013189€/kWh (news.belgium, 2023). Thus, the actual expenses of the logistics company are obtained in Tab. 3.2. Now that the kilowatt-hour cost is known for each scenario, it can be combined with the consumption of the aircraft *Alice* determined in section 3.3 i.e. 1.768 kWh/km for the current version and 1.128 kWh/km for the version with 800 km range. Then, the kilowatt-hour price per kilometre is known and appears in Tab. 3.2.

Regarding the remaining variable costs, these have been taken from an analysis already done on the *Pilatus PC-12* by Liberty Jet and Compare Private Planes (Liberty Jet, 2023) & (Compare Private Planes, 2023). These are the following:

- maintenance cost: to ensure the aircraft is safe for flight,
- engine overhaul,
- traffic charges: depends a lot on the destinations visited and the roads taken (therefore difficult to evaluate),
- miscellaneous costs to fill in the costs that would have been forgotten.

3 Indeed, from one continent to another, the price of kerosene can change significantly.

In the reference analysis, the costs listed are given considering that the *Pilatus PC-12* flies 200 and 400 hours per year with an average speed of 250 mph or 402.34 km/h. It is noticed that the cost between 200 hours and 400 hours of flight per year is simply doubled. Hence, by considering the average speed and the variable costs in the reference analysis, it is possible to calculate each cost per kilometre by using a proportional relationship i.e. a rule of three. In addition, the rule of three formula also involves converting the price given in dollars in the reference analysis into euros. Hence, the formula is as follows:

$$\text{Var. cost per km [€/km]} = \frac{\text{Var. cost for Xh flight [\$]} \times \text{Conv. coef. € to \$ [€/\$]}}{\text{X h of flight [h]} \times \text{Average speed of flight [km/h]}}, \quad (3.3)$$

where X is either 200 hours or 400 hours, the conversion coefficient was taken on February 12, 2023 and was 1$ was 0.94€. Thanks to Eq. 3.3, all the variable costs of the *Pilatus PC-12* are determined and are summarised in Tab. 3.3.

For the *Alice* aircraft, as said previously, given that no information is yet available on the value of the variable costs, the latter are taken from those obtained with the *Pilatus PC-12* with an adjustment coefficient if necessary. This is the case for determining the cost of maintenance and engine overhaul. Indeed, by experience of electric cars, it is known that maintenance costs about 30% less in the case of electric engines compared to thermal ones (Houguet, 2021). Hence, a coefficient of 0.7 is added to the numerator of Eq. 3.3, for maintenance and engine overhaul costs. This therefore gives all the necessary variables for the two planes and are summarised in Tab. 3.3.

[€/km]	*Pilatus PC-12*		*Alice*	
	All 3 scenarios	Benelux	400 km	800 km
Fuel/Electricity Consumption	0.3995	0.2961	0.3331	0.2349
Maintenance	0.5563	0.3894	0.3894	0.3894
Engine Overhaul	0.4505	0.3153	0.3153	0.3153
Traffic Charges	0.2336	0.2336	0.2336	0.2336
Miscellaneous Variable	0.0584	0.0584	0.0584	0.0584
Total	1.64	1.2929	1.3300	1.2317

Table 3.3: Summary of the variable costs for *Pilatus PC-12* & *Eviation Alice*

3.4.1.2 Fixed costs

The reference analyses done by Liberty Jet and Compare Private Planes also suggest a breakdown of fixed costs (Liberty Jet, 2023) & (Compare Private Planes, 2023). However, the latter does not take into account an essential factor which is the depreciation of the vehicle. It is therefore chosen in the context of this thesis to add to these costs that of the depreciation of the vehicle. In addition, depreciation and other fixed costs such as insurance depend on the acquisition value of the vehicle. Thus, it is essential to differentiate between the version with a driver and the autonomous one, unlike the variable costs that do not make this distinction. Indeed, it is considered that autonomous vehicles are equipped with more efficient autopilots to ensure the execution of tasks in a completely independent manner. Therefore, a 25% increase in its acquisition value has been considered. (Volvert, 2020). As for the variable costs, the reference analyses mentions prices in dollars and are converted into euros according to the conversion rate of February 12, 2023, which is 0.94€ for 1$. The fixed costs taken into account in this work are determined in the following.

First, the depreciation of the *Pilatus PC-12* is based on its estimated acquisition value of 4.4 million dollars. On average, an airplane is estimated to be able to fly between 25 and 30 years. The duration of aircraft depreciation may be shortened to 10-15 years for low-cost civil airlines that use their aircraft more intensively (AirIndemnité, 2019). This thesis considers a moderate approach, assuming a lifespan of 20 years. In addition, since it involves the transportation of goods rather than people, there are fewer risks to human life, so the lifespan can be extended compared to the civilian sector. This therefore leads to an amortisation of 206,800€/year. For the autonomous version, as previously stated, the acquisition value of the standard version is retaken but increased by 25%. With regard to the lifespan, the latter is reduced to 15 years because it is considered that the use of autonomous aircraft can be more intense given the absence of pilots and its legislation. Hence, this results in amortisation of 344,667€/year. Concerning the *Alice*, the same hypotheses on the lifespan are made except that the acquisition cost is 4 million dollars. As a consequence, this leads to a depreciation of 188,000€/year for the version with pilot and 313,333€/year for the autonomous version.

The cost of insurance is taken directly from the cost breakdown proposed by Liberty Jet and is 18,941$. However, as the insurance cost is determined based on the acquisition value of the vehicle, it is assumed that the insurance price for the autonomous version can be estimated by adjusting the latter for the regular *Pilatus PC-12* using a rule of three calculation. For the *Alice*, as no data is currently available, the same rule of three principle from the *Pilatus PC-12* is used. The obtained costs are shown in Tab. 3.4.

Compare Private Planes also provides a cost called Jet Management (Compare Private Planes, 2023). Indeed, when holding aircraft, an aircraft management company is needed. The latter offers a comprehensive range of services required for operating the aircraft such as managing pilots, ensuring airworthiness, and other related tasks. It is therefore necessary to provide for costs called Jet Management. The latter is assumed to be identical to each aircraft considered in this thesis and is estimated to be 30,000$/year. Then, comes the cost of renting a hangar to park the planes. Once again, this cost comes directly from that determined for the *Pilatus PC-12* and is considered to be the same for each of the aircraft studied. The latter is estimated at 28,827$/year.

For the standard versions with pilot, crew training costs to maintain the crew level must be planned. The cost presented for the *Pilatus PC-12* by Liberty Jet reflects the price of a single pilot. Thus, the latter must be doubled in the case that there are two pilots in the cockpit. The same cost is taken into account for the *Alice* and amounts to 10,898$/year. Obviously, for the autonomous version of the two planes this cost is equal to zero. Finally, as in the case of variable costs, miscellaneous fixed costs are considered to take into account any costs that may be omitted. The latter is once again the same for all aircraft considered and is 7,485$/year.

It should be noted that the fixed costs are generally expressed "per year" and remain constant. As explained above, they do not depend on the number of customers visited or the number of kilometres traveled. However, to obtain a more accurate estimate within the maximum 48-hour time frame for cost analysis of the delivery company in this thesis, the fixed costs are converted to a daily cost. The summary of all fixed costs presented is shown in Tab. 3.4.

	Pilatus PC-12		*Alice*	
	Driver	Autonomous	Driver	Autonomous
Depreciation [€/year]	206,800	344,667	188,000	313,333
Crew Training [€/year]	10,244	0	10,244	0
Insurance [€/year]	17,805	22,256	16,186	20,232
Hangar [€/year]	27,097	27,097	27,097	27,097
Jet Management [€/year]	28,200	28,200	28,200	28,200
Miscellaneous Fixed [€/year]	7,036	7,036	7,036	7,036
Days of use /year	231	303	231	303
Total fixed cost [€/year]	297,182	429,256	276,763	395,899
Total fixed cost [€/day]	1,286	1,416	1,198	1,307

Table 3.4: Summary of the fixed costs for *Pilatus PC-12* & *Eviation Alice*

From this table, it can be computed for all the planes studied, the depreciation represents between 70% and 80% of the total fixed costs. This obviously represents a significant cost for the delivery company.

3.4.1.3 Salary costs

As for the pilots' salary, this is once again taken directly from the list of operational costs presented by Liberty Jet and Compare Private Planes and amounts to 79,464$/year or 74,696€/year. As with the fixed cost of crew training, this cost is relative to a single pilot. In the case that there are two pilots in the cockpit, the salary cost must be doubled. When the pilot is forced to spend the night away from home, then an indemnity must be paid for his expenses and amounts to 37.18€/night (Securex, 2018).

For the autonomous version since there is no pilot driving the plane, no salary or indemnity needs to be provided. However, a person must be in charge of unloading goods from the plane and doing the other operations necessary for the plane to be able to leave and go to the next customer. To evaluate this cost, the same assumption is made as in Volvert's thesis (Volvert, 2020) which is to say that a vehicle operator costs about 28€/h and takes about 10 minutes per vehicle to do all the tasks assigned to him. Therefore, the salary cost considered is evaluated at 4.67€/customer.

3.4.2 Cost of the Mercedes Sprinter & Mercedes eSprinter

Now that the cost breakdown has been determined for planes, the same is done for vans. Once again, the breakdown of costs has already been studied in Volvert's thesis as part of the VRP study for trucks (Volvert, 2020). This decomposition has been taken and added with the case of vans considered i.e. *Mercedes Sprinter* and *Mercedes eSprinter*.

3.4.2.1 Variable costs

The first variable cost to be taken into account is the fuel/electricity consumption of the two vehicles. As in the case of planes, depending on the country, the latter varies. To take this effect into account while remaining simple, an average price is determined according to the countries considered in each scenario. The diesel price was taken in February 2023 according to (Autotraveler, 2023). These result in Tab. 3.5. As with electricity, taxes and excise duties can be recovered. The tax being 21% of the sum considered, the latter varies according to the scenario. Whereas for excise, only one value is taken into account and amounts to 0.205€/l (UPTR, 2023). By removing excise duty and tax, the deducted price per litter is obtained for each scenario. Then, by combining this deducted price per litre with the consumption of the *Mercedes Sprinter* determined in section 3.3, a consumption price per kilometre is obtained. As a consequence, this results in the true expense per kilometre received by the delivery company in Tab. 3.5. For the price of electricity, the latter has already been presented for the aircraft *Alice* and the effective price per kilowatt-hour to pay by the delivery company is shown in Tab. 3.2. The *Mercedes eSprinter*'s consumption per kilometre, as determined in section 3.3, is much lower than that of the *Alice*, resulting in a lower price of consumption per kilometre. The latter appears in Tab. 3.6.

Scenario	Price [€/l]	Tax (21%) [€/l]	Deduced Price [€/l]	Consumption Price [€/km]
Benelux	1.677	0.3522	1.1198	0.1041
400 km	1.737	0.3647	1.1668	0.1085
800 km	1.794	0.3768	1.2124	0.1128

Table 3.5: Diesel price, deduced price & consumption price depending on the scenario

Then, come the costs for maintenance and repairs. For a *Mercedes Sprinter* the latter amounts to 0.0435€/km (Sprinter Discovery, 2023). As mentioned in the aviation section, an electric motor costs about 30% less than a combustion engine due to greater simplicity in terms of mobile parts. Thus, the price of maintenance and repairs for the *Mercedes eSprinter* amounts to 0.03046 €/km. Furthermore, the cost of tires is factored in by dividing their market price by the guaranteed distance they can cover. Thus, the price per kilometre for the tires amounts to 0.0114€/km (Ebay, 2023).

Finally, unlike vehicles exceeding a maximum authorised weight (MMA) of 3.5 tonnes, the *Mercedes Sprinter* and *eSprinter* are not subject to the toll. However, in some countries such as Italy or Austria, the use of bridges, tunnels or motorways is chargeable for all users. To take this factor into account, an average of the price of motorways is calculated for each scenario (Roadsurfer, 2023). These are listed in Tab. 3.6.

Therefore, the variable costs can be summarised according to the following Table:

[€/km]	*Mercedes Sprinter*			*Mercedes eSprinter*		
	Benelux	400 km	800 km	Benelux	400 km	800 km
Fuel/Electricity Consumption	0.1041	0.1085	0.1128	0.0645	0.0725	0.0802
Maintenance & repairing	0.0435	0.0435	0.0435	0.0305	0.0305	0.0305
Tires	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114
Toll	0	0.020	0.038	0	0.020	0.038
Total	0.1591	0.1834	0.2054	0.1063	0.1344	0.1598

Table 3.6: Summary of the variable costs for *Mercedes Sprinter* & *Mercedes eSprinter*

3.4.2.2 Fixed costs

As with the case of aviation, the cost of depreciation is taken into account first. The standard and autonomous versions must be distinguished once again as they have different acquisition values and depreciation periods. The autonomous versions have recorded a 25% increase in acquisition value compared to the standard versions, as previously operated. This once again can be explained by the presence of a more efficient autopilot system in the autonomous version. Thus, for the *Mercedes Sprinter* its catalogue value is 44,645€ for the standard version and the standalone version is then 55,806€. For the *Mercedes eSprinter* the standard and standalone version are 58,935€ and 73,669€ respectively (Mercedes-Benz, 2023c). Moreover, the depreciation period for commercial vehicles is usually 5 years but in cases where the latter is intensively used, the duration can be reduced to 4 years (Centaure, 2016). This will therefore present another difference between the standard and autonomous versions, since the latter can be used more intensely in the absence of driver and its regulations. The value of depreciation calculated for each vehicle is summarised in Tab. 3.7.

The next consideration is the road tax, which differs depending on the type of vehicle. Currently, electric vehicles are exempt from road tax (Centaure, 2023), while for utility vehicles with a combustion engine, it depends on their maximum authorised weight. The amount of road taxes in Wallonia are given by the SPW Fiscalité (SPW Fiscalité, 2023). Thus, in the case of the *Mercedes Sprinter* and *eSprinter*, the latter having an MMA of 3.5 tones, the annual tax is 148.78€/year.

In Volvert's thesis, two insurances are taken into account, i.e. that of the vehicle and that called CMR (Volvert, 2020). The first, as its name suggests, is insurance on the van itself, while the second is an insurance on the goods transported. As explained in his work, the price of insurance on the vehicle varies with their acquisition price and the latter made a rule of three to determine the price of the autonomous version of the truck. As insurance prices are quite complex to find, a rule of three is also applied based on its results for the vehicles considered in this thesis. Insurance values of for the van are summarised in Tab. 3.7. A slightly higher value has been assigned to the CMR insurance due to the possibility of more luxurious goods being transported in vans, as they have smaller capacities compared to trucks. As a result, the CMR insurance value has been set at 800€.

Finally, as for aviation, additional costs that are not detailed are grouped together in the fixed miscellaneous costs. The latter constitute the costs of the hangar, electricity, heating, etc. For this fixed cost, the same value as in Volvert's thesis was considered and is 15,000€

(Volvert, 2020).

Therefore, the fixed costs can be summarised according to the following table:

	Mercedes Sprinter		*Mercedes eSprinter*	
	Driver	Autonomous	Driver	Autonomous
Depreciation [€/year]	8,929	13,952	11,787	18,417
Road Tax [€/year]	148.78	148.78	0	0
Van insurance [€/year]	2,679	3,348	3,536	4,420
CMR insurance [€/year]	800	800	800	800
Miscellaneous Fixed [€/year]	15,000	15,000	15,000	15,000
Days of use /year	231	303	231	303
Total fixed cost [€/year]	27,556	33,249	31,123	38,637
Total fixed cost [€/day]	119.29	109.73	134.73	127.52

Table 3.7: Summary of the fixed costs for *Mercedes Sprinter* & *Mercedes eSprinter*

From Tab. 3.7, it can be computed again that vehicle depreciation accounts for a large part of the total fixed cost. Indeed, the latter can vary between 30% and 50% of the total fixed cost. However, in this case, miscellaneous costs account for a significant portion of the total fixed cost, unlike aircraft where the cost breakdown is more detailed. As a result, miscellaneous costs for vans include more cost elements, leading to a higher and more significant value compared to the breakdown of fixed costs for aircraft.

3.4.2.3 Salary costs

The salary relating to the driver is once again taken from Volvert's thesis. The latter considers the brute salary of 12,104€/h to which he adds 6,777€/h of employee contribution and 3,355€/h of additional expenditure on driver seniority and other ancillary expenses. This therefore leads to a total of 22.24€/h. For more details see (Volvert, 2020) & (Lambert, 2019). Once again, in the case when the driver spends the night abroad, the latter will receive a compensation of 37.18€/night.

As in the case of aviation, the autonomous version does not require direct salary costs since no driver is present to drive the vehicle. However, a sum must be paid to take into account the labour which will take care of unloading the delivery and preparing the vehicle to leave for its next destination. The same value is taken as in the case of aviation and is 4.67€/customer.

3.4.3 Comment on all the costs

Upon evaluating all the calculated costs for various vehicle types and their corresponding pilot/driver configurations, it becomes apparent that airplanes remain significantly more expensive by a factor of approximately 10 compared to vans. This difference holds true for both variable and fixed costs. Referring to Tab. 3.8, the transition to electric air transport leads to a reduction in variable costs ranging from 18 to 25%, and a decrease in fixed costs of 6 to 7%. Similarly, in the context of road transport, even more substantial savings are anticipated, with variable costs projected to decrease by 22 to 33%, and fixed costs to see a reduction of 13 to 16%. These percentages are derived from Tabs. 3.3, 3.4, 3.6 & 3.7, where each instance involves a comparison between combustion engine and electric versions based on the different scenarios (Benelux, 400km, and 800km) for variable costs and the consideration of autonomy or not for fixed costs.

	Variable costs [%]	Fixed costs [%]
Aviation	18-25	6-7
Vans	22-33	13-16

Table 3.8: Savings made for variable and fixed costs when electrifying vehicles

Drawing from the aforementioned discussions and the outcomes presented in Tab. 3.8, it can already be inferred that while the electrification of the aviation sector has the potential to render it relatively more cost-effective, it will likely remain significantly more expensive than road transport. Regarding variable costs, the principal factors contributing to this contrast are energy consumption and maintenance expenses. In terms of fixed costs, the substantial disparity arises from the higher depreciation expenses in aviation, primarily attributed to the considerable acquisition costs associated with aircraft. The subsequent chapter will serve to validate these findings in a practical context through VRP simulations. Consequently, these simulations will replicate real-world scenarios involving the utilisation of these vehicles within the framework of delivery routes.

4

OPTIMISED ROUTES OF VANS & AIRPLANE FOR FREIGHT TRANSPORT

In the previous chapters, the mathematical model of the VRP was presented with all the assumptions made on the latter in order to obtain a realistic representation of the air and road dispatching situation in Europe. It is now possible to launch VRP simulations to finally answer the main question posed in this thesis which is to determine if it is nowadays economically interesting to go electric in the world of logistics. In a second step, it will also be possible to determine how advantageous it is to reduce the number of crew members initially from two to one pilot and ultimately transitioning to a fully autonomous vehicle.

To do this, as explained in the preceding chapter, each of the three study scenarios will be simulated a large number of times, each time choosing customers randomly from the list of destinations in Tab. 3.1. As explained in Chapter 2, the computation time complexity of the VRP increases sharply when the number of destinations taken into account raises. It is for this reason that in this work, the number of customers considered was limited to a maximum of 10. Then by the same idea, the number of simulations for each scenario has been limited to 100 due to the time-consuming nature of the computations, particularly when dealing with a large number of customers. However, 100 simulations already provides a good general and fairly precise vision of the result to be deduced. Consequently, in each of the three scenarios, a range of 1 to 10 cities to be visited is considered, and 100 simulations are conducted for each number of cities. This process is repeated for both planes and vans, while also varying the number of crew members/drivers operating the vehicles.

Regarding the results, these are shown in three phases. First, a typical route on the map is shown in each of the three scenarios comprising 10 customers. For one particular case with 10 randomly selected clients, it will be possible to see the number of vehicles needed to serve all customers, at what time each vehicle leaves one destination and arrives at another. This first phase is an opportunity to visualise the result returned by a VRP simulation. Then, the results related to the 100 simulations are shown. These are revealed in the form of boxplots showing the total cost per customer according to the number of customers. Therefore, the effect of the number of clients on the total cost of the entire delivery trip per customer can be seen through this. In addition, each boxplot directly compares the results between fuel-powered and electric vehicles. Thus, it will be clearly visible in which case the electric plane is economically advantageous and vice versa. Finally, from a few interesting situations, a cost breakdown is carried out in order to see what are the main factors forming the total price of the tour and how does their relative share evolve according to the number of customers.

4.1 Case study with planes: Benelux

The first case study considers the smallest perimeter of destination by taking into account the three countries constituting the Benelux. As a reminder, in this case study, the suppliers only have 9 hours to serve all customers. The latter being open only between 8 a.m. and 5 p.m..

4.1.1 Typical journey analysis

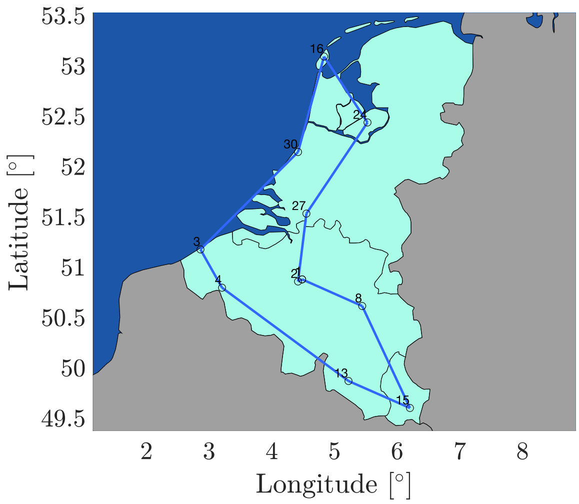


Figure 4.1: Path taken by the aircraft (for all cockpit & vehicle configurations): Benelux

	Two Pilots				One Pilot				Autonomous			
	Electric		Fuel		Electric		Fuel		Electric		Fuel	
Stop	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure
1	-	M 07:59	-	M 07:59	-	M 07:59	-	M 07:59	-	M 07:59	-	M 07:59
2	M 08:00	M 08:30	M 08:00	M 08:30	M 08:00	M 08:30	M 08:00	M 08:30	M 08:00	M 08:30	M 08:00	M 08:30
27	M 08:41	M 09:11	M 08:41	M 09:11	M 08:41	M 09:11	M 08:41	M 09:11	M 08:41	M 09:11	M 08:41	M 09:11
24	M 09:21	M 09:59	M 09:21	M 09:59	M 09:21	M 09:59	M 09:21	M 09:59	M 09:29	M 09:59	M 09:21	M 09:59
16	M 10:12	M 10:42	M 10:12	M 10:42	M 10:12	M 10:42	M 10:12	M 10:42	M 10:12	M 10:42	M 10:12	M 10:42
30	M 10:58	M 11:28	M 10:58	M 11:28	M 10:58	M 11:28	M 10:58	M 11:28	M 10:58	M 11:28	M 10:58	M 11:28
3	M 11:50	M 12:20	M 11:50	M 12:20	M 11:50	M 12:20	M 11:50	M 12:20	M 11:50	M 12:20	M 11:50	M 12:20
4	M 12:27	M 12:57	M 12:27	M 12:57	M 12:27	M 12:57	M 12:27	M 12:57	M 12:27	M 12:57	M 12:27	M 12:57
13	M 13:23	M 13:53	M 13:23	M 13:53	M 13:23	M 14:38	M 13:23	M 14:38	M 13:23	M 13:53	M 13:23	M 13:53
15	M 14:05	M 14:35	M 14:05	M 14:35	M 14:50	M 15:20	M 14:50	M 15:20	M 14:05	M 14:35	M 14:05	M 14:35
8	M 14:53	M 15:23	M 14:53	M 15:23	M 15:38	M 16:08	M 15:38	M 16:08	M 14:53	M 15:23	M 14:53	M 15:23
1	M 15:34	-	M 15:34	-	M 16:19	-	M 16:19	-	M 15:34	-	M 15:34	-

Table 4.1: Flight schedule and trajectory for all cockpit & vehicle configurations: Benelux

As can be seen in Fig. 4.1, the VRP model finds the same optimum path to follow for all configurations. Whether for the number of members in the cockpit or for the type of engine of the aircraft. Moreover, despite the rather tight time frame to serve the 10 customers, a single plane is enough. However, as can be seen in Tab. 4.1 the latter does not always arrive at the same times at the various destinations. Indeed, as highlighted in red in Tab. 4.1, in the case of the cockpit with one pilot, the latter suffers a delay compared to the other configurations when departing from destination 13 to go to destination 15. This delay is simply explained by the fact that the legislation in the one-pilot version requires the pilot to rest on the ground for 45 minutes after 6 hours of work, whereas the other two-pilot and autonomous versions do not do not have this constraint. Hence the 45-minute delay in the one pilot version compared to the others. Here, as the distances are relatively short, the charging time for electric vehicles never exceeds the half-hour s dedicated to unloading the plane at destination i. Thus, the same results are observed between electric and fuel vehicles.

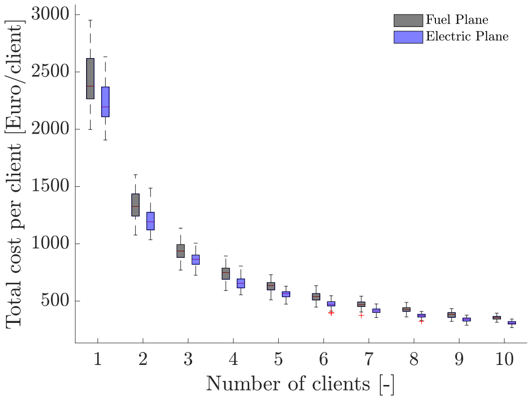
	Two Pilots		One Pilot		Autonomous	
	Electric	Fuel	Electric	Fuel	Electric	Fuel
Total working time	7h35	7h35	7h35	7h35	7h35	7h35
Total driving time	2h35	2h35	2h35	2h35	2h35	2h35
Total distance [km]	1049	1049	1049	1049	1049	1049
Total cost [€]	3249	3763	2769	3395	2712	3247

Table 4.2: Total cost, distance and working & driving time (planes): Benelux

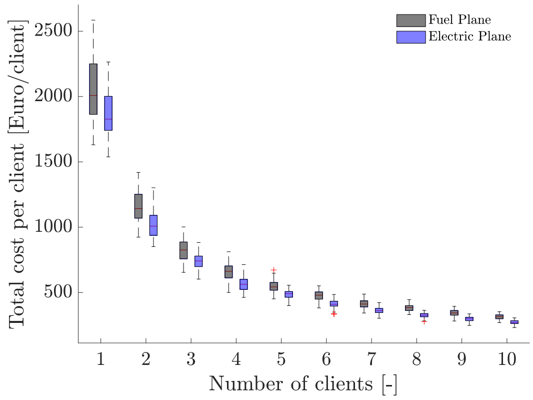
In Tab. 4.2 it can be seen that the driving time is exactly the same in all configurations. This can be attributed to the uniform cruising speeds assumed and the equal distances covered throughout the entire delivery route. In terms of working time, a consistent duration is observed whereas in Tab. 4.1, the schedules are different for the one pilot version. The reason for this is that the calculation of working time does not include any consideration of rest periods. Finally, concerning the total cost, it can also be seen that the fuel version is each time more expensive than the electric version and the more the number of members in the cockpit is reduced, the total cost also decreases.

4.1.2 Cost per client

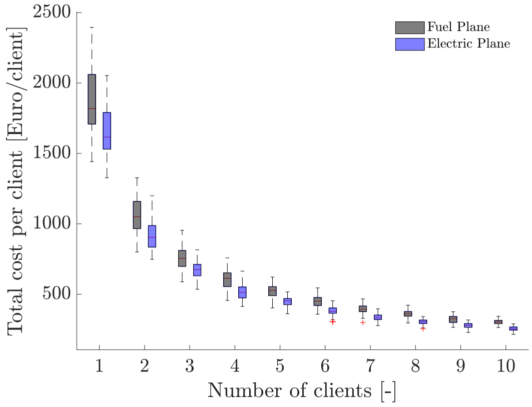
Now that a typical trip has been analysed, it is time to look at what the VRP gives in general with a large number of simulations. As explained before, the results shown below correspond to VRPs considering a number of customers varying from 1 to 10. Furthermore, for every customer count considered, 100 simulations are conducted for both the electric and fuel-powered planes, with destinations being randomly selected from the city list shown in Tab. 3.1. The results are shown in the following figures.



(a) Two Pilots



(b) One Pilot



(c) Aunonomous

Figure 4.2: Total cost per client of electric & fuel-powered planes: Benelux

As can be seen in Figs. 4.2a, 4.2b & 4.2c, the results are shown in boxplot form. Thus, an overall statistical view can be seen of the total cost of the tour per customer according to the number of customers. In this case, the decision was made to display the total cost per customer as it provides more comprehensive information compared to solely presenting the overall route cost. Indeed, it is reasonable to expect that as the number of customers increases, the total cost of the tour will also increase. On the other hand, the more the number of customers increases, the more the cost of the tour per customer is supposed to decrease. The figures presented above clearly demonstrate a decreasing exponential trend in the curve, highlighting the expectations. Furthermore, it is evident that the interquartile range and the whiskers consistently decrease in width as the number of customers increases. The reason is that when there are few customers taken into account, the distance to be covered by the vehicles can vary greatly between two simulations. Hence, the total costs of the delivery round show a larger variance as they are influenced by variable costs, which in turn are dependent on the distance travelled. Nevertheless, the width of the whiskers and of the interquartile range decrease fairly regularly and still remain fairly narrow for all the customer cases taken into account compared to the scenarios shown afterwards.

In the three cockpit configurations, some outliers can be noticed between 6 and 8 customers considered. Nonetheless, these are quite rare compared to the other scenarios that will follow and remain very close to the ends of the whiskers or even the median. This observation can be attributed to the relatively small geographical scope of the considered destinations (i.e., the Benelux) for an aircraft, given its high speed. Even in extreme cases where the distances to be covered deviate significantly from the median value, they remain relatively small and can be traversed quickly by the latter. Hence, the outliers present in the figures above are once again due to the variations of the variable costs which depend on the distance travelled. From Figs. 4.2a, 4.2b & 4.2c, it can also be deduced that in all cases of simulations, only one aircraft was used. As emphasised in section 3.4 when calculating the different costs, it was noted that aircraft, especially with their depreciation, have significant fixed costs. These fixed costs are calculated on a per-vehicle and per-day basis. In the present scenario, which allows for only one day, the use of multiple aircraft is feasible. However, if multiple aircraft were to be utilised in certain simulations, it is expected that outliers deviating significantly from the medians would be observed. This observation will be further explored in future scenarios.

Ultimately, upon a closer analysis of the costs, it becomes evident as during the typical journey analysis that the total cost of delivery decreases as the number of people in the cockpit decreases. This makes sense given that the salaries of the pilots determined in section 3.4.1.3 are quite substantial. From Tab. B.1 in Appendix B, going from a two-pilot version to standalone can save up to 26% in cases where there is one customer considered and 15% in the case of 10 customers. More details on cost comparisons are available in Appendix B. Then, for each cockpit configuration, the electric and fuel-powered aircraft are compared. In all three cases, the electric aircraft always generates a lower total delivery cost than that of the fuel-powered one. Once again from Tab. B.1 in Appendix B, electric aviation saves up to 11% compared to the fuel version when when one customer and 17% when 10 customers are considered. Again, more details on the cost comparisons are available in Tab. B.1 in Appendix B.

4.1.3 Cost breakdown

In the previous section on total delivery costs, a lot of information has already been mentioned on the factors that make up the latter. In this section, the breakdown of the costs generating the total costs with their relative share is shown graphically. To see the evolution of the different factors according to the number of customers, two key situations are shown. The one with one client and the one with 10 clients. Moreover, the graphs shown in this section correspond to the case forming the medians in Figs. 4.2a, 4.2b & 4.2c (with 1 and 10 customers).

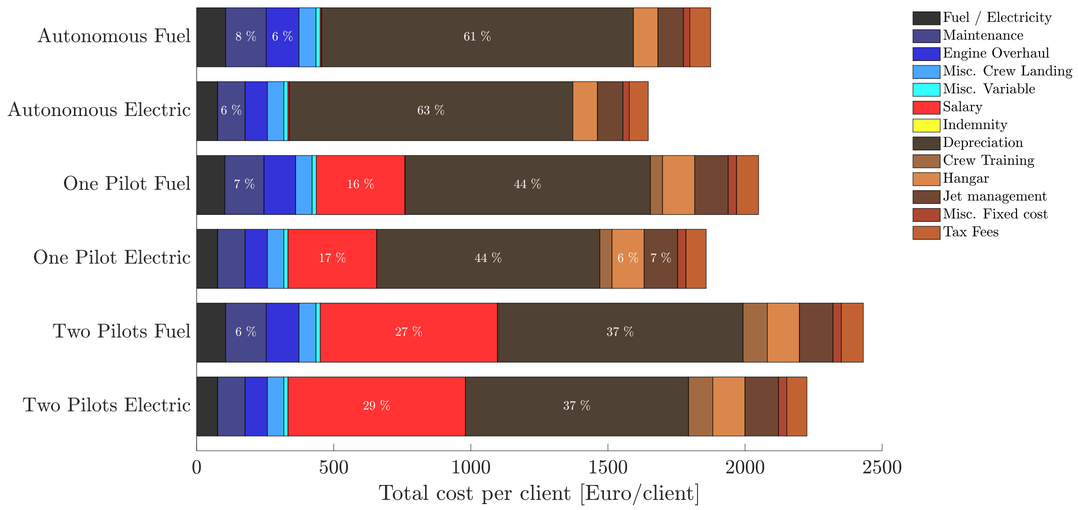


Figure 4.3: Cost breakdown with planes: Benelux - one client

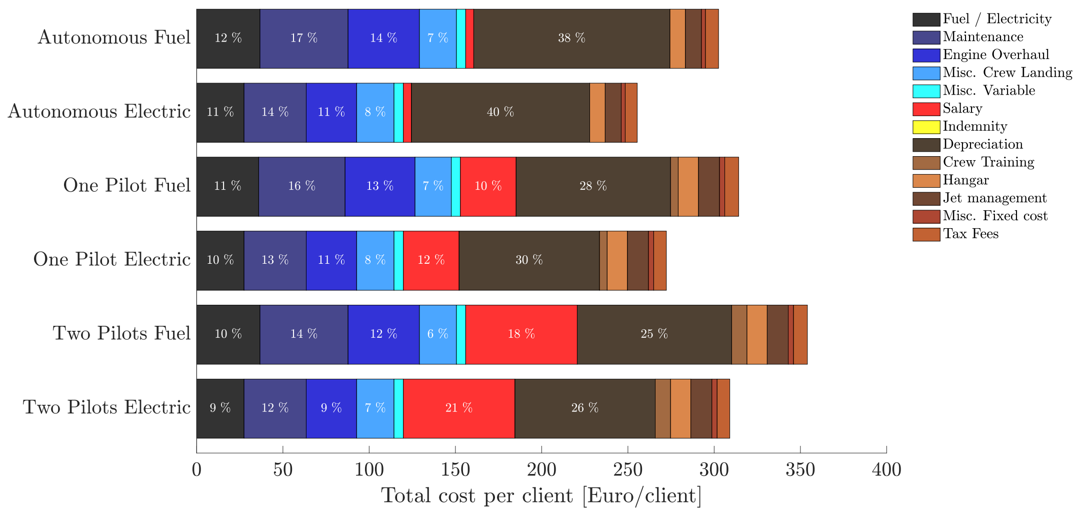


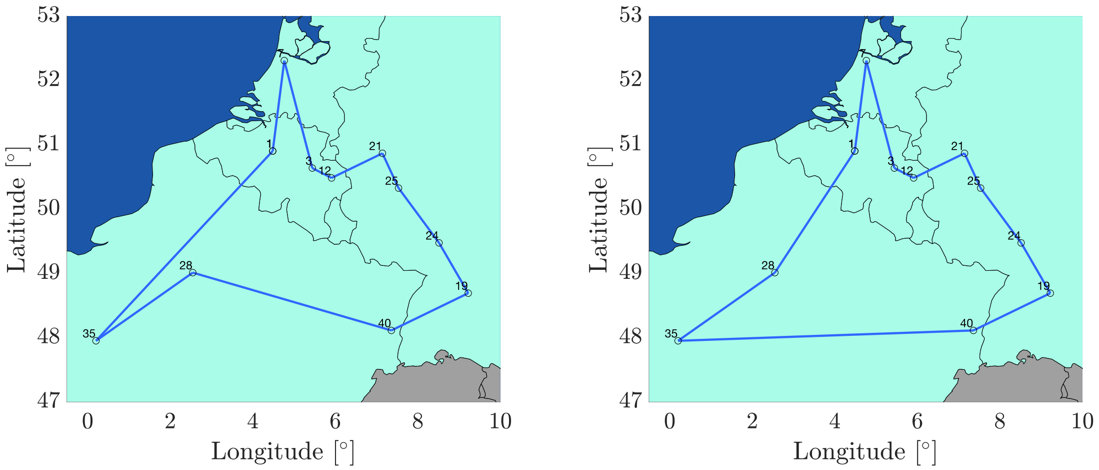
Figure 4.4: Cost breakdown with planes: Benelux - 10 clients

From Figs. 4.3 & 4.4, the deductions made in the previous section are confirmed. Indeed, in all cases, the two largest contributors to the total cost formation are the depreciation of the vehicle and the salary when drivers are present. Together, they constitute almost 60% of the total cost when only one customer is considered. However, as the number of customers increases, their relative share decreases, accounting for only approximately 40% collectively. Actually, this is due to the fact that the latter represent fixed costs and are constant regardless of the number of customers. As a result, the parts that increase when the number of customers increases are the variable costs, in particular with the cost of fuel/electricity, maintenance and engine overhaul. In addition, it can also be noticed that the variable costs of the electric versions are lower than those of the fuel versions, explaining the lower total costs encountered in the previous sections of the electric aircraft.

4.2 Case study with planes: 400 km

The second case study focuses on destinations that are within a 400 km radius of the main depot, located in Brussels. Destinations in the United Kingdom are not included in this study. For this scenario, the time frame is expanded to two consecutive working days, and the customers' opening hours are set between 6 a.m. and 10 p.m..

4.2.1 *Typical journey analysis*



(a) Electric Plane (b) Fuel-powered Plane

Figure 4.5: Path taken by the aircraft (for all cockpit & vehicle configurations): 400 km

	Two Pilots		One Pilot		Autonomous			Two Pilots		One Pilot		Autonomous	
Stop	Arrival	Departure	Arrival	Departure	Arrival	Departure	Stop	Arrival	Departure	Arrival	Departure	Arrival	Departure
1	-	M 04:53	-	M 04:53	-	M 04:53	1	-	M 05:37	-	M 05:37	-	M 05:37
35	M 06:00	M 07:08	M 06:00	M 07:08	M 06:00	M 07:08	7	M 06:00	M 06:30	M 06:00	M 06:30	M 06:00	M 06:30
28	M 07:39	M 08:11	M 07:39	M 08:11	M 07:39	M 08:11	3	M 06:58	M 07:28	M 06:58	M 07:28	M 06:58	M 07:28
40	M 09:05	M 10:01	M 09:05	M 10:01	M 09:05	M 10:01	12	M 07:34	M 08:04	M 07:34	M 08:04	M 07:34	M 08:04
19	M 10:23	M 10:53	M 10:23	M 11:38	M 10:23	M 10:53	21	M 08:18	M 08:48	M 08:18	M 08:48	M 08:18	M 08:48
24	M 11:08	M 11:38	M 11:53	M 12:23	M 11:08	M 11:38	25	M 08:58	M 09:28	M 08:58	M 09:28	M 08:58	M 09:28
25	M 11:55	M 12:25	M 12:40	M 13:10	M 11:55	M 12:25	24	M 09:45	M 10:15	M 09:45	M 10:15	M 09:45	M 10:15
21	M 12:35	M 13:05	M 13:20	T 05:46	M 12:35	M 13:05	19	M 10:30	M 11:00	M 10:30	M 11:45	M 10:30	M 11:00
12	M 13:19	T 05:55	T 06:00	T 06:30	M 13:19	M 13:49	40	M 11:22	M 11:52	M 12:07	M 12:37	M 11:22	M 11:52
3	T 06:00	T 06:30	T 06:35	T 07:05	M 13:55	M 14:25	35	M 13:11	T 05:29	M 13:56	T 05:29	M 13:11	M 13:41
7	T 06:58	T 07:28	T 07:34	T 08:04	M 14:53	M 15:23	28	T 06:00	T 06:30	T 06:00	T 06:30	M 14:12	M 14:42
1	T 07:51	-	T 08:27	-	M 15:46	-	1	T 07:07	-	T 07:07	-	M 15:19	-

(a) Electric Plane (b) Fuel-powered Plane

Table 4.3: Flight schedule and trajectory for all cockpit & vehicle configurations: 400 km

From Figs. 4.5a & 4.5b, the electric plane does not follow the same optimal path as the fuel plane. In fact, the loop is executed in the opposite direction, and a slight variation in the order of visited destinations can be observed between destinations 28 and 35. However, larger differences are seen in Tabs. 4.3a & 4.3b where electric and fuel plane schedules are displayed for the three cockpit configurations. Indeed, in the case of the electric plane, the longer distances result in a greater depletion of the battery, leading to longer recharging times. In some cases, the recharging times of the electric plane can exceed the allocated half an hour s for unloading at the destination of arrival. In Tab. 4.3a, these instances where the recharge time exceeds the half-hour mark are indicated in green. In the versions with pilots, the additional recharge times count in the pilot's FDP hours and are not considered as breaks because the latter must remain vigilant to the state of the aircraft. Consequently, the recharge times of the electric plane have a slowing effect, limiting the number of destinations that can be visited in a day. This is evident when comparing Tabs. 4.3a & 4.3b, specifically in the cockpit versions with one or two pilots.

Then come the breaks imposed by pilot legislation. Once again, it can be seen in red in the single pilot version the short breaks that the pilot must take after 6 hours of flights in the case where the latter is alone. Due to the extended duration of the delivery tour, it is not possible to visit all destinations within a single day due to the maximum FDP limit of 9 hours. Hence the hours highlighted in blue, representing the time the pilots resume after the 13 hours of mandatory rest between two FDPs.

In this typical journey scenario, when at least one pilot is present, both the electric plane and the fuel-powered plane require two days to complete the delivery round. As a result, the fixed costs, which are determined on a daily basis, will be doubled. However, in other cases where the delivery loop is shorter, the fuel-powered aircraft could manage to make all the deliveries in one day while the electric aircraft requires a second day. In this case, the fuel-powered aircraft would remain more advantageous. This will be noticed and discussed in more detail in the next section on cost analysis.

Finally in the autonomous case, electric aviation suffers a slight delay but given the absence of legislation on the number of hours of driving, the latter still manages to visit all destinations on the same day as for the plane at fuel. In addition, the tour being carried out in one day, the fixed costs therefore remain at a minimum. Hence, generating a total cost of the tour much cheaper than for the versions with pilots which make the tour in two days. This can be confirmed in Tab. 4.4 where the total costs of the standalone versions show a decrease of almost 40% compared to the two-pilot version. Moreover, as in the Benelux scenario, the electric version turns out to be significantly less expensive than the fuel version each time. Indeed, the electric plane can save up to 16% on the delivery round. Similarly, reducing the number of pilots from two to one can spare up to 15%.

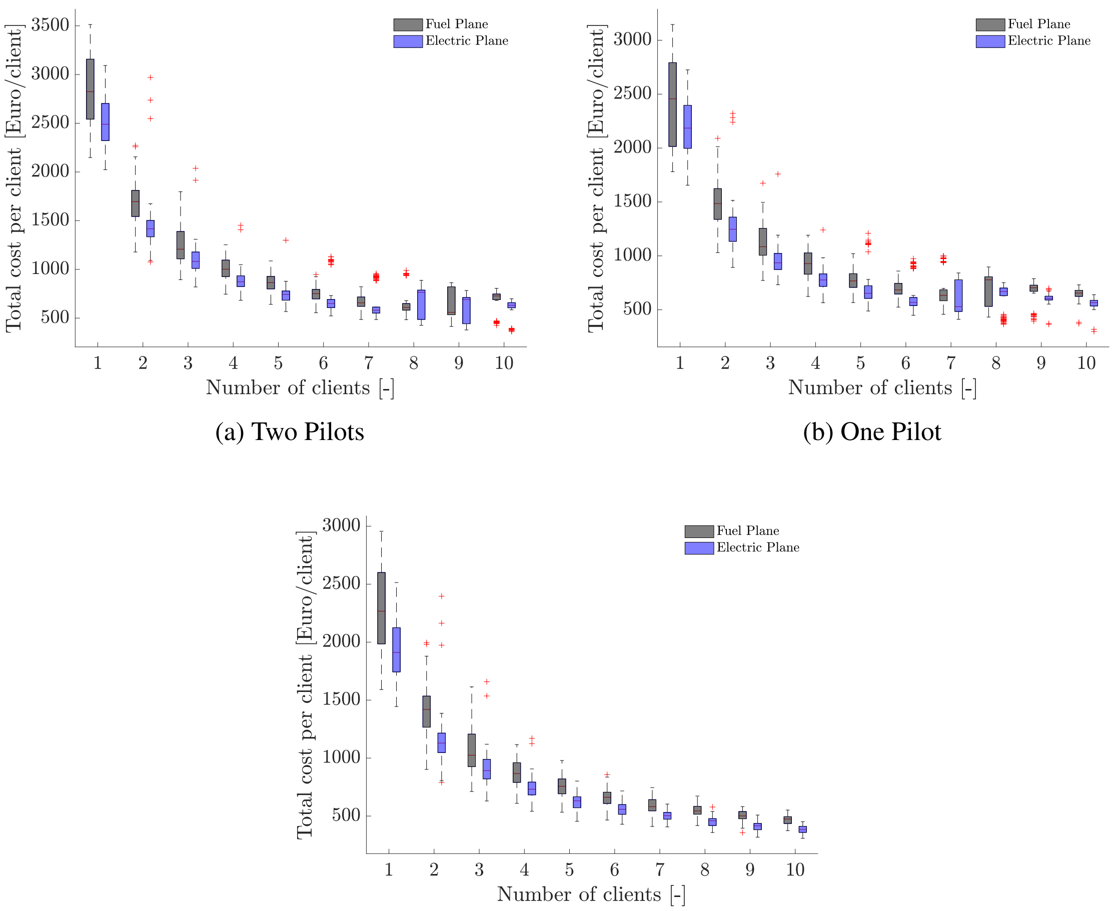
	Two Pilots		One Pilot		Autonomous	
	Electric	Fuel	Electric	Fuel	Electric	Fuel
Total working time	10h53	9h42	10h53	9h42	9h47	9h42
Total driving time	4h47	4h42	4h47	4h42	4h47	4h42
Total distance [km]	1949	1914	1949	1914	1914	1914
Total cost [€]	6415	7251	5445	6516	3948	4717

Table 4.4: Total cost, distance and working & driving time (planes): 400 km

In Tab. 4.4, the distances of the tours travelled show that the latter turn out to be slightly longer in the case of the electric plane leading to slightly longer total driving times. Then, due to the additional aircraft recharging times that are included in the FDP, the working time observed in the case of electric aircraft is also higher than in the case of fuel-powered aircraft. However, this does not prevent the electric plane from remaining much cheaper than the fuel plane. Again, the one-pilot version gives the same number of working hours as the two-pilot version as small breaks of 45 minutes are not included in the working time count. In the autonomous version, exactly 5 hours separate the driving time from the working time, which is justified by the 10 half-hours of unloading at the 10 customers.

4.2.2 *Cost per client*

To get an overall statistical idea of the analysis of the total costs of the delivery round, a large number of VRP simulations are carried out according to the same mode explained previously in the Benelux scenario. The results are shown in the following figures.



(a) Two Pilots

(b) One Pilot

(c) Autonomous

Figure 4.6: Total cost per client of electric & fuel-powered planes: 400 km

From Figs. 4.6a, 4.6b & 4.6c, the same exponential decreasing trend can be observed as in the case of Benelux. In contrast, the interquartile ranges and whiskers are wider this time, indicating a greater variability in the variable costs. This increased variability is primarily driven by the larger variance in the total distances covered in the routes. At the same time, a larger number of outliers are observed, and in certain instances, they significantly deviate even from the extremities of the whiskers. The main culprit is the large variance in fixed costs. Indeed, these are doubled when a second day is required to deliver the last customers. As the fixed costs are substantial, they quickly drive up the total costs. This explains the majority of outliers when the number of customers considered is between 4 and 8 in Figs. 4.6a & 4.6b.

Indeed, in general one day is enough to deliver everyone but in some cases the destinations generate long distances to travel. Hence, a second day is necessary. Between 8 and 10 customers, the opposite occurs. In general, two days are required to deliver all destinations but in some cases if the tour is short then it may be that one day is enough. Thus, making the total cost of the tour much less expensive. It should be noted that these remarks are only valid for the versions with pilots due to the legislations constraining to divide the round in two days.

For the standalone version in Fig. 4.6c, this explanation of the outliers is not valid because the latter manage to close the delivery round each time in one day. For values close to whiskers, these are due to a strong variation in variable costs. On the other hand, to explain the values that stand out strongly from the box-plots, it can be noticed that the latter only appear in the case of the electric plane. This can be attributed to the limited range of the planes. When two destinations are located at opposite ends of the designated perimeter, it necessitates the use of two planes. This is because, according to the assumption, the plane cannot return to the depot before proceeding to the next destination. Thus, as in the case where a second day is required, the fixed costs are directly doubled. Hence, all the strongly outlying values in the case of electric aircraft when considering 2 to 4 customers in all three cockpit configurations can be explained by this reason.

Regarding the price analysis, on the whole, the electric plane turns out to be cheaper than the fuel plane. Nevertheless, the latter is not advantageous in the following cases. As explained in the previous paragraph, in very rare cases, a second plane must be required, whereas one is enough in the case of fuel, leading to double the fixed costs in the case of the electric plane. On the other hand, more frequently encountered when more customers are considered, the fuel plane can complete the delivery round in one day while the electric plane needs a second day due the recharging times that slow it down. Thus, much higher fixed costs will be again observed for the electric plane. In the two-pilot version, this is noticeable between 6 and 7 customers considered, whereas in the one-pilot version the latter appears earlier between 5 and 6 customers. To find out more information on numerical comparisons between the different configurations, these are available in Tab. B.2 of Appendix B.

Finally, if the costs per customer are compared with those obtained in the Benelux scenarios, the latter are higher. This is perfectly logical given the increase in variable costs due to longer distances travelled and the increase in fixed costs in the event that two days are required to complete the delivery round.

4.2.3 Cost breakdown

Similar to the Benelux scenario, a detailed analysis of the cost breakdown is conducted to identify the primary factors contributing to the total cost of the tour and assess their dependence on the number of customers. Two scenarios are presented: the first with one customer and the second with 10 customers. These scenarios represent the median results obtained from 100 simulations showed in previous section on the total costs per client. The results are outlined below.

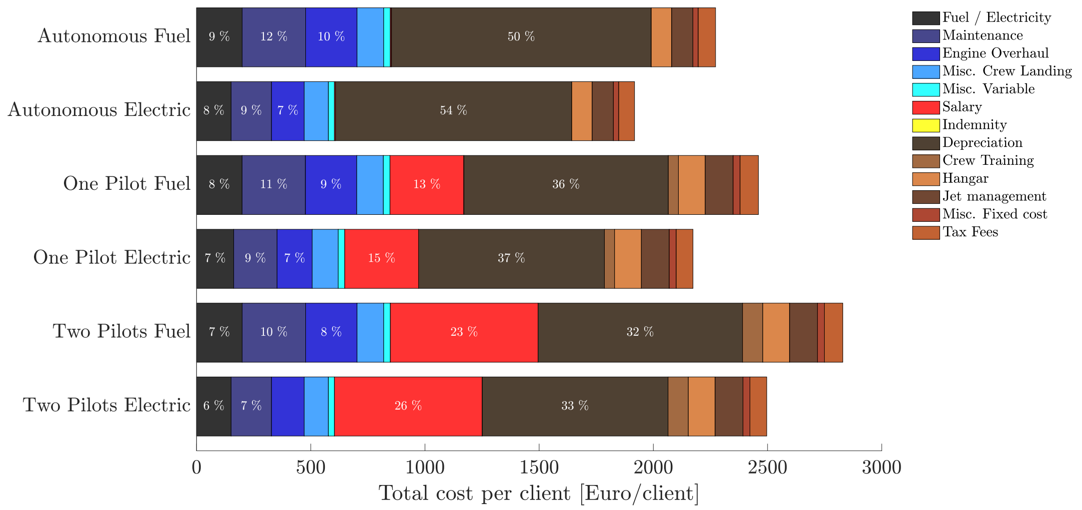


Figure 4.7: Cost breakdown with planes: 400 km - one client

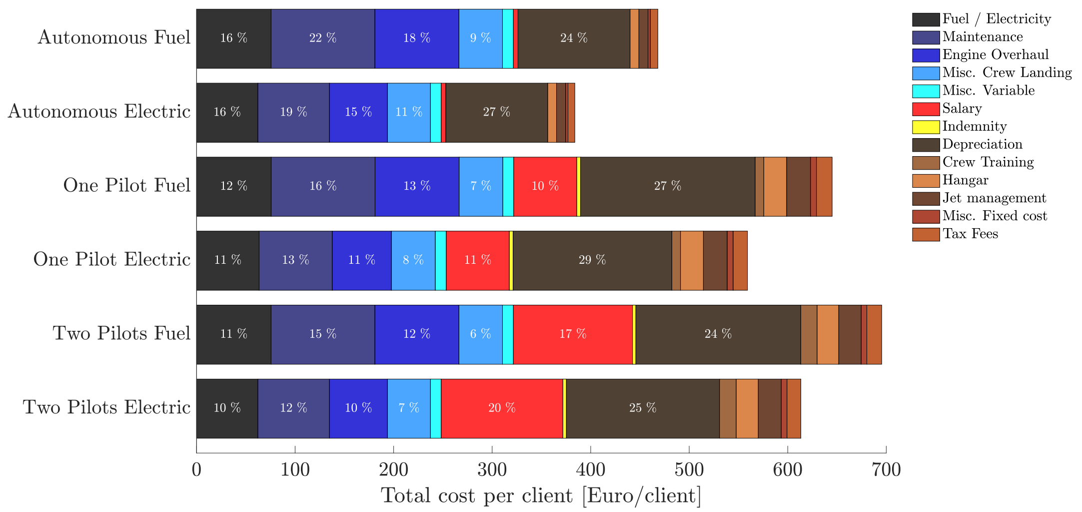


Figure 4.8: Cost breakdown with planes: 400 km - 10 clients

Similar observations can be made as in the case of the Benelux scenario. Indeed, the depreciation of the vehicle and the salary constitute a significant portion of the total cost of the delivery round, accounting for approximately 50% to 60% when considering a single customer. However, as the number of customers increases, their contribution to the total cost tends to decrease, representing about 25% to 45% when considering 10 customers. On the other hand, the variable costs increase due to the longer distances travelled. Comparing this cost breakdown, variable costs take a slightly larger share than in the case of Benelux. The reason is due to the longer distance travelled in this scenario. As a result, it follows that the fixed costs are slightly lower. Finally, as noticed during the typical journey analysis, the standalone version is the cheapest version followed by the one-pilot version and then the two-pilot version which is the most expensive.

4.3 CASE STUDY WITH PLANES: 800 KM

The third and final scenario replicates the methodology employed in the Benelux and 400 km scenarios, but with an expanded scope of destinations within an 800 km radius around the central depot in Brussels. This scenario aims to emphasise the primary advantage of aviation, which is its ability to provide swift service over longer distances. In this case, the electric aircraft utilised exhibits improved features, particularly in terms of autonomy, surpassing the capabilities of the aircraft used in the previous two scenarios. This aircraft represents a futuristic version as the current reference electric aircraft is unable to meet the requirements of the present scenario. However, as highlighted in section 3.3.2.3, it is anticipated that with advancements in battery technology, the reference electric aircraft could soon be capable of meeting the requirements. Regarding the time frame granted, it remains two days but the opening hours of the destinations are from 0 a.m. to 12 p.m..

4.3.1 *Typical journey analysis*

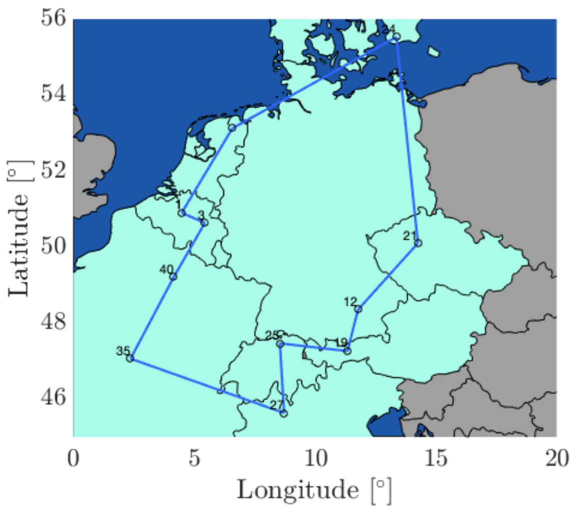


Figure 4.9: Path taken by the aircraft (for all cockpit & vehicle configurations): 800 km

	Two Pilots				One Pilot				Autonomous			
	Electric		Fuel		Electric		Fuel		Electric		Fuel	
Stop	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure
1	-	M 00:00	-	M 00:00	-	M 00:00	-	M 00:00	-	M 00:00	-	M 00:00
3	M 00:10	M 00:40	M 00:11	M 00:41	M 00:10	M 00:40	M 00:11	M 00:41	M 00:10	M 00:40	M 00:11	M 00:41
40	M 01:05	M 01:35	M 01:08	M 01:38	M 01:05	M 01:35	M 01:08	M 01:38	M 01:05	M 01:35	M 01:08	M 01:38
35	M 02:12	M 02:42	M 02:18	M 02:48	M 02:12	M 02:42	M 02:18	M 02:48	M 02:12	M 02:42	M 02:18	M 02:48
27	M 03:51	M 04:35	M 04:04	M 04:34	M 03:51	M 04:35	M 04:04	M 04:34	M 03:51	M 04:35	M 04:04	M 04:34
25	M 05:03	M 05:33	M 05:04	M 05:34	M 05:03	M 06:18	M 05:04	M 06:19	M 05:03	M 05:33	M 05:04	M 05:34
19	M 06:01	M 06:31	M 06:05	M 06:35	M 06:46	M 07:16	M 06:50	M 07:20	M 06:01	M 06:31	M 06:05	M 06:35
12	M 06:48	M 07:18	M 06:54	M 07:24	M 07:33	T 00:00	M 07:39	T 00:00	M 06:48	M 07:18	M 06:54	M 07:24
21	M 07:54	M 23:38	M 08:03	T 00:00	T 00:36	T 01:06	T 00:39	T 01:09	M 07:54	M 08:24	M 08:03	M 08:33
24	T 01:00	T 01:52	T 01:29	T 01:59	T 02:28	T 03:20	T 02:38	T 03:08	M 09:46	M 10:38	M 10:02	M 10:32
7	T 03:02	T 03:46	T 03:15	T 03:45	T 04:29	T 05:14	T 04:24	T 04:54	M 11:48	M 12:32	M 11:48	M 12:18
1	T 04:24	-	T 04:27	-	T 05:52	-	T 05:36	-	M 13:10	-	M 13:00	-

Table 4.5: Flight schedule and trajectory for all cockpit configurations: 800 km

The map depicted in Fig.4.9 reveals that all configurations adhere to the same route and requiring only one plane for the journey. By examining Tab.4.5, a similar pattern is observed as in the 400 km scenario, with the electric versions frequently surpassing the designated half-hour time for unloading goods (highlighted in green). Additionally, versions with pilots must once again split the work schedule into two days to accommodate the mandatory 13-hour rest period after completing 9 hours of FDP. The blue highlights indicate the resumption of pilots' duty hours after their extended breaks to commence a new FDP. In the case of the single pilot version, a red marking represents the mandatory 45-minute break that the pilot must take after 6 hours of FDP.

The remaining observations are consistent with those made during the 400 km scenario, except for one key difference. Despite the long recharge times, the electric aircraft in the autonomous plane scenario does not encounter significant delays and, on certain occasions, is even able to catch up with the schedule. This can be attributed to the higher cruising speed of the electric plane, which is 444 km/h, compared to the fuel-powered plane's speed remaining at 407 km/h. The same trend is observed in the versions with pilots, although it is less pronounced due to the breaks mandated by regulations.

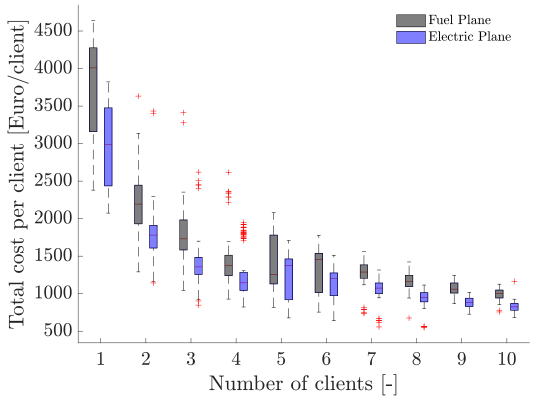
	Two Pilots		One Pilot		Autonomous	
	Electric	Fuel	Electric	Fuel	Electric	Fuel
Total working time	13h10	13h00	13h10	13h00	12h20	13h00
Total driving time	7h20	8h00	7h20	8h00	7h20	8h00
Total distance [km]	3257	3257	3257	3257	3257	3257
Total cost [€]	8270	9532	7100	8797	5802	6998

Table 4.6: Total cost, distance and working & driving time (planes): 800km

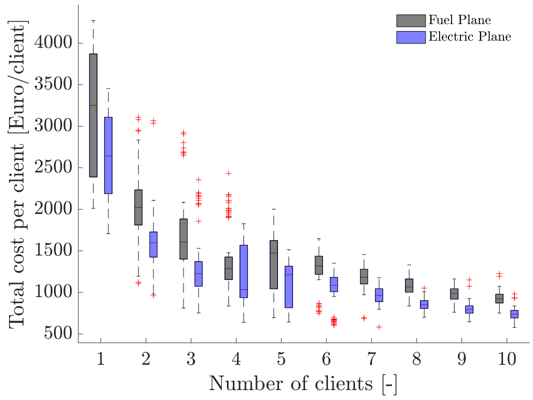
From Tab. 4.6, as the routes are the same, it makes sense to see the same distances travelled in all configurations. As said before, the cruising speed of the electric aircraft is higher therefore leading to shorter flight times than the fuel versions. On the other hand, given that the recharging times are included in the total working time, the latter are higher in the case of the electric plane with pilots. For the fuel versions, the working times differ from 5 hours to the flight times representing once again the 10 half-hours of unloading goods to the 10 customers. As in the 400 km scenario, the autonomous version gives clearly lower total costs mainly due to the fact that the delivery round is completed in one day while the versions with pilots require two days. Thus, leading to doubling the fixed costs which are substantial. Similarly, reducing the cockpit from two pilots to one also reduces the cost of the delivery round. Therefore, Tab. 4.6 demonstrates a reduction of approximately 15% and 30% when transitioning from a two-pilot cockpit to one pilot and autonomous mode, respectively. Finally, as in the previous scenarios, the electric versions make it possible to carry out the tour at a lower price compared to fuel. Indeed, the electric version can save between 15% to 20%.

4.3.2 Cost per client

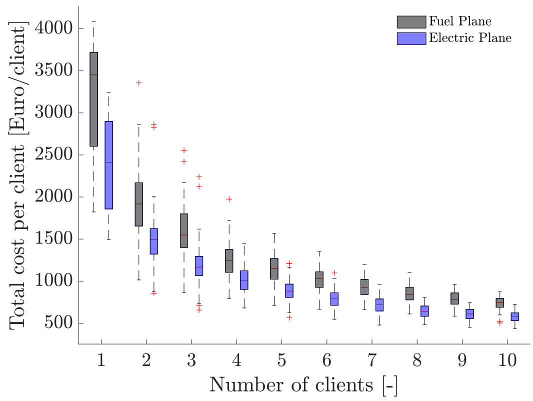
Once again, a statistical analysis is carried out on a large number of VRP simulations to deduce the different trends that the number of customers taken into account bears on the total costs of the tour. This study is carried out according to the same procedure as in the previous scenarios. The results are shown in the following figures.



(a) Two Pilots



(b) One Pilot



(c) Autonomous

Figure 4.10: Total cost per client of electric & fuel-powered planes: 800 km

In Figs. 4.10a, 4.10b & 4.10c, a trend of exponential decrease in costs per customer is observed when these are increased. Considering the outliers, their presence is significant in terms of numbers and can be attributed to the same factors as explained in the 400 km scenario. Indeed, outliers when few customers are taken into account and which deviate greatly from the median appear in the case of the electric aircraft. These are due to the fact that two planes must be used if two destinations are at two opposite ends and the electric plane does not have sufficient range to get there. Thus, the fixed costs are doubled. On the other hand, the outliers near the ends of the whiskers are mainly due to strong variations in variable costs. This is especially noticed for the autonomous version in Fig. 4.10c.

Outliers due to the change from one day to two day delivery trip and vice versa are also present. However, this time the latter appears much earlier in terms of customers considered. Indeed, the latter arrives between 3 and 4 customers for the journeys starting to require two days. For the versions with pilot, between 4 and 6 clients, large boxplots can be seen and some do not contain any outliers. This shows the pivotal moments when depending on the destination draws, the tour could be done in a day or two. Outside this pivot zone, when fewer customers are considered one day is usually enough. Conversely, when more customers are considered then two days are necessary (while keeping a single plane in almost all cases). The notable outliers just after the pivot area (between 6 and 8 clients) are instances where the arrangement of destinations enables the completion of the tour in one day, despite an average requirement of two days. Hence, the outliers giving costs significantly lower than the median.

Once again, electric aviation is in most cases cheaper except in unstable areas at pivot points in Figs. 4.10a & 4.10b where the latter might require two days of touring while the fuel-powered plane can wrap it all up in just one day. Alternatively, in very uncommon scenarios where two planes are required due to limitations in autonomy. Comparing the value of the total costs, these have increased further compared to the 400 km scenario. This time, the reason is mainly due to an increase in variable costs. Once again, more quantified information on the savings generated by the electric aircraft on the fuel version or on reducing the number of people in the cockpit are available in Tab. B.3 of Appendix B.

4.3.3 Cost breakdown

Similar to the previous two scenarios, an analysis of cost breakdown is conducted to identify the primary factors contributing to the total cost of the tour. This analysis also explores the influence of the number of customers on these factors. Once again, two instances of cost breakdown are presented, considering one customer and 10 customers respectively, representing the median outcome of the 100 simulations. The findings are as follows.

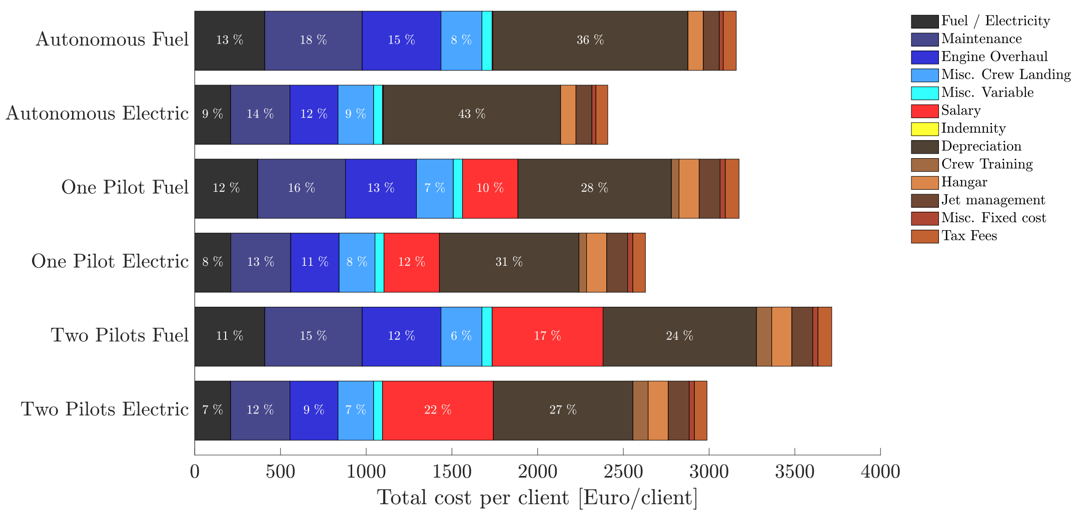


Figure 4.11: Cost breakdown with planes: 800 km - one client

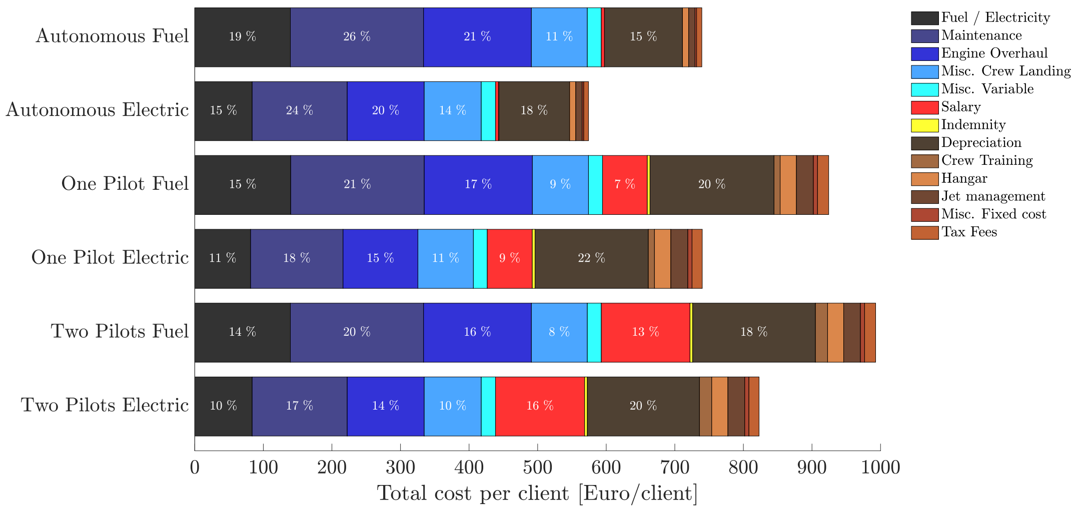


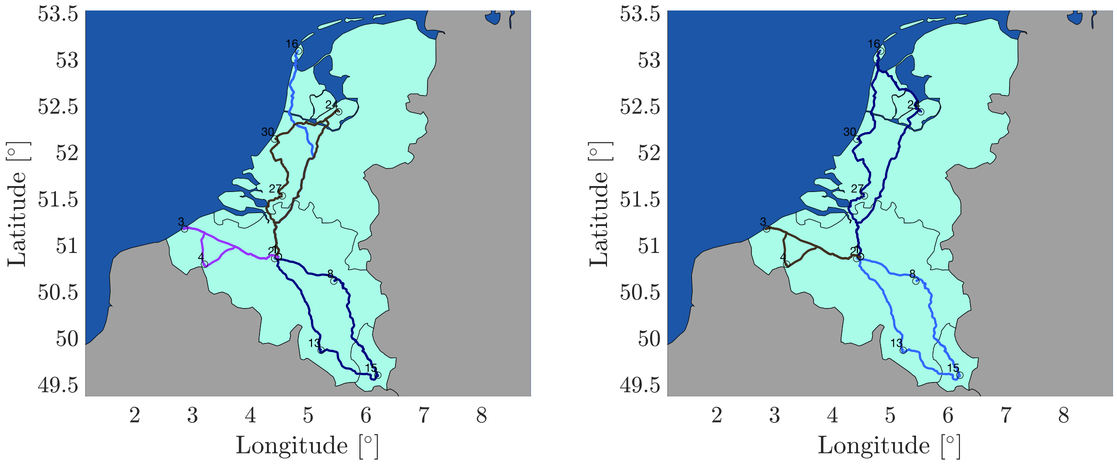
Figure 4.12: Cost breakdown with planes: 800 km - 10 clients

From Figs. 4.11 & 4.12, the same observations can be made as in the 400 km scenario. Indeed, the depreciation of the vehicles once again counts for a large part of the fixed costs and the total costs of the delivery round. However, the relative share of salary and depreciation decreased this time. Indeed, their combined contribution ranges from 36% to 50% when considering one customer, and it decreases further to 15% and 36% when considering 10 customers. The reason behind this is the substantial increase in variable costs resulting from significantly longer distances travelled. In fact, as can be seen in both Figs. 4.11 & 4.12, their relative parts have greatly increased compared to previous scenarios.

4.4 Case study with vans: Benelux

Having examined all three scenarios involving airplanes, the focus now shifts to delivery vans to assess the economic viability of electrifying them. In this initial scenario, the Benelux region is considered, with the same customers and conditions as those imposed on the aircraft: delivering to all customers within a single day, with customer opening hours between 8 a.m. and 5 p.m..

4.4.1 *Typical journey analysis*



(a) Non autonomous (b) Autonomous

Figure 4.13: Routes taken by the vans with driver and autonomous: Benelux.

		Driver						Autonomous				
		Electric		Fuel				Electric			Fuel	
Vehicle	Stop	Arrival	Departure	Arrival	Departure	Vehicle	Stop	Arrival	Departure	Stop	Arrival	Departure
1	1	-	M 07:46	-	M 07:46	1	1	-	M 06:52	1	-	M 05:34
	2	M 08:00	M 08:30	M 08:00	M 08:30		27	M 08:00	M 08:34	24	M 08:00	M 08:30
	13	M 10:45	M 11:25	M 10:15	M 10:45		30	M 09:57	M 10:27	16	M 10:48	M 11:18
	15	M 12:34	M 13:04	M 11:55	M 12:25		24	M 11:39	M 12:09	30	M 13:34	M 14:04
	8	M 15:58	M 16:28	M 15:21	M 15:51		16	M 14:29	M 14:59	27	M 15:23	M 15:53
	1	M 17:32	-	M 16:54	-		1	M 20:18	-	1	M 17:01	-
2	1	-	M 02:41	-	M 04:00	2	1	-	M 07:46	1	-	M 07:46
	16	M 08:00	M 08:30	M 08:00	M 08:30		2	M 08:00	M 08:30	2	M 08:00	M 08:30
	1	M 13:49	-	M 13:15	-		13	M 10:55	M 11:25	8	M 09:40	M 10:10
3	1	-	M 06:52	-	M 06:52		15	M 12:34	M 13:04	15	M 12:21	M 12:51
	27	M 08:00	M 08:34	M 08:00	M 08:30		8	M 15:58	M 16:28	13	M 14:01	M 14:31
	30	M 09:57	M 10:27	M 09:49	M 10:19		1	M 17:32	-	1	M 16:09	-
	24	M 11:39	M 12:09	M 11:30	M 12:00	3	1	-	M 06:46	1	-	M 06:32
	1	M 15:56	-	M 15:11	-		4	M 08:00	M 08:36	3	M 08:00	M 08:30
4	1	-	M 06:46	-	M 06:46		3	M 09:36	M 10:06	4	M 09:23	M 09:53
	4	M 08:00	M 08:36	M 08:00	M 08:30		1	M 12:13	-	1	M 11:08	-
	3	M 09:36	M 10:06	M 09:23	M 09:53							
	1	M 12:13	-	M 11:21	-							

Table 4.7: Route schedule and its destinations for vans: Benelux

Based on Figs. 4.13a & 4.13b, it is evident that multiple vehicles are required to ensure timely deliveries. This is due to the relatively slower speed of vans compared to planes. In the case of the autonomous version, three vans are sufficient, while four vans are needed for the driver-operated ones. The reason behind this is the regulatory requirements mandating breaks for drivers, which inevitably slows down the overall delivery process.

Tab. 4.7 presents the timetables of vans in different configurations. Due to the limited range of the vans, frequent recharging is necessary. To maintain clarity, battery recharge times are not highlighted in green. Similarly, breaks taken by drivers are not highlighted as they typically occur between destinations rather than at the actual delivery points. This pattern will also be observed in subsequent tables presenting van schedules in the following scenarios. However, based on Tab. 4.7, both in the driver-operated and autonomous versions, it is evident that the electric vans reach the same destinations as the fuel-powered ones, but always with a delay after the initial battery recharge time has passed.

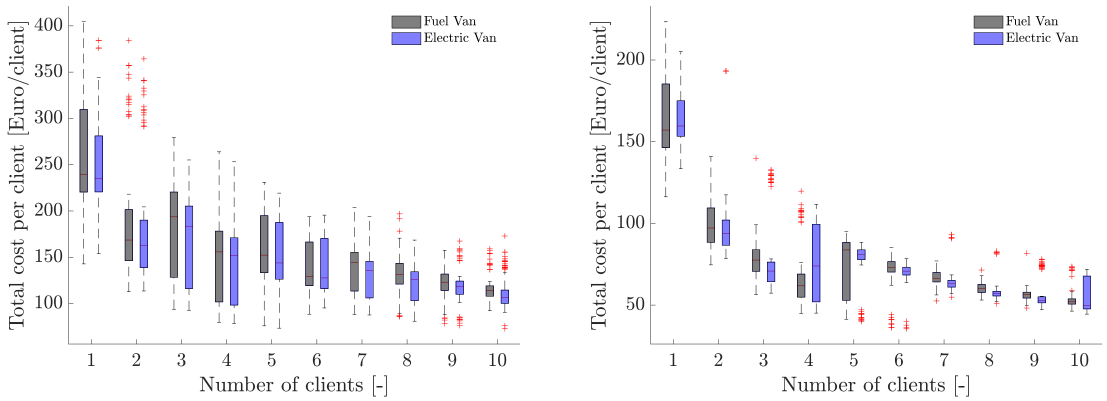
	Driver		Autonomous	
	Electric	Fuel	Electric	Fuel
Total working time	29h01	29h01	24h53	24h25
Total driving time	24h01	24h01	19h53	19h25
Total distance [km]	1937	1937	1530	1485
Total cost [€]	1375	1324	685	623

Table 4.8: Total cost, distance and working & driving time (vans): Benelux

From Table 4.8, several observations can be made. Firstly, the total cost of the tour is approximately half the price in the autonomous versions compared to the driver-operated ones. This is primarily due to the use of an additional vehicle, which increases fixed costs. Consequently, the total distances travelled are longer, leading to an increase in variable costs. Then, the absence of salary costs in the autonomous version significantly contributes to its overall cost reduction compared to the driver-operated version. Regarding driving times, the versions with drivers have longer durations due longer distances travelled. Similar to the plane scenario, there is a 5-hour difference between the working time and the driving time, accounting for the 10 half-hour unloading periods at each of the 10 customer locations. Finally, when comparing the fuel-powered and electric versions, the total costs are generally comparable, albeit slightly higher for the electric version. The next subsection shows if this is also the case for a large number of simulations.

4.4.2 Cost per client

As in the case of aircraft, a large number of VRP simulations were carried out in order to have an overall idea and to see the effect that the number of customers has on the total costs per customer. The procedure is exactly the same as that carried out with aircraft, thus giving the following results.



(a) Non autonomous (b) Autonomous

Figure 4.14: Total cost per client of electric & fuel-powered vans: Benelux

When examining Figs. 4.22a & 4.22b, it becomes apparent that the interquartile ranges and whiskers are quite wide, indicating a significant variation in costs. Additionally, a considerable number of outliers are present. This can be attributed to the strong dependency of the number of vans required on the total distance of the delivery round. Consequently, from one simulation to another, the number of vans needed can vary greatly, both in the non-autonomous and autonomous versions.

Similar to airplanes, as the number of customers increases, the total costs per customer tend to decrease, although not as consistently due to the same reason explaining the large presence of outliers. Upon comparing the medians of electric and fuel-powered vans, it becomes apparent that in most cases, electric vans are slightly less expensive. This is in contrast to the previous subsection, where the opposite was observed. More detailed comparisons can be found in Tab. B.4 of Appendix B.

As provided in subsection 3.4.3, when comparing these results to those obtained with planes in the Benelux scenario, vans demonstrate significantly lower costs by a factor of around 10, despite the utilisation of multiple vehicles. This confirms that air travel is more luxurious. Therefore, if aircraft were to be utilised in the realm of logistics for short distances like in the Benelux region, other justifications would need to be presented apart from economic considerations.

4.4.3 Cost breakdown

Similar to aircraft, a detailed analysis of cost breakdown is conducted to identify the primary factors contributing to the total cost of the tour, along with the influence of the number of customers. Two scenarios are presented, one with a single customer and the other with ten customers, based on the median outcomes from the previous subsection's 100 simulations. The findings are outlined below.

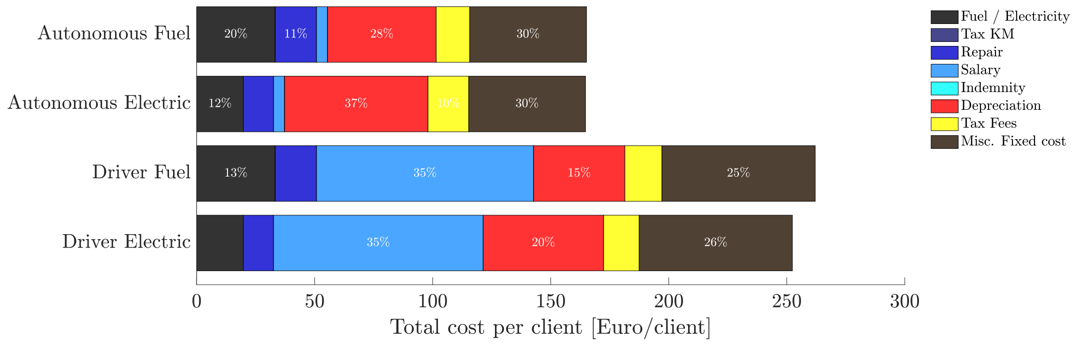


Figure 4.15: Cost breakdown with vans: Benelux - 1 client

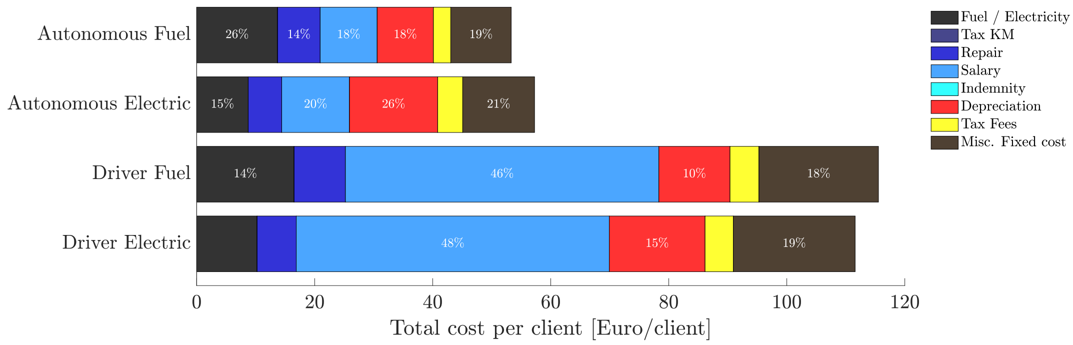


Figure 4.16: Cost breakdown with vans: Benelux - 10 clients

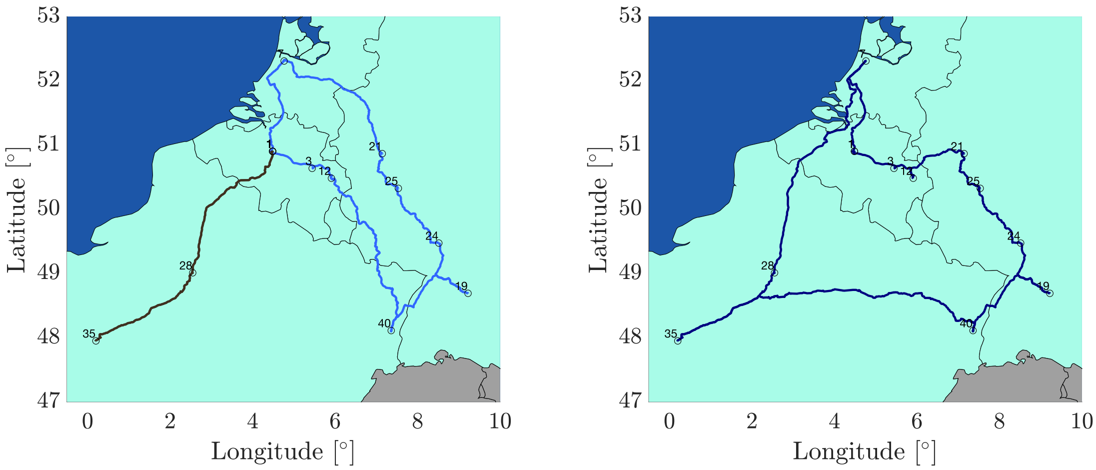
Upon analysing Figs. 4.15 & 4.16, it is evident that both salary and vehicle depreciation play significant roles in determining the total cost of the delivery round, similar to the previous scenarios. However, this time the salary component occupies a larger proportion in the non-autonomous versions. Specifically, it represents approximately 35% to 48% of the total cost when considering one customer and 10 customers, respectively. Hence, the stark difference observed in the total costs of delivery rounds between autonomous and non-autonomous vans.

While fixed costs decrease with an increase in the number of customers, the relative share of salary costs and variable costs both tend to rise. The reason behind the increase in salary costs can be attributed to the utilisation of additional vehicles, resulting in increased wages for drivers. Then, for the variable costs, its increase is due to an increase in the total distance of the delivery round.

4.5 CASE STUDY WITH VANS: 400 KM

Similar to the aircraft scenario, the second scenario involves expanding the range of destinations to a 400 km radius around the central depot located in Brussels. The delivery time frame is extended to two days, with customer availability from 6 a.m. to 10 p.m..

4.5.1 *Typical journey analysis*



(a) Non Autonomous (b) Autonomous

Figure 4.17: Routes taken by the vans with driver and autonomous: 400 km

		Driver						Autonomous				
		Electric		Fuel				Electric			Fuel	
Vehicle	Stop	Arrival	Departure	Arrival	Departure	Vehicle	Stop	Arrival	Departure	Stop	Arrival	Departure
1	1	-	M 04:57	-	M 04:57	1	1	-	M 04:57	1	-	M 02:56
	3	M 06:00	M 06:30	M 06:00	M 06:30		3	M 06:00	M 06:30	28	M 06:00	M 06:30
	12	M 07:16	M 07:46	M 07:16	M 07:46		12	M 07:16	M 07:46	35	M 09:12	M 09:42
	40	M 14:07	M 14:37	M 12:53	M 13:23		21	M 10:04	M 10:34	40	M 17:12	M 17:42
	19	M 17:42	M 18:12	M 15:49	M 16:19		25	M 11:50	M 12:20	19	M 20:07	M 20:37
	24	T 08:00	T 08:30	T 07:44	T 08:14		24	M 14:52	M 15:22	24	T 06:00	T 06:30
	25	T 11:00	T 11:30	T 10:03	T 10:33		19	M 17:27	M 17:57	25	T 08:19	T 08:49
	21	T 12:46	T 13:16	T 11:49	T 12:19		40	M 21:02	M 21:32	21	T 10:05	T 10:35
	7	T 17:42	T 18 :12	T 16:07	T 16 :37		35	T 08:22	T 08:52	12	T 12:13	T 12:43
	1	W 09:20	-	W 08:47	-		28	T 12:14	T 12:44	3	T 13:29	T 13:59
2	1	-	M 01:36	-	M 02:56		7	T 19:54	T 20:24	7	T 16:52	T 17:22
	28	M 06:00	M 06:30	M 06:00	M 06:30		1	T 23:14	-	1	T 19:32	-
	35	M 09:52	M 10:22	M 09:57	M 10:27							
	1	T 05:20	-	T 06:09	-							

Table 4.9: Route schedule and its destinations for vans with driver: 400km

From Figs. 4.18a & 4.18b, it is evident once again that an additional vehicle is required in the non-autonomous version compared to the autonomous one due to legislations requirements. Tab. 4.9 provides further evidence that the electric version is slower than the fuel-powered version due to battery recharge times. However, in the non-autonomous version, the difference is less pronounced compared to the autonomous case. This can be attributed to the legislation constraints placed on the driver when operating the vehicle. In the case of the electric van, frequent battery recharges are considered as breaks for the driver. Indeed, unlike in the plane scenario, the driver has to worry less about the state of his vehicle and can even take a nap when the latter is recharging. In contrast, the fuel-powered driver is required to take a long break after 9 hours of work per day, resulting in an earlier end to their delivery tour and a longer break approaching the maximum limit of 13 hours. On the other hand, the electric van's long mandatory break occurs later in the day, nearing the minimum allowable limit of 11 hours. Thus, at the end of the day, approximately the same number of destinations have been visited. In the autonomous versions, the difference between electric and fuel-powered vans is primarily due to the absence of legislation imposing breaks. Otherwise, apart from the requirement of two days to supply all the customers and possibly three days to return from the last customer to the depot, the remaining findings are consistent with those observed in the previous case.

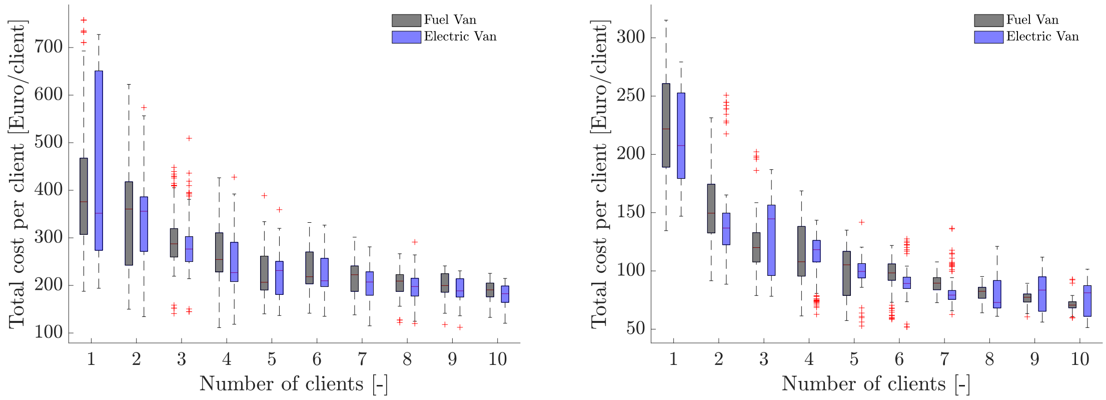
	Driver		Autonomous	
	Electric	Fuel	Electric	Fuel
Total working time	34h48	34h48	32h49	32h39
Total driving time	29h48	29h48	27h49	27h39
Total distance [km]	2669	2669	2451	2422
Total cost [€]	1903	1829	631	577

Table 4.10: Total cost, distance and working & driving time (vans): 400km

From Tab. 4.10, it is evident that the difference in total costs between the autonomous and non-autonomous versions is significantly larger this time. The autonomous version proves to be nearly three times cheaper than the driver-operated version. This can be attributed to the absence of a driver's salary, reduction in fixed costs, and lower variable costs due to the decreased total distance travelled, as indicated in Tab. 4.10. Similar deductions can be made regarding working and driving times, as observed in previous scenarios.

4.5.2 Cost per client

The following analysis was conducted to examine the costs per customer based on varying numbers of customers in a significant number of VRP simulations. The methodology employed for the computations remained consistent with the approach used in previous scenarios. The results of this study are presented below.



(a) Non autonomous

(b) Autonomous

Figure 4.18: Total cost per client of electric & fuel-powered vans: 400 km

When examining Figs. 4.18a & 4.18b, it can be seen that there are wide interquartile ranges, extensive whiskers, and a substantial number of outliers. The reasons behind these observations are consistent with the previous case of vans in the Benelux. However, an additional factor comes into play here, which is the division of the delivery round into two days. This division has a significant impact on the fixed costs, which in turn greatly influence the total cost. Consequently, splitting the delivery round into two days can lead to a notable increase in the total cost, providing an explanation for the majority of outliers observed when considering 4 to 7 customers in the case of autonomous vans.

When directly comparing fuel-powered and electric vans, it can be observed that in the non-autonomous scenario, the electric version generally tends to be slightly cheaper. This can be attributed to the fact that, as seen during the analysis of the typical day's schedule, there is minimal difference due to legislation that mandates breaks for drivers. Consequently, despite the electric version being slowed down by battery recharges, the number of vehicles used and the duration of their usage remain largely the same.

However, in the case of the autonomous scenario, it is common for the electric version to be disadvantageous and costlier. This is primarily due to significant time disparities between electric and fuel-powered vans. When considering a small number of customers, the fuel-powered version often completes all deliveries within a single day, while the electric version requires an additional day. If a larger number of customers are considered, the electric version may even require two vehicles or, in some cases, an extra day to return to the depot, whereas the fuel-powered version rarely necessitates such measures.

After a brief comparison of the costs presented between the standalone and non-standalone versions, it is evident that the autonomous version is significantly cheaper, with a cost reduction of 2 to 3 times. More detailed numerical data can be found in Tab. B.5 of Appendix B. Additionally, when contrasting these findings with those obtained for the plane under similar circumstances, it becomes once again clear that the van continues to be a considerably more cost-efficient mode of logistical transportation (by a factor of approximately 10), particularly for short distances such as 400 km.

4.5.3 Cost breakdown

Similar to aircraft, an analysis of cost breakdown is conducted to identify the primary factors contributing to the total tour cost and their dependence on the number of customers. Once again, two scenarios are considered: one with a single customer and another with 10 customers. These scenarios represent the median results obtained from the previous subsection's 100 simulations. The outcomes are summarised as follows.

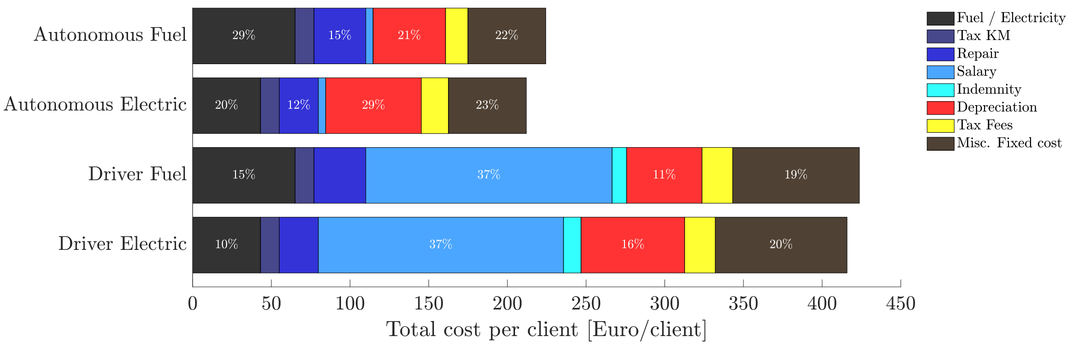


Figure 4.19: Cost breakdown with vans: 400 km - 1 client

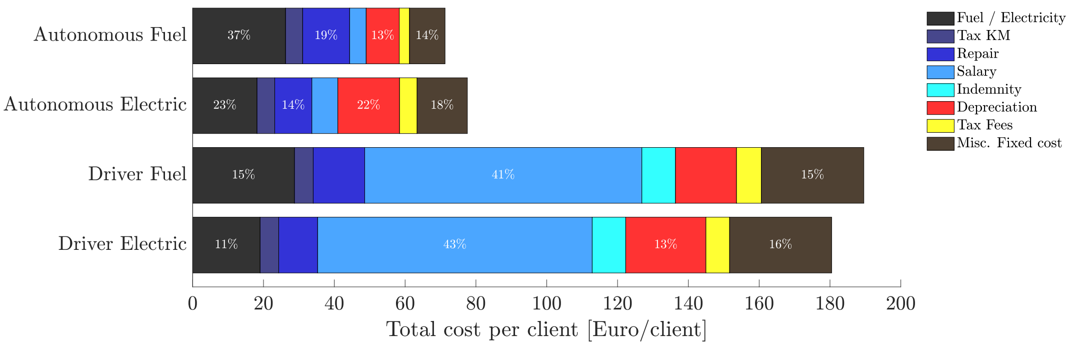


Figure 4.20: Cost breakdown with vans: 400 km - 10 clients

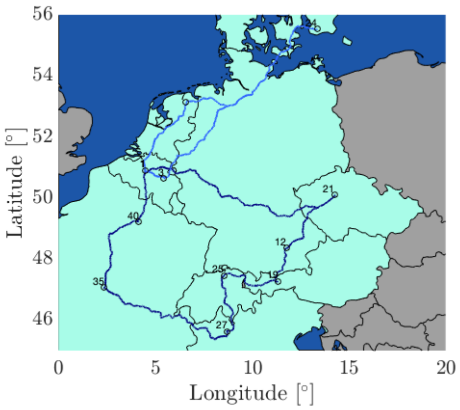
From Figs. 4.19 & 4.20, similar observations can be made as in the analysis of the aircraft scenario. The increased total distances of the delivery rounds lead to higher variable costs, which further escalate with a larger number of customers. In line with the Benelux case, the salary component represents the largest proportion in non-autonomous versions. In contrast, the relative share of fixed costs decreases, especially as more customers are considered.

A noteworthy point is the comparison between electric and fuel vehicles in the autonomous versions. It is evident that the advantage of electric vehicles diminishes with an increasing number of customers. This is primarily attributed to the extended distances covered in the delivery round, necessitating more battery recharging times for electric vehicles.

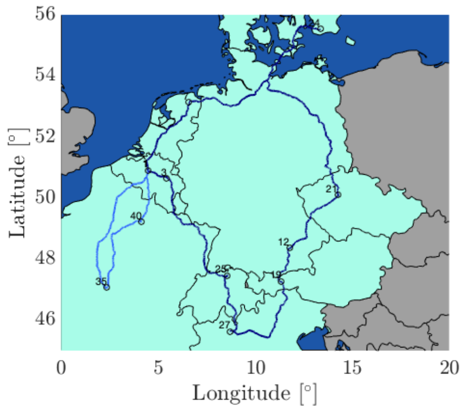
4.6 CASE STUDY WITH VANS: 800 KM

The final scenario replicates the methodology employed in previous case studies. Similar to the airplane analysis, the third study involves expanding the range of destinations to a radius of 800 km around Brussels. The allocated time frame remains unchanged, spanning two days, and customers can be served from 0 a.m. to 12 p.m.

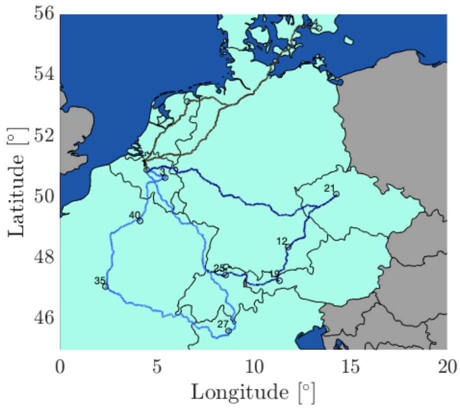
4.6.1 Typical journey analysis



(a) Autonomous Electric



(b) Autonomous Fuel



(c) Non autonomous Electric & Fuel

Figure 4.21: Routes taken by the vans with driver and autonomous: 800 km

Driver						Autonomous						
		Electric		Fuel				Electric		Fuel		
Vehicle	Stop	Arrival	Departure	Arrival	Departure	Vehicle	Stop	Arrival	Departure	Stop	Arrival	Departure
1	1	-	M 00:00	-	M 00:00	1	1	-	M 00:00	1	-	M 00:00
	25	M 10:06	M 10:36	M 07:33	M 08:03		40	M 03:31	M 04:01	3	M 01:03	M 01:33
	19	T 01:29	T 01:59	T 01:16	T 01:46		35	M 09:47	M 10:17	25	M 08:06	M 08:36
	12	T 04:57	T 05:27	T 04:05	T 04:35		27	M 21:39	M 22:09	27	M 12:04	M 12:34
	21	T 10:43	T 11:13	T 09:16	T 09:46		25	T 02:57	T 03:27	19	M 17:25	M 17:55
	1	W 13:28	-	W 09:50	-		19	T 07:59	T 08:29	12	M 20:13	M 20:43
2	1	-	M 00:00	-	M 00:00		12	T 11:27	T 11:57	21	T 00:39	T 01:09
	3	M 01:03	M 01:33	M 01:03	M 01:33		21	T 17:13	T 17:42	24	T 12:50	T 13:20
	40	M 05:45	M 06:15	M 04:25	M 04:55		1	W 07:39	-	7	T 21:31	T 22:01
	35	M 11:57	M 12:27	M 10:03	M 10:33					1	W 01:38	-
	27	T 12:07	T 12:37	T 09:14	T 09:44	2	1	-	M 00:00	1	-	M 00:00
	1	W 13:10	-	W 10:05	-		3	M 01:03	M 01:33	35	M 06:01	M 06:31
3	1	-	M 00:00	-	M 00:00		24	M 16:46	M 17:16	40	M 10:54	M 11:24
	7	M 05:00	M 05:30	M 03:37	M 04:07		7	T 04:44	T 05:14	1	M 14:11	-
	24	T 04:03	T 04:33	T 03:03	T 03:33		1	T 10:10	-			
	1	W 07:58	-	W 06:04	-							

Table 4.11: Route schedule and its destinations for vans with driver: 800km

By examining Figs. 4.21a, 4.21b & 4.21c, it can be seen that, similar to the previous scenarios, the autonomous version necessitates one less vehicle compared to the driver-operated version. However, a slight distinction arises in the chosen routes between fuel-powered and electric vans. Regarding the analysis of schedules for the various configurations, the same observations can be made as in the 400 km scenario.

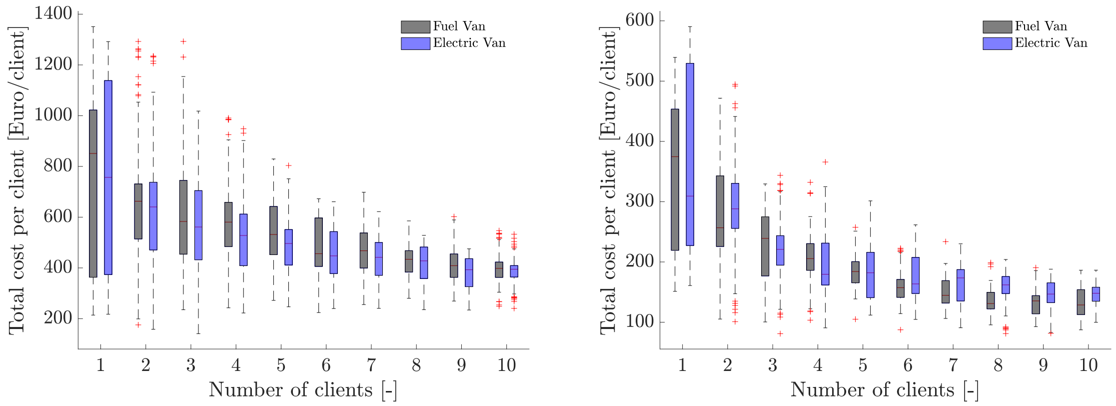
	Driver		Autonomous	
	Electric	Fuel	Electric	Fuel
Total working time	79h14	79h14	65h48	63h49
Total driving time	74h14	74h14	60h48	58h49
Total distance [km]	6532	6532	5247	5031
Total cost [€]	4217	4051	1571	1291

Table 4.12: Total cost, distance and working & driving time (vans): 800km

Tab. 4.12 once again demonstrates a threefold difference in costs between the autonomous and driver-operated versions. The reasons behind this disparity remain the same as those explained in the 400 km scenario. Notably, in this case, the distances travelled are approximately double compared to the 400 km scenario, which accounts for the corresponding increase in driving and working hours. Consequently, the generated total costs are also doubled. When comparing the electric and fuel-powered versions, it is evident that, in this typical scenario, neither the non-autonomous nor the autonomous version favours the use of electric vans.

4.6.2 *Cost per client*

Once again, a comprehensive analysis of costs per customer is conducted, following the same operating mode and objective of gaining a broad understanding based on a substantial number of simulations.



(a) Non autonomous

(b) Autonomous

Figure 4.22: Total cost per client of electric & fuel-powered vans: 800 km

Upon analysing Figs. 4.22a & 4.22b, it is observed that graphs resemble to those obtained in the previous scenario. However, there is a notable difference in the wider interquartile range and whiskers, which can be attributed to the increased variance in distances travelled and the consequent variation in the number of vehicles utilised. As for the presence of outliers, the reasons remain consistent with those encountered in the 400 km scenario.

Once again, when comparing the autonomous and non-autonomous versions, there is a significant cost savings of two to three times in favour of the autonomous vans. When comparing electric vans to fuel-powered vans, the electric option remains advantageous in the non-autonomous case, thanks to relevant legislation. However, this advantage diminishes in the autonomous case, particularly as the number of customers increases and the total tour distance expands. Overall, when comparing the costs with those obtained in the 400 km scenario, the latter are approximately twice as high, as explained in the previous section, due to the doubled distances and total working times. More detailed numerical data can be found in Tab. B.6 of Appendix B. Once more, when these findings are compared with those achieved in the aviation context, transportation via vans remains more cost-effective by approximately a factor of 10.

4.6.3 Cost breakdown

Lastly, a detailed analysis of the cost breakdown is conducted to identify the primary factors contributing to the total cost of the tour. Additionally, the influence of the number of customers on these factors is examined. Similarly to before, two scenarios are presented, one with a single customer and another with 10 customers, representing the median outcome from the 100 simulations discussed earlier. The findings are summarised below.

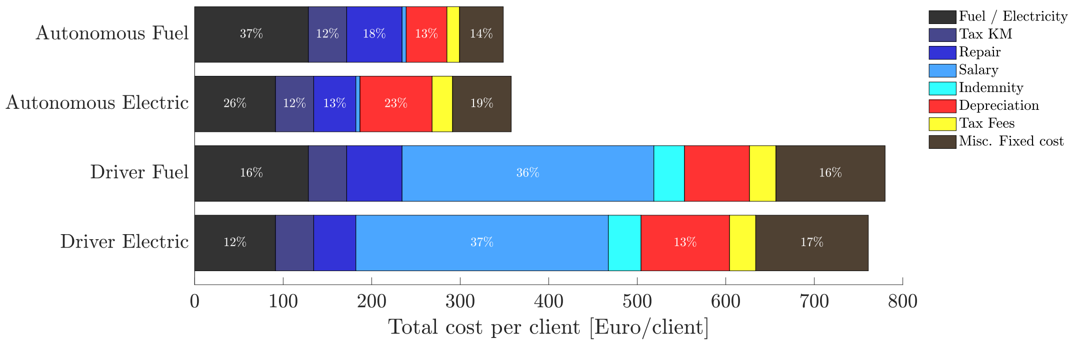


Figure 4.23: Cost breakdown with vans: 800 km - one client

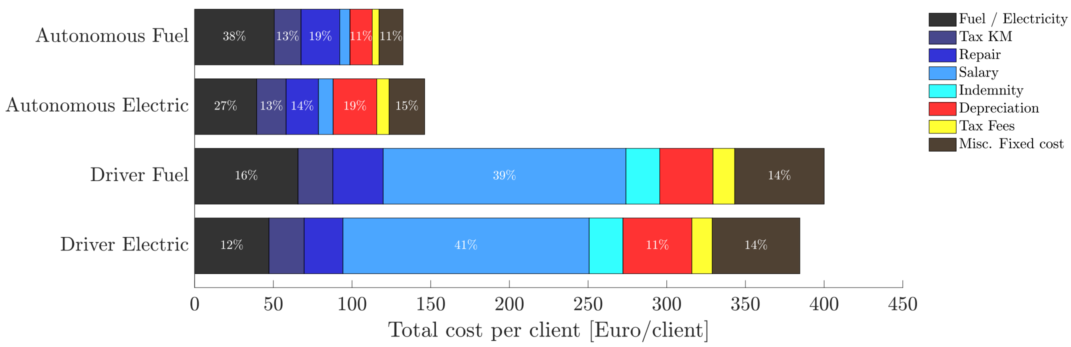


Figure 4.24: Cost breakdown with vans: 800 km - 10 clients

Upon analysing Figs. 4.23 & 4.24, similar patterns emerge as observed in the comparison between the 400 km and Benelux scenarios. The longer tour distances lead to increased variable costs, which further escalate with the number of customers considered. Consequently, the proportionate contribution of fixed costs decreases. Notably, the relative share of salaries remains relatively stable, despite the increased number of vehicles and drivers compared to the 400 km scenarios. Lastly, similarly to the previous section, it can be seen that electric versions of non-autonomous vans generally result in slightly lower total costs while for autonomous vans the latter tends to be more expensive.

4.7 Conclusion

Upon gathering all the analysis results, it is possible to provide a summary as follows. In the context of aviation, electrification generally leads to cost savings across the entirety of the delivery process. These savings typically range between 10% and 20%, with a constant increase with the perimeter of consideration of destinations. Nonetheless, in specific scenarios, electric aviation might incur higher costs. This arises from inherent constraints related to battery charging durations and operational autonomy. These constraints could potentially require the inclusion of extra days or aircraft, when compared with the traditional internal combustion engine counterpart, to ensure adherence to delivery timelines. Similarly, the notion of reducing the number of pilots also presents an opportunity for cost savings in the delivery process. These savings range from around 10% for a single pilot reduction to as much as 40% for a completely autonomous version. Hence, there are evident economic advantages in transitioning to electric aircraft and minimising crew requirements.

In the case of electrifying vans for road transport, the gains are less conspicuous. The achieved savings typically range between 1% and 8%, and the larger the operational perimeter becomes, the less advantageous it is to electrify road transport. This can be attributed to the extended charging times and limited autonomy of electric vans. For non-autonomous vans, due to legal considerations, this drawback is less pronounced. However, in the case of autonomous vans, considering the absence of legislation, electric vans become considerably less advantageous, if not even more expensive. Regarding the elimination of drivers, as observed in aviation, this concept allows for the total cost of delivery rounds to be halved or even reduced to a third, compared to when a driver is employed.

Finally, as established in subsection 3.4.3, aviation retains its status as a luxurious mode of transportation, even with cost reductions achieved through electrification. The difference in magnitude still persists at approximately a factor of 10 compared to road transport.

5

CONCLUSION

In today's context, concerns about climate change are growing, and the issue is being taken very seriously. Numerous initiatives are being undertaken to curtail the emission of greenhouse gases, with the aim of achieving carbon neutrality by 2050, in alignment with the European Commission's Green Deal initiative. These efforts primarily target sectors that contribute significantly to greenhouse gas emissions, among which transportation holds a prominent place, accounting for about 23% of the EU's greenhouse gas emissions in 2020 (Eurostat, 2020). To address this challenge, one of the viable solutions on the horizon is the electrification of the transportation sector, with a particular focus on road and air transport. This gave rise to the initial research query of this thesis: Does the financial aspect make transitioning to electric vehicles for express delivery by both planes and vans worthwhile?

Concurrently, as the reliability of autopilot systems improves and ensures robust flight safety, airlines are increasingly inclined to explore the reduction or elimination of onboard pilots as a means to cut costs. The second question asked during this thesis is therefore to quantify the potential gains that a crew reduction could bring. Thus, transitioning from two pilots to one, to the extreme case of fully autonomous flight. In parallel, the possibility of eliminating drivers within the context of road transport is also under scrutiny.

To address these inquiries, a practical scenario involving a delivery route across the European continent has been meticulously analysed. The state of the art of this analysis is based on the Vehicle Routing Problem (VRP) resolution. However, prior to this, a comprehensive evaluation of fixed and variable costs was essential across all potential crew/driver configurations and various customer radius considerations (Benelux, 400 km, and 800 km around Brussels). Throughout the analysis of these diverse cost factors, it became evident that electrification could lead to cost reductions ranging from 6% to 33%. Simultaneously, the findings highlighted that despite these cost reductions, aviation continues to be a more premium mode of transportation, by a factor of approximately 10 compared to road transport.

Combined with dynamic programming, the VRP can be customised to incorporate European regulations concerning pilot/driver rest breaks and other vehicle-related constraints (such as electric vehicle autonomy and charging times). In the context of road transport, an API facilitated the provision of real routes taken between different destinations, while air transport naturally utilised the as the crow flies distances. Once the VRP is resolved, it yields the optimal path for delivering customers within the stipulated timeframe and at the lowest cost. Consequently, for each crew/driver configuration scenario and across various customer radius considerations, the solutions were analysed and compared.

Upon completing all the investigations, the following results can be deduced. In the realm of aviation, electrification typically leads to cost savings in the overall delivery route expenditure. Generally, these savings fall within the range of 10% to 20%, exhibiting a consistent increase as the scope of destinations under consideration expands. However, in specific circumstances, electric aviation might prove to be more costly. This is due to the presence of constraints related to battery recharging times and operational range. Consequently, additional days or planes may be required compared to its internal combustion engine counterpart to fulfill the delivery mission within the stipulated timeframe. As for the reduction in pilots, this notion also holds the potential for cost savings in the delivery route expenses, ranging from around 10% for a reduction to a single pilot, up to 40% for a fully autonomous version. Hence, there are evident economic benefits in transitioning to electric aircraft and downsizing the crew.

When considering the electrification of vans for road transport, the achieved benefits are less pronounced. Typically, the achieved savings fall within the range of 1% to 8%. Moreover, as the operational scope expands, the advantages of electrifying road transport diminish. This trend is attributed to the prolonged charging times and the limited range of electric vans. In the context of non-autonomous vans, legislative considerations mitigate this drawback since stops due to reloads can be used as breaks for the driver. However, for autonomous vans, the absence of regulatory constraints renders electric vans significantly less advantageous or even more costly. As for the elimination of drivers, echoing the aviation sector, this concept can lead to a reduction of the total delivery round cost by half or even threefold compared to employing a driver.

Regarding recommendations and future work, the VRP model under consideration exclusively addressed the DCVRP due to the distance constraint imposed by electric vehicles, and the TWVRP stemming from the express delivery route requirement, which enforces a delivery time limit. In the future, the CVRP could also be incorporated to integrate vehicle loading capacity.

Subsequently, when encoding inputs into the VRP model, more realistic assumptions could have been considered. For instance, instead of encoding uniform opening and closing hours between destinations, actual opening hours could have been inputted since they were available. Additionally, due to the fact that the aircraft *Alice* has not yet taken flight, information pertaining to it, such as consumption, maintenance costs, and autonomy, had to be established based on strong assumptions or preliminary values. Once definitive values become available, they can be incorporated into the existing VRP model.

Finally, a significant concept briefly discussed in this thesis is the CO_2 emissions from vehicles. Indeed, in Chapter 3, during the vehicle presentation, the emissions per kilometre from internal combustion engine vehicles were determined solely during their use. It was observed that the reference aircraft *Pilatus PC-12* emits approximately 6 times more CO_2 than the *Mercedes Sprinter*. Conversely, for electric vehicles, since CO_2 emissions are evaluated solely during usage, they amount to zero. However, the production of electricity and batteries is a process that generates a significant amount of greenhouse gases prior to the vehicle's utilisation. Thus, it is crucial to verify whether the complete carbon dioxide emissions are genuinely diminished when electric vehicles are considered, taking into account their entire lifecycle, rather than focusing solely on their operational phase.

A

LONGITUDE & LATITUDE OF VISITED CITIES

N°	City	Airport Name	Latitude	Longitude
1	Zaventem	Aéroport de Bruxelles-National	50.9013	4.4844
2	Haren	Aérodrome de Haren	50.8803	4.4192
3	Ostende/Bruges	Aéroport d'Ostende-Bruges	51.1989	2.8622
4	Wevelgem	Aéroport de Courtrai-Wevelgem	50.8186	3.2064
5	Deurne	Aéroport d'Anvers	51.1894	4.4603
6	Weelde	Base aérienne de Weelde	51.3942	4.9592
7	Brustem	Base aérienne de Brustem	50.7919	5.2017
8	Liège	Aéroport de Liège	50.6364	5.4428
9	Spa	Aérodrome de Spa-La Sauvenière	50.4825	5.9103
10	Gosselies	Aéroport de Charleroi Bruxelles-Sud	50.4600	4.4528
11	Cerfontaine	Aérodrome de Cerfontaine	50.1528	4.3872
12	Saint-Hubert	Aérodrome de Saint-Hubert	50.0358	5.4042
13	Jehonville	Base aérienne de Bertrix	49.8917	5.2239
14	Zwartberg	Aérodrome de Genk-Zwartberg	51.0153	5.5264
15	Luxembourg City	Luxembourg Airport	49.6233	6.2044
16	Texel	Aéroport international de Texel	53.1153	4.8336
17	Rotterdam	Aéroport de Rotterdam-La Haye	51.9569	4.4372
18	Haarlemmermeer	Aéroport d'Amsterdam-Schiphol	52.3081	4.7642
19	Eindhoven	Aéroport d'Eindhoven	51.4500	5.3744
20	Eelde	Aéroport de Groningue-Eelde	53.1250	6.5833
21	Aix-la-Chapelle	Aéroport de Maastricht-Aix-la-Chapelle	50.9158	5.7769
22	Deventer	Aéroport international de Teuge	52.2447	6.0467
23	Weert	Aéroport de Kempen	51.2544	5.6008
24	Lelystad	Aéroport de Lelystad	52.4603	5.5272
25	Hoogeveen	Aéroport de Hoogeveen	52.7308	6.5161
26	Middelbourg	Aéroport de Midden-Zeeland	51.5122	3.7311
27	Hoeven	Aéroport international de Bréda	51.5547	4.5525
28	Enschede	Aéroport d'Enschede-Twente	52.2758	6.8892
29	Soesterberg	Base aérienne de Soesterberg	52.1342	5.2831
30	Leyde	Base aéronavale de Valkenburg	52.1667	4.4192

Table A.1: Geographical coordinates of the airports taken into account in the scenario: Benelux

N°	City	Airport Name	Latitude	Longitude
1	Zaventem	Aéroport de Bruxelles-National	50.9013	4.4844
2	Ostende/Bruges	Aéroport d'Ostende-Bruges	51.1989	2.8622
3	Liège	Aéroport de Liège	50.6364	5.4428
4	Gosselies	Aéroport de Charleroi Bruxelles-Sud	50.4600	4.4528
5	Luxembourg City	Luxembourg Airport	49.6233	6.2044
6	Rotterdam	Aéroport de Rotterdam-La Haye	51.9569	4.4372
7	Haarlemmermeer	Aéroport d'Amsterdam-Schiphol	52.3081	4.7642
8	Eelde	Aéroport de Groningue-Eelde	53.1250	6.5833
9	Eindhoven	Aéroport d'Eindhoven	51.4500	5.3744
10	Enschede	Aéroport d'Enschede-Twente	52.2758	6.8892
11	Hoeven	Aéroport international de Bréda	51.5547	4.5525
12	Spa	Aérodrome de Spa-La Sauvenière	50.4825	5.9103
13	Bremen	Bremen Airport	53.0475	8.7866
14	Hanover	Hannover Airport	52.4594	9.6925
15	Dortmund	Dortmund Airport	51.5183	7.6122
16	Düsseldorf	Düsseldorf Airport	51.2894	6.7667
17	Kassel	Kassel Airport	51.4208	9.3922
18	Frankfurt	Frankfurt Airport	50.0333	8.5706
19	Stuttgart	Stuttgart Airport	48.6900	9.2219
20	Münster	Münster Osnabrück International Airport	52.1361	7.6858
21	Cologne	Cologne Bonn Airport	50.8658	7.1428
22	Bielefeld	Bielefeld Airport	51.9650	8.5444
23	Saarbrücken	Saarbrücken Airport	49.2144	7.1094
24	Mannheim	Mannheim City Airport	49.4725	8.5142
25	Koblenz	Koblenz-Winningen Airport	50.3250	7.5331
26	Bitburg	Bitburg Airport	49.9453	6.5650
27	Amiens	Amiens – Glisy Aerodrome	49.8731	2.3869
28	Paris	Paris Charles de Gaulle Airport	49.0097	2.5478
29	Strasbourg	Strasbourg Airport	48.5419	7.6344
30	Dijon	Dole–Jura Airport	47.0428	5.4350
31	Caen	Caen – Carpiquet Airport	49.1733	-0.6167
32	Reims	Reims – Prunay Aerodrome	49.2086	4.1567
33	Nancy	Metz–Nancy–Lorraine Airport	48.9783	6.2467
34	Orléans	Orléans – Saint-Denis-de-l'Hôtel Airport	47.8975	2.1642
35	Le Mans	Aéroport Le Mans-Arnage	47.9492	0.2017
36	Rouen	Aéroport Rouen Vallée de Seine	49.3922	1.1839
37	Lille	Lille Airport	50.5633	3.0869
38	Calais	Calais–Dunkerque Airport	50.9608	1.9514
39	Troyes	Troyes – Barberey Airport	48.3217	4.0167
40	Colmar	Colmar - Houssen Airport	48.1103	7.3592

Table A.2: Geographical coordinates of the airports taken into account in the scenario: 400 km

N°	City	Airport Name	Latitude	Longitude
1	Zaventem	Aéroport de Bruxelles-National	50.9013	4.4844
2	Ostende/Bruges	Aéroport d'Ostende-Bruges	51.1989	2.8622
3	Liège	Aéroport de Liège	50.6364	5.4428
4	Gosselies	Aéroport de Charleroi Bruxelles-Sud	50.4600	4.4528
5	Luxembourg City	Luxembourg Airport	49.6233	6.2044
6	Rotterdam	Aéroport de Rotterdam-La Haye	51.9569	4.4372
7	Haarlemmermeer	Aéroport d'Amsterdam-Schiphol	52.3081	4.7642
8	Dortmund	Dortmund Airport	51.5183	7.6122
9	Hamburg	Hamburg Airport	53.6303	9.9911
10	Frankfurt	Frankfurt Airport	50.0333	8.5706
11	Stuttgart	Stuttgart Airport	48.6900	9.2219
12	Munich	Munich International Airport	48.3539	11.7861
13	Dresden	Dresden Airport	51.1344	13.7681
14	Berlin	Berlin Brandenburg Airport Willy Brandt	52.3667	13.5033
15	Kassel	Kassel Airport	51.4208	9.3922
16	Düsseldorf	Düsseldorf Airport	51.2894	6.7667
17	Leipzig	Leipzig/Halle Airport	51.4239	12.2364
18	Nuremberg	Nuremberg Airport	49.4986	11.0781
19	Innsbruck	Innsbruck Airport	47.2603	11.3439
20	Salzburg	Salzburg Airport	47.7944	13.0033
21	Prague	Václav Havel Airport Prague	50.1017	14.2603
22	Copenhagen	Copenhagen Airport	55.6181	12.6561
23	Aalborg	Aalborg Airport	57.0928	9.8492
24	Malmö	Malmö Airport	55.5300	13.3714
25	Zürich	Zürich Airport	47.4647	8.5492
26	Geneva	Geneva Airport	46.2375	6.1092
27	Milan	Milan Malpensa Airport	45.6300	8.7231
28	Turin	Turin Airport	45.2025	7.6494
29	Amiens	Amiens – Glisy Aerodrome	49.8731	2.3869
30	Limoges	Limoges – Bellegarde Airport	45.8608	1.1803
31	Lyon	Lyon–Saint Exupéry Airport	45.7256	5.0811
32	Bordeaux	Bordeaux–Mérignac Airport	44.8283	-0.7156
33	Nantes	Nantes Atlantique Airport	47.1569	-1.6078
34	Paris	Paris Charles de Gaulle Airport	49.0097	2.5478
35	Bourges	Bourges Airport	47.0608	2.3700
36	Brest	Brest Bretagne Airport	48.4472	-4.4217
37	Strasbourg	Strasbourg Airport	48.5419	7.6344
38	Dijon	Dole–Jura Airport	47.0428	5.4350
39	Caen	Caen – Carpiquet Airport	49.1733	-0.6167
40	Reims	Reims – Prunay Aerodrome	49.2086	4.1567

Table A.3: Geographical coordinates of the airports taken into account in the scenario: 800 km

B

DETAILS ON COST SAVINGS FROM ELECTRIFICATION & CREW REDUCTION

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Two pilots	2376	2194	7.7	355	307	13.5
One pilot	2008	1827	9.0	315	270	14.3
Autonomous	1819	1616	11.1	303	253	16.5
Two pilots → One pilot: ↘ [%]	15.5	16.7		11.7	12.0	
Two pilots → Autonomous: ↘ [%]	23.5	26.3		14.6	17.6	

Table B.1: Total cost per client & cost savings when electrifying aviation and reducing the crew size: Benelux

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Two pilots	2824	2490	11.8	728	630	13.5
One pilot	2457	2185	11.1	655	566	13.6
Autonomous	2267	1911	15.7	474	384	19.0
Two pilots → One pilot: ↘ [%]	13.0	12.3		10.0	10.1	
Two pilots → Autonomous: ↘ [%]	19.7	23.3		34.9	39.0	

Table B.2: Total cost per client & cost savings when electrifying aviation and reducing the crew size: 400 km

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Two pilots	4009	2987	25.5	1003	824	17.9
One pilot	3252	2643	18.7	922	738	20.0
Autonomous	3452	2408	30.2	750	577	23.1
Two pilots → One pilot: ↘ [%]	18.9	11.5		8.1	10.4	
Two pilots → Autonomous: ↘ [%]	13.9	19.4		25.2	30.0	

Table B.3: Total cost per client & cost savings when electrifying aviation and reducing the crew size: 800 km

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Driver	239	235	1.67	114	107	4.86
Autonomous	157	159	-1.27	52	50	3.85
Driver → Autonomous: ↘ [%]	34.3	32.3		54.4	53.3	

Table B.4: Total cost per client & cost savings when electrifying vans and reducing the crew size: Benelux

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Driver	376	351	6.65	191	183	4.19
Autonomous	222	208	6.31	71	81	-14.1
Driver → Autonomous: ↘ [%]	40.9	40.7		62.8	55.7	

Table B.5: Total cost per client & cost savings when electrifying vans and reducing the crew size: 400 km

Total cost per client [€/client]	1 client			10 clients		
	Fuel	Electric	Electric ↘ [%]	Fuel	Electric	Electric ↘ [%]
Driver	851	757	11.1	398	395	0.75
Autonomous	375	310	17.3	129	148	-14.7
Driver → Autonomous: ↘ [%]	55.9	59.1		67.6	62.5	

Table B.6: Total cost per client & cost savings when electrifying vans and reducing the crew size: 800 km

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