Electric Ground Support Equipment at Airports

The impact of implementing eGSE on the capacity and demand of GSE fleets

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TU Delft
KLM Royal Dutch Airlines
NACO a company of Royal HaskoningDHV

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by

K. Timmermans

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Preface

You are reading the thesis report that concludes my master's program in Mechanical Engineering at Delft University of Technology. Because of my broad interest in technology, I pursued a bachelor's degree in Mechanical Engineering. As part of my bachelor's program, I took a minor in Airport Development because my interest in aviation has also always been present. However, I found the logistical challenges surrounding the use of technology even more intriguing. Therefore, after completing my bachelor's, I chose to pursue the master's track in Multi-Machine Engineering (formerly Transport Engineering & Logistics). I aimed to undertake a thesis research that incorporated all these elements. I started early, put in the effort, and succeeded. Collaborating with NACO, I embarked on a thesis research involving a significant amount of logistics and operations research, and, of course, all set in an airport environment! To bring the research into practice, I partnered with KLM, adding an extra layer to my study. Although GSE only contributes to a small part of aviation's carbon emissions, electrification does directly improve the immediate environment of an airport. It is therefore nice to be able to contribute to the sustainability of airports with this research.

It turned out that Ground Support Equipment (GSE) operations at airports form a world of their own. Have you ever thought about the fact that sometimes more than 12 different types of equipment are needed to prepare your aircraft? And soon more and more electric variants will be driving around. So, next time you arrive at your gate, consider taking a window seat and looking outside instead of searching for the nearest spot with a power socket to charge your phone. After reading my thesis, I'm curious to know which GSE types you recognize!

I hope you enjoy reading my thesis, and hopefully, you become as enthusiastic about this topic as I have!

Koen Timmermans
Bergen op Zoom, November 2023

Acknowledgements

In the theses that I read from others to gain inspiration, I notice that the acknowledgements of many other students consist of no more than a few sentences. My acknowledgement section is perhaps at the opposite extreme. Everyone who contributed to my thesis did so from a different role or position. However, during my thesis, I have come to realize that it is not so self-evident that everyone makes time for you and extends a helping hand. This is the time and place to put the gratitude that I have for all the people that were there along the way leading up to my MSc defense into words. People who were there to help, to supervise, to correct, to criticize, but also to brainstorm with, to laugh with, to complain to, to travel with, to collaborate with, and so much more.

Let me start by thanking my supervisory team: **Bilge Atasoy** (TU Delft), **Paul Roling** (TU Delft), **Remco Troquete** (NACO), **Gideon Wiebenga** (KLM) and **Gautham Ram Chandra Mouli** (TU Delft). I could not have concluded this MSc thesis without them.

Bilge, from the moment I approached you after a lecture to discuss the possibility of a thesis, I had the feeling that you were supporting me. This was already in May 2022. In June I came up with a possible topic during an exploratory conversation with NACO. In my email to you I wrote "research into and scheduling of GSE (Ground Support Equipment) (electric) at airports based on flight schedules as input using a model that can be widely used for multiple airports". You replied with "looks exciting, happy for you and we will discuss (after the summer I assume) more specifics about your thesis work". During the progress meetings that followed, I always left feeling satisfied, provided with new insights, valuable feedback and a pleasant conversation. I was amazed at how quickly you can switch between the content of all the projects you are involved in. Based on your agenda and the stories I have heard from fellow students, I consider myself lucky to have had a supervisor like you.

Paul, already during the Airport Development minor in the COVID-19 lockdown, I became enthusiastic about your aviation knowledge during the online lectures that I attended from home. I was therefore happy to be able to meet you in person at the faculty of aerospace engineering, when I was orientating myself on my thesis back in May 2022. And although I was able to solve many problems with Bilge, I was happy to have you as a second supervisor. The additional knowledge and perspective on (sustainable) aviation, together with your knowledge of optimization problems, often provided a valuable perspective on my research from a different point of view.

Remco, from a conversation that I had with a student who was already graduating with NACO, it became already clear to me that you would be a good supervisor for my thesis. Looking back, I can only conclude that this was the case. It was nice to have a supervisor who made time when necessary and trusted me to let me do my thing in the meantime. Because you also graduated from TU Delft, you understood how the process works and you regularly reminded me what had priority when I had too many ideas again. And although we were both professional when necessary, we also built up a relationship as friends over the course of time. As children in the candy store, we enjoyed a visit to Schiphol's airside together and we have been laughing a lot in the office. I believe that the adventure we had in Panama is the best illustration of the unique bond we have developed over the course of a year.

Gideon, you became my "new" supervisor after your colleague left KLM in the first weeks of my project. And although guiding a student, the graduation process, and the academia's approach were all new to you, the way you handled this is commendable. From day one, you emphasized that I should not only focus on theory but also look at the practical aspects. As I progressed in my research, I began to understand this statement more when I realized how many variables are involved in managing KLM's operations and how challenging it is to describe this in a model. At the beginning of my project, you referred me to various colleagues within KLM to learn more about the processes and challenges. You may not be a theorist, but as you describe yourself on LinkedIn, you're an "allround people manager". Your practical contribution has greatly contributed to my research, both in theory and, especially, in practice.

Gautham Ram, by chance, we came into contact when I was looking for someone within TU Delft who could explain more to me about the energy consumption and the charging of electric vehicles. And not "by chance" because of this topic, as it is your area of expertise, but mainly because of the TULIPS (Green Airports) project that you and PhD student Yawen Liang were working on. For this research, you were tasked with mapping out what is needed to fully electrify Schiphol, and eGSE was of course also a part of that. Ultimately, it turned out that I could help you with explaining the working principles of GSE, and you could help me with the electrical engineering-related questions I had. Your enthusiasm during the few meetings we had and your request to use my research for the TULIPS project motivated me with the idea that my research can really contribute to something.

Since I worked in a collaboration with two companies, I had many colleagues around me who helped along the way. I spent most of the time at NACO, in the office in The Hague. I want to thank all colleagues from the Airport Strategy & Planning department and especially the colleagues I was regularly around: **Niek**, **Stefan**, **Max**, **Pieter**, **Maarten**, **Philippe**, **Floor**, **Julia**, **Paul**, **Quinty**, **Joris**, **Jan**, **Michiel**, and **Adam**. Whether just by chit-chat, in-depth discussions, giving advise, having lunch, sharing the office, showing interest in my project, or sharing work frustrations, you have all made my time on the 11th floor more enjoyable. I would specifically like to thank **Niek** for his input on the setup of my MILP model and my thesis in general. When I joined NACO, you were already in the process of finishing your thesis. We had a lot of fun together, so I was happy that you stayed at NACO as a colleague. **Stefan**, for thinking along about my model, proofreading my literature research and the laughs we had together. **Pieter**, for the help with the mechanical engineering related questions I had. Compared to me, you are a real mechanical engineer. And **Quinty**, for the help with some of my Python related questions. In addition, I would like to thank **Tessel**, **Vivek**, and **Eoghan**, who contributed to the realization of my thesis project. **Tessel**, for providing the opportunity to carry out my graduation project at NACO within your department. **Vivek**, for assisting in the development of my thesis topic. And **Eoghan**, for the interest in my graduation project and the enjoyable meetings we have had. I have benefited greatly from your expertise in the (e)GSE field throughout my project.

In addition, I have regularly been at KLM, in the Topside office at Schiphol. I want to thank all colleagues from the Operational Support unit within the Apron Services department and especially the colleagues I was regularly around: **Erwin**, **Ed**, **Ömer**, **Michiel**, and **Jorben**. You have all made my time on the 6th floor more valuable by showing interest in my project, providing me with the right documents, explaining operational processes, or just having lunch. I would like to specifically thank **Erwin** for the enjoyable conversations and the help with the many questions and requests I had. And **Jorben**, for your interest in me and my graduation project, and the feedback you have given. It was very nice to be able to have an in-depth discussion on my model, as you also did the Multi-Machine Engineering track at TU Delft. I would also like to thank **Nico** and **Danny** for the time they took to explain the details of the airside operations to me. Additionally, I am grateful to **Nico** for the valuable tour he gave on Schiphol's airside. And thanks to **Martijn** and **Stefan**, for the time they made available to discuss and arrange the data that I required.

I want to thank two friends as well, both of whom contributed to my thesis. **Thijs**, in the first year of the bachelor, we were in a project group together for the first time. After that, whenever we had the chance, we always ended up in the same project group. Both of us share an interest in aviation, so during COVID-19, we were in countless online meetings analyzing flight schedules and other airport-related things for the Airport Development minor. This allowed us to better understand each other and identify our strengths and weaknesses. After the bachelor's, we both chose the same master's program. And again, we collaborated on almost all projects. Especially at the beginning of my thesis, you often were a lifesaver when debugging my MILP model. Because even though it wasn't your model, you still couldn't handle not understanding why some things didn't work as expected. In general, you grasp concepts much quicker than I do, and after all our projects you are trained in spotting the "classic Koen mistakes". Over the past few years, we've shared many laughs and experiences, not only related to the courses we took together but for example also during our adventures around Schiphol, trying to spot an A380. I want to thank you for listening to my thesis frustrations, helping with the debugging of my model, proofreading parts of my thesis, and for the joy and friendship over the past years. And **Stijn**, we met each other in high school. After that, you went on to study computer science. We have been able to help each other with various things, based on our studies. Over the past years, you've taught me things related to programming for various courses I was taking. You explained to me what you can do with classes in Python, which, in hindsight, has proven to be very valuable information. When I had a bug in my code that I couldn't figure out myself, you often helped me find a solution. Thank you for listening to my thesis stories and assisting in the development of the model.

And lastly, I want to thank my sister, **Noortje**, and my parents, **Hans** and **Monique**, for the support throughout my entire studies. Thank you for listening to all my stories, showing interest, providing guidance in the choices I had to make, and serving cups of tea with something to snack at the moments when they were most needed. I consider myself fortunate for the environment you provided for me to come this far. **Noortje**, thank you for listening to my thesis-related stories during lunch and dinner. Although your interests lie elsewhere, I (almost) never heard you complain about my aviation-related stories. **Hans**, thank you for the time and effort you invested in me during high school to teach me the principles of mathematics and physics. As my studies progressed, the content of the courses I had surpassed your knowledge, but I owe my interest in technology and the choice to study at TU Delft to you. And **Monique**, even though you have little affinity with technology, I have a lot to thank you for. Thanks for the care and support when I was feeling down. And thanks for the linguistic support and proofreading, as you have been doing since high school. I have inherited from you the trait of always approaching everyone and engaging in conversation. This has brought me a lot in the recent years. Moreover, it can't be denied that I owe my affinity with aviation to you. Thank you for the times you took me on a flight.

Abstract

In 2017, the aviation sector was the second most important source of Greenhouse Gas (GHG) emissions in the transport sector after road traffic, and it seems that these environmental problems will continue, as the current traffic growth is outpacing fuel efficiency improvements and reductions of emissions from other sectors. To mitigate climate change and control temperature rise, the aviation sector needs to reduce GHG emissions, like CO_2, and the emission of air pollutants from fossil fuels. Ground Support Equipment (GSE), which supports the turnaround process of aircraft, also has a share in these emissions. Hence, to reduce both carbon and air pollutant emissions from GSE, airports and airlines are examining and committing to the electrification of GSE.

The two main challenges that arise as a fully electrified fleet of GSE is realized pertain the significantly longer charging time compared to refueling conventional fossil-fueled vehicles and the increased burden on the electric grid. Electric versions already exist for a number of (especially smaller) GSE types, but these are still being developed for other larger vehicles. For the early stage decision making of different stakeholders, it is therefore important to be able to estimate the required quantity of electric Ground Support Equipment (eGSE), the charging requirements of eGSE, the change of airport electricity requirements, and the scheduling possibilities of eGSE charging for the existing turnaround procedures.

To get insight into the required number of vehicles and the energy consumption, a model was developed to simulate and optimize the GSE operations at airports. This was done by means of a Task Scheduling Problem (TSP), that is optimized using Mixed-Integer Linear Programming (MILP). To this extent, (literature) research was conducted about airport operations, the influence of eGSE compared to the conventional non-electric GSE, and the modeling of GSE. Based on interviews and observations, the decision was made to focus on simulating and optimizing GSE operations and their associated energy consumption while excluding the charging of eGSE in this research.

A case study was performed on KLM's GSE fleet at Amsterdam Airport Schiphol (AAS). Based on this, it was concluded that the impact of implementing eGSE on the capacity and demand of a GSE fleet depends on the type of GSE. For GSE types that can last an entire day on a single battery charge, there is no difference in the capacity that can be achieved. These vehicles can therefore be directly replaced one-to-one compared to their conventional counterparts. This primarily applies to smaller vehicles under the condition that the vehicles are not needed at night, so that they can be charged again. Due to nighttime curfews, this is possible at many airports. However, another group of GSE types experiences battery depletion before the day concludes, requiring increased vehicle deployment, daytime charging, higher-capacity batteries, or equipment with an improved efficiency to maintain the capacity. Daytime charging effectiveness depends on task distribution. The model assists in determining additional vehicle needs and estimating the possibilities for interim charging through opportunity charging, without including daytime charging. Yet, achieving optimality requires further research, particularly in developing charging strategies for specific GSE types.

The literature review identified differences among GSE types, leading to the categorization of similar groups for broader applicability. The results indicate the model's suitability for strategic decision-making, aligning with airport master planning. Strategic use benefits from a simplified approach, such as using an assignment problem or grouping locations. However, at the operational level, individual GSE types' specifics impact accuracy. The model, incorporating essential components from literature, interviews, and observations, is effective on an operational level, and includes factors like distance, vehicle starting locations, and aircraft types. The use of the model has the potential to make the use of resources in the operation more efficient. Further accuracy improvements for operational use require detailed consideration of individual GSE types, disruptions, and specific airport configurations.

Abstract (Dutch)

In 2017 was de luchtvaartsector na het wegverkeer de op een na belangrijkste bron van broeikasgas emissies, en het lijkt erop dat deze milieuproblemen zullen aanhouden, aangezien de huidige verkeersgroei de verbetering van de brandstofefficiëntie en de emissiereducties van andere sectoren overtreft. Om klimaatverandering tegen te gaan en de temperatuurstijging onder controle te houden, moet de luchtvaartsector de broeikasgas emissies, zoals CO_2, en de uitstoot van luchtverontreinigende stoffen uit fossiele brandstoffen verminderen. Ground Support Equipment (GSE), dat het turnaround proces van vliegtuigen ondersteunt, draagt ook bij aan deze emissies. Daarom onderzoeken luchthavens en luchtvaartmaatschappijen de elektrificatie van GSE om zowel koolstof- als luchtverontreinigende emissies te verminderen.

De twee belangrijkste uitdagingen die ontstaan bij de realisatie van een volledig geëlektrificeerd wagenpark van GSE hebben betrekking op de aanzienlijk langere oplaadtijd in vergelijking met het tanken van conventionele fossiele voertuigen en de verhoogde belasting van het elektriciteitsnet. Elektrische versies bestaan al voor een aantal (vooral kleinere) soorten GSE, maar deze moeten nog ontwikkeld worden voor andere grotere voertuigen. Voor het vroegtijdige besluitvormingsproces van verschillende belanghebbenden is het daarom belangrijk om de benodigde hoeveelheid electric Ground Support Equipment (eGSE)-types, de laadvereisten van eGSE, de verandering van de elektriciteitsbehoeften van de luchthaven en de planningsmogelijkheden van eGSE-lading voor de bestaande turnaround procedures te kunnen schatten.

Om inzicht te krijgen in het benodigde aantal voertuigen en het energieverbruik, werd een model ontwikkeld om de GSE-activiteiten op luchthavens te simuleren en optimaliseren. Dit werd gedaan aan de hand van een Task Scheduling Problem (TSP), geoptimaliseerd met behulp van Mixed-Integer Linear Programming (MILP). Hiervoor werd (literatuur)onderzoek uitgevoerd naar luchthavenactiviteiten, de invloed van eGSE vergeleken met de conventionele niet-elektrische GSE, en de modellering van GSE. Op basis van interviews en observaties werd besloten om de focus te leggen op het simuleren en optimaliseren van GSE-activiteiten en hun bijbehorende energieverbruik, met uitsluiting van het opladen van eGSE in dit onderzoek.

Een casestudy werd uitgevoerd op de GSE-vloot van KLM op Amsterdam Airport Schiphol (AAS). Hieruit werd geconcludeerd dat de impact van de implementatie van eGSE op de capaciteit en vraag van een GSE-vloot afhangt van het type GSE. Voor GSE-types die een hele dag op een enkele acculading kunnen functioneren, is er geen verschil in de haalbare capaciteit. Deze voertuigen kunnen daarom direct een-op-een worden vervangen ten opzichte van hun conventionele tegenhangers. Dit geldt voornamelijk voor kleinere voertuigen onder de voorwaarde dat de voertuigen 's nachts niet nodig zijn, zodat ze opnieuw kunnen worden opgeladen. Door een nachtelijk verbod op vliegbewegingen is dit mogelijk op veel luchthavens. Een andere groep GSE-types heeft echter een lege accu voordat de dag eindigt, wat resulteert in een verhoogde inzet van voertuigen, overdag opladen, accu's met een hogere capaciteit of equipment met een verbeterde efficiëntie om de capaciteit te behouden. De effectiviteit van het overdag opladen hangt af van de verdelen van de taken. Het model helpt bij het bepalen van de extra voertuigbehoefte en het inschatten van de mogelijkheden voor tussentijds opladen via "opportunity charging" zonder dat er overdag opgeladen wordt. Toch vereist het bereiken van optimaliteit verder onderzoek, met name bij het ontwikkelen van laadstrategieën voor specifieke GSE-types.

Het literatuuronderzoek identificeerde verschillen tussen GSE-types, wat leidde tot de categorisering van vergelijkbare groepen voor een bredere toepasbaarheid. De resultaten geven aan dat het model geschikt is voor strategische besluitvorming, in lijn met de masterplanning van luchthavens. Strategisch gebruik profiteert van een vereenvoudigde aanpak, zoals het gebruik van een "assignment problem" of het groeperen van locaties. Op operationeel niveau beïnvloeden de bijzonderheden van individuele GSE-types de nauwkeurigheid. Het model, waarin essentiële componenten uit literatuur, interviews en observaties zijn meegenomen, is operationeel effectief en bevat factoren zoals afstand, startlocaties van voertuigen en vliegtuigtypes. Het gebruik van het model heeft potentie om het gebruik van de beschikbare middelen in de operatie efficiënter te maken. Verdere verbeteringen in nauwkeurigheid voor operationeel gebruik vereisen gedetailleerde beschouwing van individuele GSE-types, verstoringen en specifieke luchthavenconfiguraties.

Contents

List of Abbreviations

Aviation

A-CDM Airport Collaborative Decision Making
ACU Air Climate Unit
APU Auxiliary Power Unit
ASU Air Starter Unit
ATM Air Traffic Movement

eGSE electric Ground Support Equipment

GOMS Ground Operations Manual Schiphol
GPU Ground Power Unit
GSE Ground Support Equipment

MARS Multiple Aircraft Receiving Stand
MGHA Main Ground Handling Agency
MRO Maintenance, Repair, and Overhaul

NABO Narrow-Body

PBB Passenger Boarding Bridge
PCA Pre-Conditioned Air

ULD Unit Load Device

WIBO Wide-Body

Electricity

AC Alternating Current

CC Constant Current
CV Constant Voltage

DC Direct Current

General flight cycle

AIBT Actual In-Block Time
AOBT Actual Out-Block Time
AROT Arrival Runway Occupancy Time
AT Air time
ATA Actual Time of Arrival
ATD Actual Time of Departure

CTOT Calculated Take-Off Time

DROT Departure Runway Occupancy Time

EOBT Expected Out-Block Time

GT Ground time

IRT Inbound Roll Time

ORT Outbound Roll Time

SIBT Scheduled In-Block Time
SOBT Scheduled Out-Block Time
STA Scheduled Time of Arrival
STD Scheduled Time of Departure

TIT Taxi-In Time
TOBT Target Out-Block Time
TOT Taxi-Out Time
TSAT Target Start-up Approval Time
TTOT Target Take-Off Time

Miscellaneous

CLD Causal Loop Diagram

GHG Greenhouse Gas

KPI Key Performance Indicator

PRM Person with Reduced Mobility

RQ Research Question

SQ Sub Question

Modeling

ALNS Adaptive Large Neighborhood Search

CP Constraint Programming
CWS Clarke and Wright Savings

EVRP Electric Vehicle Routing Problem
EVRPTW Electric Vehicle Routing Problem with Time Windows
EVRPTWMF Electric Vehicle Routing Problem with Time Windows and Mixed Fleet

GA Genetic Algorithm
GVNS Generalised Variable Neighborhood Search

HVRP	Heterogenous Vehicle Routing Problem
LNS	Large Neighborhood Search
MILP	Mixed-Integer Linear Programming
MIMO-AEM	Multi-Input Multi-Output Airport Energy Model
MIP	Mixed-Integer Programming
RCPSP	Resource-Constrained Project Scheduling Problem
TSP	Task Scheduling Problem
VCSAP	Vehicle-to-Charging Station Assignment Problem
VND	Variable Neighborhood Descent
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem with Time Windows
VRSPTW	Vehicle Routing and Scheduling Problem with Time Windows
VSTAP	Vehicle Sharing and Task Allocation Problem

Organizations

AAS	Amsterdam Airport Schiphol
ACRP	Airport Cooperative Research Program
FAA	Federal Aviation Administration
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
KLM	Royal Dutch Airlines
NACO	Netherlands Airport Consultants
SAE	Society of Automotive Engineers

Vehicles

BMS	Battery Management System
CCS	Combined Charging System
DOD	Depth of Discharge
EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle

RBS Regenerative Braking System

SOC State of Charge
SOH State of Health

Glossary

Airport Collaborative Decision Making The Airport Collaborative Decision Making (A-CDM) is a EUROCONTROL concept which has now been implemented at 32 European airports. It aims to improve the efficiency and resilience of airport operations by optimizing the use of resources and improving the predictability of air traffic. It achieves this by encouraging the airport partners (airport operators, aircraft operators, ground handlers and air traffic control) and the network manager to work more transparently and collaboratively, exchanging relevant accurate and timely information. It focuses especially on aircraft turnaround and pre-departure processes (EUROCONTROL, n.d.). According to EUROCONTROL (2016), A-CDM airports realise significant local operational benefits through the adoption of A-CDM processes, and a dramatic improvement in levels of take-off predictability.

Airport Cooperative Research Program In 2005, the Airport Cooperate Research Program (ACRP) was established by the Federal Aviation Administration (FAA) to solve common problems, learn about new technologies, and assess innovations in service and operations, airports need unbiased and reliable research (National Academies of Sciences, Engineering, and Medicine, n.d.).

Auxiliary Power Unit APUs are small turbine engines used by many commercial jet aircraft to start the main engines, provide electrical power to aircraft radios, lights and other equipment, and to power the onboard air conditioning (heating and cooling) system (National Academies of Sciences, Engineering, and Medicine, 2015).

International Air Transport Association The International Air Transport Association (IATA) is the trade association for the world's airlines, representing some 300 airlines or 83% of total air traffic. They support many areas of aviation activity and help formulate industry policy on critical aviation issues. It is the prime instrument for inter-airline cooperation in promoting safe, reliable, secure and economical air services, for the benefit of the world's consumers (IATA, n.d.).

International Civil Aviation Organization The International Civil Aviation Organization (ICAO) is funded and directed by 193 national governments to support their diplomacy and cooperation in air transport as signatory states to the Chicago Convention (1944). Its core function is to maintain an administrative and expert bureaucracy (the ICAO Secretariat) supporting these diplomatic interactions, and to research new air transport policy and standardization innovations as directed and endorsed by governments through the ICAO Assembly, or by the ICAO Council which the assembly elects. The stipulations that ICAO standards contain never supersede the primacy of national regulatory requirements (ICAO, n.d.).

Mixed-Integer Linear Programming Mixed-Integer Linear Programming (MILP) is a mathematical optimization technique that deals with optimization problems where some variables are restricted to be integers (either 0 or positive/negative whole numbers) while others can be continuous. MILP formulates the problem as a linear program with additional constraints, aiming to find the best feasible solution that minimizes or maximizes an objective function. Its modeling capability and the availability of good solvers make that Mixed-Integer Linear Programming (MILP) is a powerful tool for planning and control problems (Earl & D'Andrea, 2005).

State of Charge The State of Charge (SOC) is a measure of the amount of charge stored in a battery at the present moment (Zheng et al., 2016). It is defined as the ratio of the remaining charge in the battery, divided by the maximum charge that can be delivered by the battery. In this report, the SOC is defined as the remaining battery capacity divided by the rated battery capacity. By expressing this fraction as a percentage, the SOC always has a value between 0% and 100%.

State of Health The State of Health (SOH) describes the difference between a battery being studied and a fresh battery. It considers the aging of a battery, and it is defined as the ratio of the maximum battery charge to its rated capacity. The three main SOH indicators of a battery are its capacity, its internal resistance, and its self-discharge, reflecting mechanical integrity and stress-related conditions.

1
Introduction

This chapter formulates a framework for the research that will be conducted. First, a general introduction into the environmental impact of aviation is provided in Section 1.1. After that, the research motivation and scientific contribution will be covered in Section 1.2. Section 1.3 elaborates on the background of this research. Then the research questions of this research will be discussed in Section 1.4. The scope of the research and the assumptions that are made will be discussed in Section 1.5. Finally, Section 1.6 and Section 1.7 elaborate on the methodology and the structure that is used for this report.

1.1. General introduction

The percentage of all transport contributions to the production of Greenhouse Gas (GHG) emissions increased by 10% in the EU in the period from 1990 to 2017 (Andrejiová et al., 2020). In 2017, the aviation sector was accountable for 3.8% of the total GHG emissions and for 13.9% of the emissions from transport in the EU, making aviation the second most important source of GHG emissions in the transport sector after road traffic (European Commission, 2021). It seems that these environmental problems will continue, as the current traffic growth is outpacing fuel efficiency improvements and reductions of emissions from other sectors (European Union Aviation Safety Agency, 2022). Aircraft operations are expected to recover to the pre-COVID levels of 2019 in 2024 (Airports Council International, 2021), and increase to 12.2 million flights by 2050 (see Figure 1.1) (European Union Aviation Safety Agency, 2022). Before the COVID-19 crisis, the International Civil Aviation Organization (ICAO) forecasted that by 2050 international aviation emissions could even triple compared with 2015 (ICAO, 2019).

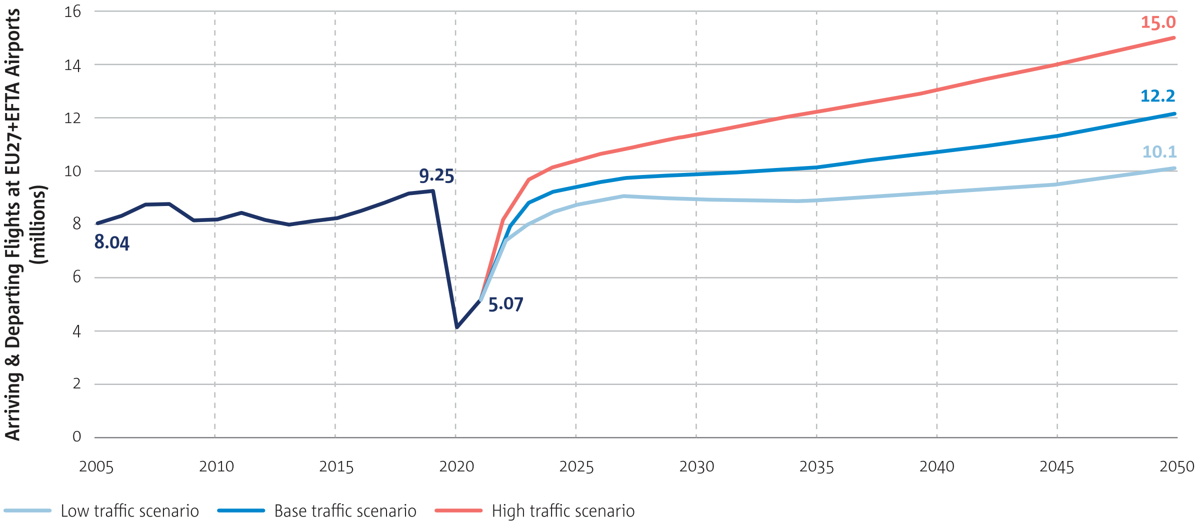


Figure 1.1: *The predicted number of arriving and departing flights at EU27+EFTA Airports (European Union Aviation Safety Agency, 2022).*

Next to GHG emissions, aviation is also an important source of air pollutants (Hsu et al., 2012), especially nitrogen oxides (NO_x) and particulate matter. In 2020, it accounted for 13.4% of all EU transport NO_x emissions and in absolute terms, NO_x emissions have almost tripled since 1990. Their relative share has even quadrupled, as other sectors have achieved significant reductions (European Union Aviation Safety Agency, 2022).

With this knowledge it is important to mitigate climate change and control temperature rise (Hu et al., 2022). To this extent the primary emitting sectors, like the aviation sector, need to reduce GHG emissions, like CO_2, and the emission of air pollutants from fossil fuels.

1.2. Research motivation and scientific contribution

According to Kirca et al. (2020) aircraft operations are accountable for the majority of the aviation carbon emissions. Hence, there are a number of projects going on to achieve technological advancements to introduce low emission aircraft (Brelje & Martins, 2019). And while aircraft dominate the carbon emissions in the aviation sector, Ground Support Equipment (GSE) also has a share (Kirca et al., 2020). GSE supports the turnaround process of aircraft between the arrival and departure at an airport and also supports the operation of the airport itself (National Academies of Sciences, Engineering, and Medicine, 2015). Besides their contribution to carbon emissions (National Academies of Sciences, Engineering, and Medicine, 2015), GSE is known to have a significant contribution to the NO_x pollution (Kirca et al., 2020). In 2012, GSE accounted for 13% of NO_x at all airports in the US (Benosa et al., 2018). According to Alruwaili and Cipcigan (2022) and Kirca et al. (2020), one path to cut airport related GHG emissions is to use low or zero-emission GSE and provide infrastructure provision for supporting decarbonization solutions since much of the GSE is at present powered by diesel or petrol fuel. Yim et al. (2013) estimated that electrification of GSE could avert 28% of the early deaths, caused by airport emissions in the UK. Hence, to reduce both carbon and air pollutant emissions from GSE at airports, airports and airlines are examining and committing to the electrification of GSE (Francfort et al., 2007; Kirca et al., 2020).

A number of challenges arise as a fully electrified fleet of GSE is realized. The two main challenges pertain the significantly longer charging time compared to refueling conventional fossil-fueled vehicles and the increased burden on the electric grid, including both rises in steady-state loads and dynamic disturbances (Gulan et al., 2019). For the early stage decision making of different stakeholders, such as 1.) airport operators, 2.) ground service providers, and 3.) airline companies, it is therefore important to be able to estimate 1.) the required quantity of electric Ground Support Equipment (eGSE), 2.) the charging requirements of eGSE, 3.) the change of airport electricity requirements, and 4.) the scheduling possibilities of eGSE charging for the existing turnaround procedures. Therefore, the primary focus of the research is the development of a model that can be used to gain insight into the operational requirements for the implementation of an eGSE fleet at airports.

1.3. Research Background

The proposed research will be carried out in collaboration with two companies. This section discusses the share and interest of both parties in this research.

1.3.1. Netherlands Airport Consultants (NACO)

This research is conducted within Netherlands Airport Consultants (NACO). Nowadays, NACO is part of Royal HaskoningDHV, which is one of the world's leading international project management and engineering consultancy service providers. Sustainability also plays an important role at NACO in the future-proof design of airports in order to comply with their sustainability goals. Electrical handling of aircraft is therefore being examined within NACO (Netherlands Airport Consultants (NACO), n.d.).

Currently, NACO is looking for a model that could give insight in the requirements of the utilisation of eGSE at airports in order to create future-proof designs. This also entails the difference between a conventional and an electric fleet.

1.3.2. KLM Ground Services

The proposed research is conducted in collaboration with KLM Royal Dutch Airlines, which has Amsterdam Airport Schiphol (AAS) as its home base. The Royal Schiphol Group aims to make the operations at AAS airport zero emission and zero waste by 2030 (Royal Schiphol Group, 2021) and KLM is also driven to work on a sustainable future for aviation (KLM Royal Dutch Airlines, n.d.-c). KLM is therefore currently enrolling the electrification program of its GSE fleet, within the KLM Ground Services department. By contributing to this research, insight can be gained into the required GSE numbers, the performance and (power) requirements for the future eGSE fleet. For the case study that includes KLM's GSE fleet, the data provided by KLM is used.

1.4. Research questions

The main Research Question (RQ) can be formulated on the basis of the above-mentioned research aim, together with the research motivation:

What is the impact of the implementation of electric Ground Support Equipment when optimizing the capacity and demand of GSE fleets?

In order to answer this question, the following set of Sub Questions (SQs) is formulated:

SQ 1. Which Ground Support Equipment types exist and what are the functions and activities of these types?

SQ 2. What are the requirements for an electric Ground Support Equipment fleet compared to a conventional Ground Support Equipment fleet?

SQ 3. What are the KPIs of a Ground Support Equipment fleet and how are they related to the parameters of it?

SQ 4. How can the existing (Ground Support Equipment operations) models be used?

SQ 5. How can the Ground Support Equipment operations be modeled?

SQ 6. What are the implications of the different scenarios in the developed model with regard to the KPIs?

1.5. Research scope & Assumptions

The focus of the proposed research will be on the development of a model that can be used to conduct innovative research into the operational requirements for the implementation of an eGSE fleet at airports. A set of boundaries will be applied to limit the scope of the model. The proposed modeling scope exists of the following aspects:

- **GSE turnaround operations:** By modeling the existing turnaround procedures, a realistic airport traffic scenario can be obtained in terms of operating times and delays.
- **Individual GSE types:** As each GSE type has its own operational characteristics, each GSE type is included as an individual component.

- **Task allocation:** To approach a realistic GSE operation, the GSE types must be realistically allocated to the different aircraft that have to be serviced.
- **Energy consumption:** To get insight in the energy requirements for the driving and aircraft servicing tasks, the energy consumption for each GSE type must be included in the model.

Next to the modeling scope, a set of assumptions is proposed to further limit the scope of the research:

- **Self-propelled GSE types:** Only GSE types that can be moved independently are included in the study. Equipment that is bound or limited in location is therefore regarded as infrastructure. An exception to this are the GSE types that exist both as a mobile and fixed version.
- **Electric GSE:** 100% electric Ground Support Equipment is the only sustainable solution that is considered. Other solutions, like hybrid and hydrogen powered vehicles, are not considered.
- **Passenger flights:** Only the turnaround process for passenger flights is considered. However, sometimes additional information about cargo flights is provided.
- **Civil airports:** Only Ground Support Equipment operations on civil airports are considered. Military airports are not included in this study.

The following aspects are outside the scope:

- **Modeling GSE charging:** The charging of GSE is not modeled in this study. Due to the night curfews on aircraft operations that exist at many airports, many airports only use the (majority of) GSE during the day, meaning they can charge at night. For the small GSE vehicles this is sufficient. For the larger GSE vehicles, charging during the day may be required.
- **Charging scheduling:** Since no realistic charging behaviour is included in the model, no scheduling of charging GSE is included in this study.
- **Work interruptions:** Work interruptions like staff breaks are not considered in this study.
- **Downtime:** The influence of maintenance and breakdown is not included in the study.
- **Level of automation:** The level of automation and the automation itself is not considered in this study.
- **Special GSE types:** The special GSE types that are not neccesarily used for each turnaround are not included in this study. These include for example de-icing vehicles, airport authority vehicles, and Person with Reduced Mobility (PRM) trucks.

1.6. Research methodology

This section describes the methodology that is used for this research. First, Section 1.6.1 explains the research strategy. After that, Section 1.6.2 discusses the research type, the data collection, and the way in which it is processed. The model development process is provided in Section 1.6.3.

1.6.1. Research strategy

The primary focus of the research is the development of a model that can be used to gain insight into the operational requirements for the implementation of an eGSE fleet at airports. To this extent, (literature) research is conducted about airport operations, the influence of electric Ground Support Equipment compared to the conventional non-electric GSE, and the modeling of GSE. Based on this, the model will be set up. To validate its functioning, the model will be applied to KLM's GSE fleet at Amsterdam Airport Schiphol (AAS). Additional literature research will therefore be conducted about AAS and specifically on the properties that are relevant to the model. In addition to the literature search, a visit will be made to AAS to observe the operation of GSE. Next to this visit, interviews with KLM employees will be conducted, in order to map out additional information and interests. One of the main inputs of the proposed model is a flight schedule that will be provided by KLM. The use of different flight schedules, together with the airport characteristics, allows for a broad applicability and the modeling of different scenarios.

1.6.2. Research type and data collection

The research employs a mixed-method approach: a combination of qualitative and quantitative research is used to answer the Research Question. To this extent, multiple data collection methods are used. Existing literature is reviewed during a literature review across the different relevant topics. In addition, several interviews are conducted and observations are made during a visit to Amsterdam Airport Schiphol. If possible, the interviews are recorded so that a transcript can be made of them later. If this is not possible, notes are taken during the interview. To process the observations made at AAS, photographs are taken that can be referred back to later. For the case study, data is collected from KLM and GSE manufacturers. The data that is obtained is checked for missing data, outliers and the correct units. If needed, measures are taken to edit the data such that it can be used for the purpose of the proposed research. Where possible, the data is compared with data from other sources.

1.6.3. Model development process

For the model development, the process that was proposed by Sargent (2010) is used. To explain this process, Figure 1.2 serves as a guide. The problem entity is the system that needs to be modeled. The conceptual model is the mathematical representation of the problem entity. Implementing the conceptual model in a computer results in the computerized model. The conceptual model is developed through an analysis and modeling phase, the computerized model is developed through a computer programming and implementation phase, and inferences about the problem entity are obtained by conducting computer experiments on the computerized model in the experimentation phase (Sargent, 2010).

Now that the model development process is clear, model validation and verification can be related to this. Conceptual model validation is defined as determining that the theories and assumptions underlying the conceptual model are correct and that the model representation is "reasonable" for the intended purpose of the model. The conceptual model validation will be performed through literature review, interviews and observations. The computerized model verification is defined as assuring that the computer programming and implementation of the conceptual model is correct. This will be done by using numerical experiments and analysis of the results. The operational validation is defined as determining that the model's output behaviour has sufficient accuracy for the model's intended purpose. Data validity is defined as ensuring that the data necessary for the model building, evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct. How this will be done is explained in Section 1.6.2.

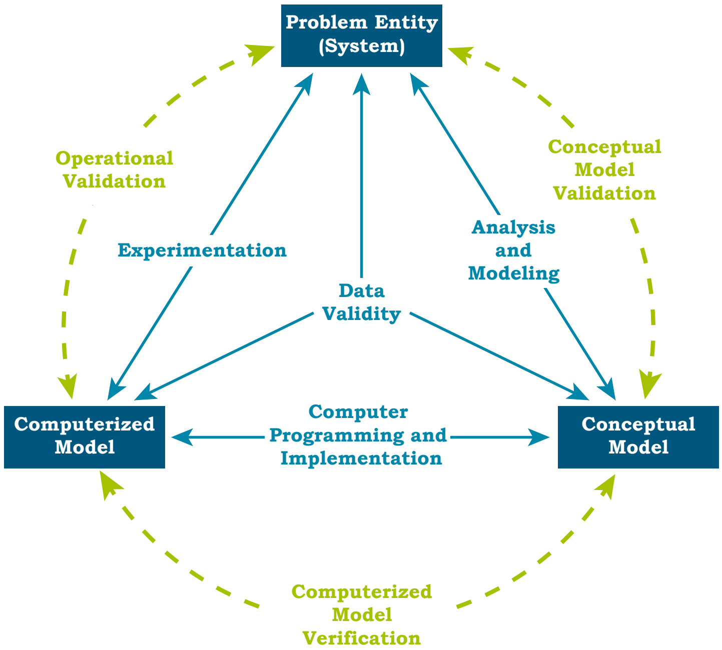


Figure 1.2: *Schematic overview of the modeling process (adapted from Sargent (2010)).*

1.7. Report structure

The different chapters in the report are used to answer the Sub Questions like shown in Figure 1.3. The methods that are used to answer these Sub Questions are depicted in this figure as well. They were discussed in Section 1.6. For the structure of the proposed research, the Design Science Research Methodology, also known as DSRM, by Peffers et al. (2007) is used as an approach. The methodology consists of six steps:

Step 1. **Problem identification and motivation:** Defining the specific research problem and justifying the value of a solution. This is done in Chapter 1, "Introduction".

Step 2. **Define the objectives for a solution:** The performance objectives of the solution need to be defined. The goal is to figure out what a possible and feasible solution is. This step will be covered in Chapter 2, "Literature research", that includes SQ 1 to SQ 4.

Step 3. **Design and development:** Create the artifact that is used to create the solution, such as a model or a method. Chapter 3, "Model development" will be dedicated to this step, based on SQ 5.

Step 4. **Demonstration:** Showing the use of the artifact to solve one or more instances of the problem. This could involve its use in experimentation, simulation, case study, proof, or other appropriate activity. This step will be covered by Chapter 4, "Case study", including SQ 6.

Step 5. **Evaluation:** Observe and measure, through the objectives defined in the second step, how well the created solution supports the problem. In Chapter 5, "Conclusion", the results of the research will be evaluated, and several recommendations for further research will be made to cover this step.

Step 6. **Communication:** Communicate the problem and its importance, the artifact, its utility and novelty, the rigor of its design, and its effectiveness to researchers and other relevant audiences. Next to the thesis report itself, a paper will be written to take care of this step. The paper can be found in Appendix A.

Figure 1.3: *Structure of the proposed report.*

2
Literature research

In this chapter, a literature review across the different relevant topics is provided. First, airport operations are explained in Section 2.1. After that, the influence of the electrification of GSE is discussed in Section 2.2. Section 2.3 elaborates on the important variables in operating a GSE fleet. At the end of the chapter, a review of the existing literature on (GSE) operations research is included in Section 2.4. On this basis, the contribution of this research is explained in Section 2.5.

2.1. Airport operations

This section provides insight into the activities and functions of Ground Support Equipment (GSE). First, in Section 2.1.1, the airport system is briefly explained. Subsequently, Section 2.1.2 elaborates on the turnaround process of an aircraft at an airport. The different types of GSE, their function and the different versions are provided in Section 2.1.3. Section 2.1.4 outlines what characterizes and influences the GSE operation. Finally, Section 2.1.5 provides a summary of this section, together with an answer to SQ 1.

2.1.1. Airports as a system

The airport forms an essential part of the air transport system, as it is the physical site at which a modal transfer is made from the air mode to the land modes or vice versa. It accommodates for the interaction of the two other major components of the air transport system, namely: the airline and the user. An airport is designed to enable an aircraft to, if required, unload and load passengers, cargo, and crew (Ashford et al., 2013). These events form the essential parts of the turnaround process of an aircraft. The turnaround process describes all operations for preparing an aircraft for the flight. It starts when the aircraft reaches the parking position after landing and it ends when the aircraft is ready to depart. The turnaround process will be further explained in Section 2.1.2. Aircraft depend on GSE to perform the required processes, such as cleaning, maneuvering and refueling (National Academies of Sciences, Engineering, and Medicine, 2015). Airports that service many yearly passengers must have ground handling service provider(s) that can supply the handling of those passengers and the servicing, maintaining, and engineering of aircraft (Ashford et al., 2013).

2.1.2. Turnaround Process

The turnaround process describes all operations for preparing an aircraft for the (next) flight. The following sections will elaborate on the importance of the duration of the turnaround process, the different turnaround operations and their dependencies, and the principle turnaround time charts.

Turnaround time

The turnaround process is performed during the Ground time (GT). It starts when an aircraft reaches its parking position (AIBT) and lasts until the aircraft is ready to depart (AOBT) (see also Appendix B) (T. Horstmeier & De Haan, 2001; More & Sharma, 2014; Schmidt et al., 2016). This is the case for flights that are made ready for take-off immediately after arrival. If aircraft are first moved to a Maintenance, Repair, and Overhaul (MRO) location or a parking stand before their departure, the turnaround period will take longer and can be divided into an inbound and outbound part, with a period in between. The required time for servicing an aircraft directly influences the stand utilization and the number of flights that can be handled daily. In general, the servicing time depends on the aircraft type, the number of passengers, the cargo to be (un)loaded as well as the business model of the aircraft operator (Schmidt et al., 2016). An efficient and reliable aircraft turnaround is an essential component of airline success, which allows it to maintain schedules (Schmidt, 2017; Vidosavljevic & Tosic, 2010). In 2019, 32.6% of all flight delays were caused by problems regarding the turnaround of aircraft at airports (EUROCONTROL, 2022). In 2021, this share, which also includes delays related to protective COVID-19 measures, has risen to 47.5%. The turnaround time has hence become a very important key parameter in determining the profitability of an airline (More & Sharma, 2014).

Turnaround operations

According to T. Horstmeier and De Haan (2001), six processes determine the turnaround time of a passenger flight from a time perspective: 1.) passenger (de)boarding, 2.) baggage handling, 3.) freight handling, 4.) refueling, 5.) catering, and 6.) waste handling (e.g. waste water, cabin dirt). A schematic turnaround cycle of an aircraft is depicted in Figure 2.1, including the inter-dependencies in time. Based on the policy of an airline, the order and dependencies of processes may differ (Business Contract Manager GSE I). After an aircraft is parked at a stand, chocks are placed before the wheels and a Ground Power Unit (GPU) is connected. Once the passenger bridge(s) or stair(s) are connected to the aircraft, the passenger disembarking begins. At the same time baggage and cargo are unloaded from the fuselage. Meanwhile, the waste water service is performed and the water is replenished. According to the safety rules stated in EU-OPS 1.305 (European Commission, 2008), the aircraft is refueled when precautions are taken or when no passengers are on board (the latter is shown in Figure 2.1). Inside the cabin of the aircraft, the catering provider exchanges the trolleys (if needed) and the cabin interior is cleaned and prepared for the next flight. Once cargo and baggage unloading is complete, the loading process for the next flight begins. Once the refueling has been completed, the passenger embarking is initiated. Once these processes are finished, the aircraft is ready for departure and the GPU is disconnected. If the aircraft is parked at a gate position, usually a push back is required. Sometimes additional operations are needed, such as any de-icing required in order to remove frozen containment of the aircraft or support from start air and air-conditioning vehicles is needed in case of failure of the Auxiliary Power Unit (APU) (Schmidt et al., 2016).

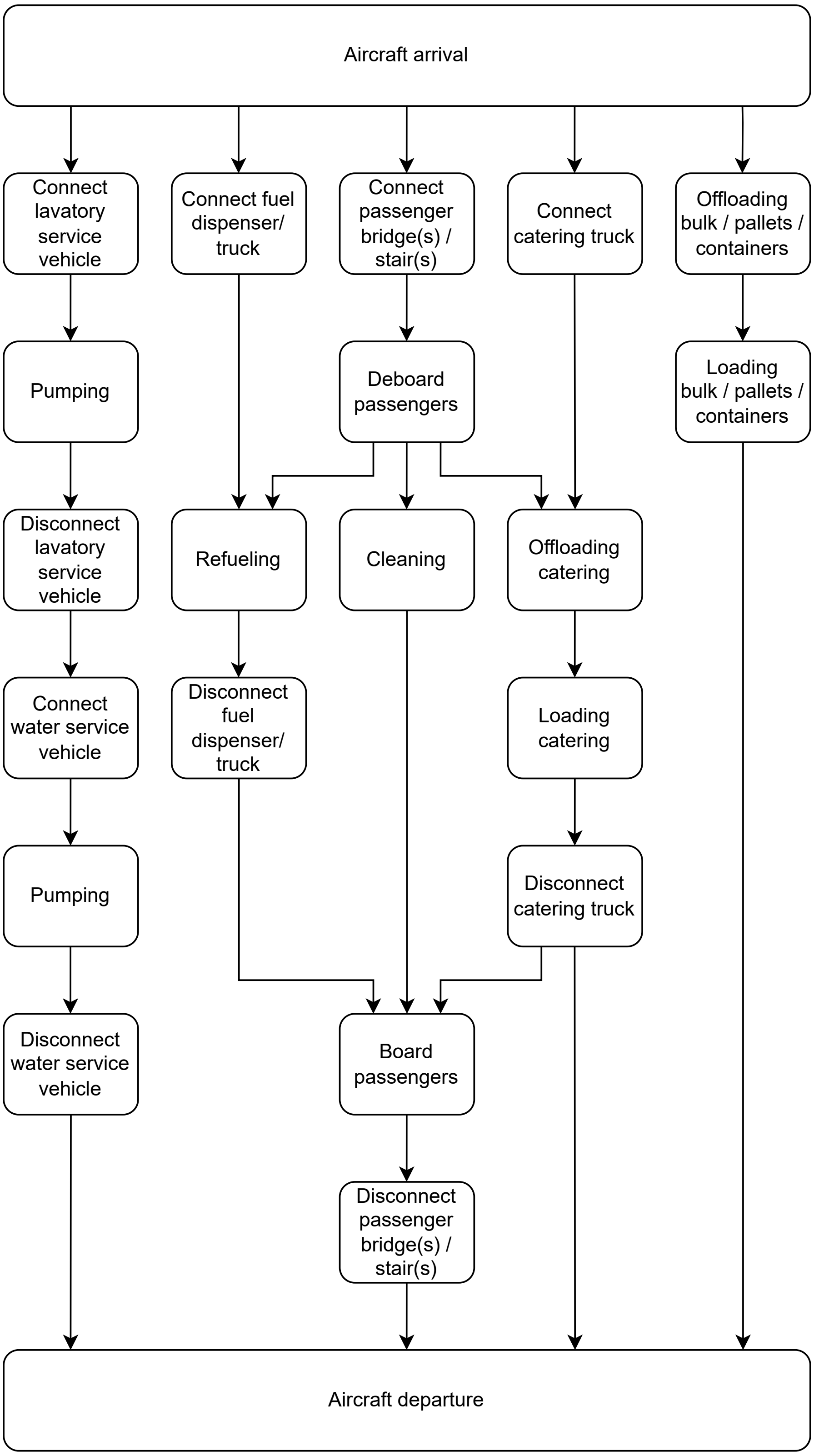
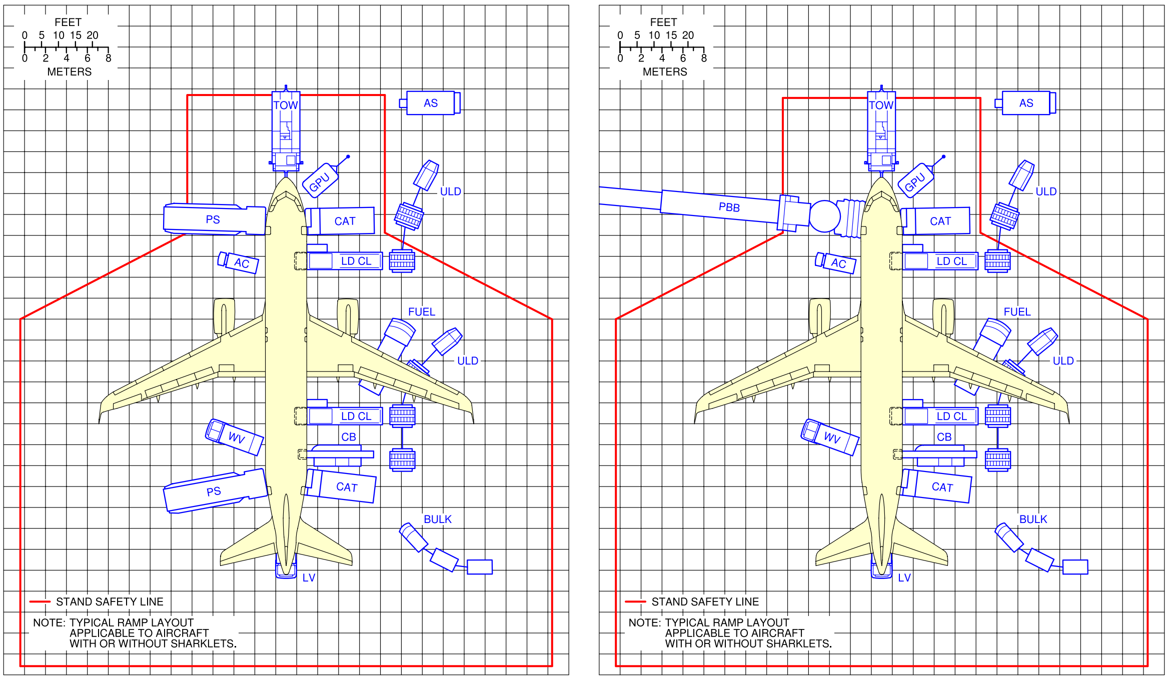


Figure 2.1: *Schematic overview of the turnaround cycle of an aircraft (adapted from T. Horstmeier and De Haan (2001)).*

Figure 2.2 shows a typical top view of the ramp layout during a turnaround cycle. The left-hand side doors are used for passenger (dis)embarking, and the right-hand side doors are used for catering and cargo handling. In this way, for safety, the passengers are separated from "the rest" of the aircraft handling. The positioning of the GSE is predefined due to the interface locations of the aircraft (Schmidt et al., 2016). The different GSE types will be discussed in Section 2.1.3.

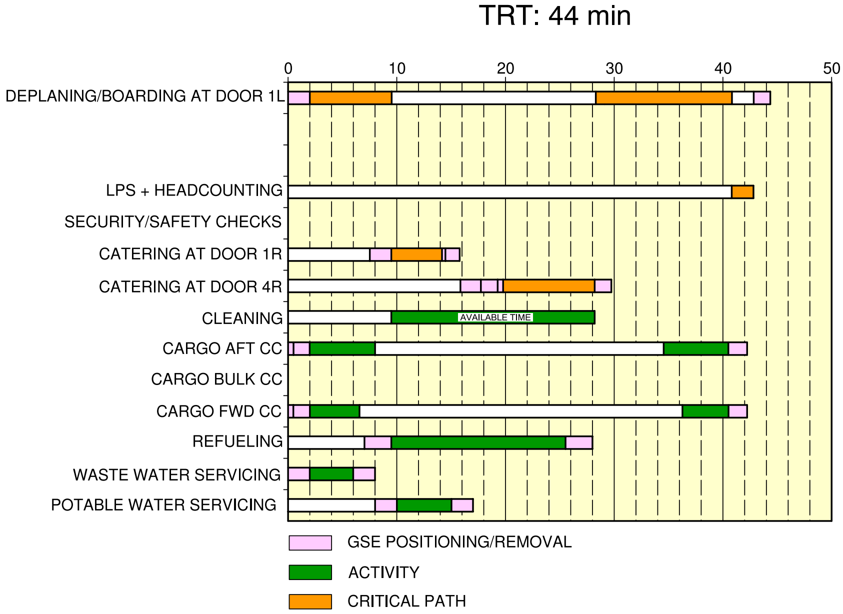


(a) *Servicing arrangement with two passenger stairs.* **(b)** *Servicing arrangement with a passenger boarding bridge.*

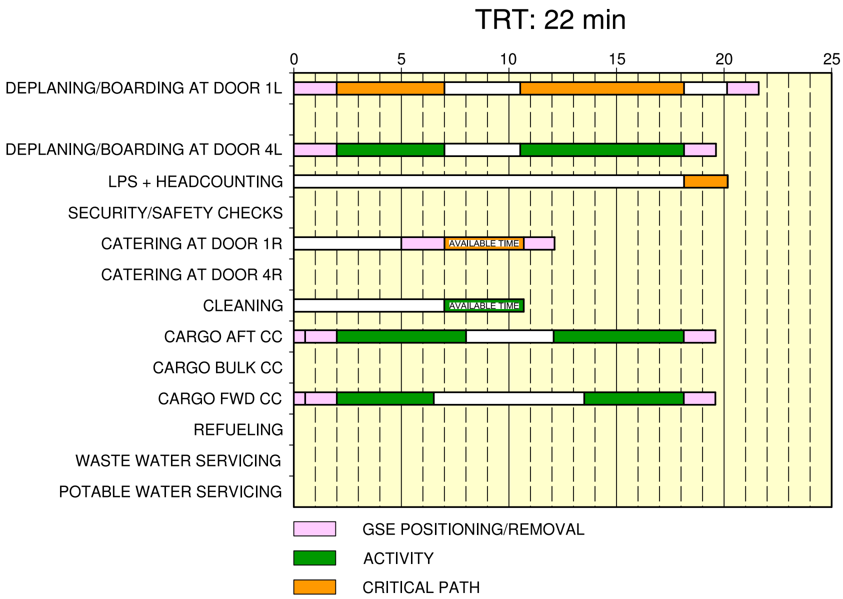
Figure 2.2: *Typical ramp layout for an Airbus A320neo (Airbus, 2020).*

Turnaround time charts

The activities that are performed during a turnaround cycle can be visualized in a Gantt-chart, referred to as a turnaround time chart. Figure 2.3 shows a typical turnaround time chart. This turnaround time chart comes from an aircraft manufacturer's manual, but ground handlers often use their own turnaround chart that deviates slightly from this. The logical chain, regulations and restrictions due to limited space around the aircraft leads to a strict chronological order for certain handling operations. These handling operations form the critical path of the turnaround process, since the minimum necessary turnaround time depends on these. Most of the times, the critical path consists of the passenger and aircraft cabin activities. Sometimes, the fueling operation may become the critical path. The other activities, such as the (un)loading of cargo and aircraft servicing, can normally be performed without impact on or from the critical path activities (Schmidt, 2017).



(a) *Full servicing turnaround.*



(b) *Outstation turnaround.*

Figure 2.3: *Typical turnaround time chart for an Airbus A320neo (Airbus, 2020).*

2.1.3. Ground Support Equipment

Each type of GSE has specific properties, activities, and duty cycles. An extensive explanation of the different GSE types is provided in Appendix C. Largely based on the available ACRP reports (National Academies of Sciences, Engineering, and Medicine, 2012, 2015) about GSE, it is possible to classify the GSE types based on their use case (see Table 2.1):

- **Ground power / Air conditioning**
  These GSE types are used to help start the engines, operate instruments and provide passenger comfort (e.g., lightning, air conditioning) while an aircraft is on the ground.

- **Aircraft movement**
  These GSE types assist with aircraft movements when an aircraft cannot operate its engines, or does not have sufficient maneuverability to move and turn under its own engine power. They are most frequently used to push an aircraft back from the gate/stand and onto the aircraft movement area (e.g., taxiway). It may also be used to move an aircraft to other locations on an airport (e.g., MRO facilities and parking bays).
- **Aircraft servicing**
  These GSE types are used for aircraft service activities including replenishing supplies, aircraft refueling and maintenance.
- **Passenger loading / unloading**
  Depending on the airport, aircraft and available airport equipment/facilities, two methods are used for the (de)boarding of passengers: boarding stairs and Passenger Boarding Bridges (PBBs).
- **Baggage / Cargo handling**
  These GSE types are used for the handling of baggage / cargo between the aircraft and the gate / terminal.

Table 2.1: *GSE classes based on use case.*

GSE class	Abbreviation	GSE type
Ground power / Air conditioning	GPU	Mobile power unit
	MPA	Mobile pre-conditioned air unit
	ASU	Air starter unit
Aircraft movement	CPB	Conventional pushback tractor
	TPB	Towbarless pushback tractor
Aircraft servicing	CAT	Catering truck
	LAV	Lavatory service
	WAT	Water truck
	FUE	Fuel bowser
	DIS	Fuel dispenser
	CLE	Cabin cleaning van
Passenger loading / unloading	PAS	Boarding stairs
	PRM	People with reduced mobility truck
	BUS	Bus
Baggage / Cargo handling	BAG	Baggage tug
	CAR	Cargo tug
	TRA	Cargo transporter
	BEL	Belt loader
	LDD	Lower-deck loader
	MDL	Main-deck loader
Miscellaneous	SUP	Supervisor vehicle
	MAI	Maintenance vehicle
	ICE	De-icer

2.1.4. Characterization of GSE operations

The operation of GSE is a function of several parameters that can vary considerably from airport to airport. They influence the type, number and operation (service time) of GSE. A distinction can be made between 1.) operational characteristics, 2.) aircraft characteristics, and 3.) airport infrastructure (see Figure 2.4) (ICAO, 2020). The different parameters will be discussed in the following sections.

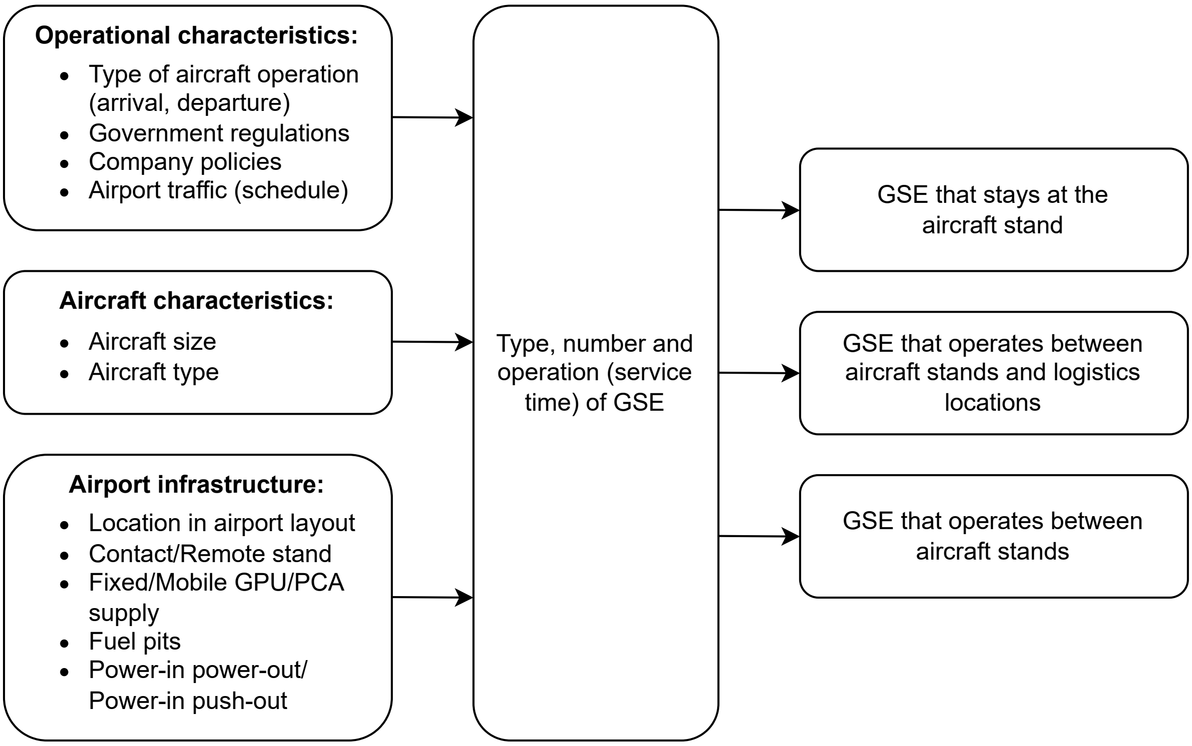


Figure 2.4: *Several parameters that influence the GSE operation (adapted from ICAO (2020)).*

Furthermore, a distinction can be made between GSE 1.) that stays at the aircraft stand, 2.) that operates between aircraft stands and logistics locations, and 3.) that operates between aircraft stands (see Table 2.2). The first category is often required for a significant part of the turnaround cycle of one aircraft, whereas the other categories are often required for a smaller part of the turnaround cycle.

Table 2.2: *GSE classes based on operating area.*

Abbreviation	GSE type	Stays at the aircraft stand	Operates between aircraft stands and logistics locations	Operates between aircraft stands
GPU	Mobile power unit	✓		
MPA	Mobile pre-conditioned air unit	✓		
ASU	Air starter unit	✓		
CPB	Conventional pushback tractor			✓
TPB	Towbarless pushback tractor			✓
CAT	Catering truck		✓	
LAV	Lavatory service		✓	
WAT	Water truck		✓	
FUE	Fuel bowser		✓	
DIS	Fuel dispenser			✓
CLE	Cabin cleaning van			✓
PAS	Boarding stairs	✓		
PRM	People with reduced mobility truck		✓	
BUS	Bus		✓	
BAG	Baggage tug		✓	
CAR	Cargo tug		✓	
TRA	Cargo transporter			✓
BEL	Belt loader			✓
LDD	Lower-deck loader			✓
MDL	Main-deck loader			✓
SUP	Supervisor vehicle			✓
MAI	Maintenance vehicle		✓	✓
ICE	De-icer	✓		

Operational characteristics

Operational procedures determine the types and amounts of GSE services required, described as follows (ICAO, 2020):

- The type of GSE used varies widely across applications. For example, different GSE types are required for servicing aircraft after landing than prior to departure.

- Government regulations (e.g. safety, operational requirements) and airport operator requirements (e.g. airport-specific procedures or restrictions) may limit or preclude the use of certain GSE.

- The airline operator, in cooperation with the ground handling service provider, might follow specific procedures that influence the GSE operation.

- The airport traffic also influences the GSE operation. The traffic displays peaking characteristics by the month of the year, by the day of the week, and by the hour of the day. The form and time of the peaks depend on the nature of the airport traffic and the hinterland served. The GSE fleet should be able to handle the peak times. This means that there is “unused” GSE at quieter times of the day. Based on Ashford et al. (2013), the following are the four most important factors that affect the peaking characteristics:

  1. Charter/Scheduled ratio: Charter flights are timetabled for maximum aircraft usage and are not necessarily operated at the peak periods found most commercially competitive by scheduled airlines.
  2. Long-haul/Short-haul: Short-haul flights are frequently scheduled to maximize the usefulness of the day either after or prior to the flight. Therefore, they peak in early morning and late afternoon.
  3. Geographic location: Schedules are set to allow passengers to arrive at a time when transportation and hotels are operating and can be used conveniently. For example, the six- to eighthour eastward transatlantic crossing is most conveniently scheduled for early-morning arrivals at the European airports, avoiding curfews on operations. Allowing for the time differences between North America and Europe, this means an evening departure from the eastern seaboard.
  4. Nature of catchment area: The nature of the region served has a strong influence on the nature of traffic peaking throughout the year. Areas serving heterogeneous industrial-commercial metropolitan areas show steady flows throughout the year. Airports in the vicinity of highly seasonal vacation areas display very significant peaks in the vacation months.

Aircraft characteristics

The aircraft characteristics influence the stand allocation and often the handling procedures involving GSE. A distinction in terms of size is made between Wide-Body (WIBO) aircraft, Narrow-Body (NABO) aircraft, and commuter/regional aircraft (ICAO, 2016):

- WIBO aircraft: A WIBO aircraft is a large aircraft with internal cabin width sufficient for normal passenger seating to be divided into three axial groups by two aisles (in practice this means not less than 4.72 meters).

- NABO aircraft: A NABO aircraft is an aircraft having only one aisle in the cabin with passenger seating divided into two axial groups.

- Commuter/Regional aircraft: Commuter aircraft and regional aircraft are aircraft used for the operation of commuter or regional air services, usually having a relatively small seating capacity (ranging from 10 to 70 seats) or payload.

The different aircraft sizes, together with their characterization, are displayed in Table 2.3.

Table 2.3: *Aircraft size characterization (adapted from ICAO (2020)).*

Aircraft size	Characterization
Wide-Body aircraft	Passenger baggage (if applicable) pre-loaded in containers Large cargo volume Passenger stairs with buses or PBB required Turnaround time could include moving aircraft (day-parking) Typical range of 15,000-18,000 km
Narrow-Body aircraft	Passenger baggage (if applicable) is bulk-loaded or pre-loaded in containers Small cargo volume Passenger stairs with buses or PBB required Short turnaround times Typical range of 5,750-7,500 km
Commuter/Regional aircraft	Passenger baggage (if applicable) bulk-loaded Carry some cargo (very small volume) Short turnaround times Built-in passenger stairs

Based on the type of traffic, a distinction can be made between the following air services (ICAO, 2016, 2018):

- Passenger air service, performed primarily for the transport of passengers. In addition to the passenger baggage cargo may be transported as well.
- Cargo air service, provided for the public transport of freight and mail.
- General aviation, air services other than commercial air transport or aerial work. This includes “private transport” and recreational aviation.

Airport infrastructure

At most airports, the following types of aircraft stands can be found (ICAO, 2016):

- Contact stands, where a Passenger Boarding Bridge connects the aircraft to the building.
- Remote/open stands, where an aircraft is parked free of direct building connections (for passenger and/or cargo operations).

The stands themselves can exhibit considerable differences in terms of location and technical equipment available, which influence the number and operations of GSE. They may also differ for reasons of dedicated usage (e.g. whether a stand is used for cargo aircraft or for passenger aircraft). The different aircraft stands, together with their properties, are displayed in Table 2.4.

Table 2.4: *Properties of aircraft stands (ICAO, 2020).*

Stand properties	GSE and operational consequences	Notes
Stand equipped with Passenger Boarding Bridge	Aircraft does not require passenger stairs	May require ACU, heating and/or GPU
Stand equipped with fixed GPU	Aircraft does not require GPU and might need Air Climate Unit (ACU)	
Additionally equipped with ACU	Aircraft does not require GPU or ACU	Stationary only together with GPU
Stand equipped with fuel pits	Aircraft does not require fuel bowser truck	Aircraft requires dispenser truck
Power-in power-out stand	Aircraft does not require pushback tractor	Not possible on stands where aircraft is parked perpendicular to terminal (power-in push-out stand)

2.1.5. Summary

This section has reviewed the, activities, functions, and types of Ground Support Equipment (GSE) at airports. Now that the underlying principles and the different applications are clear, an answer can be formulated to SQ 1: *"Which Ground Support Equipment types exist and what are the functions and activities of these types?"*.

An airport is designed to enable an aircraft to, if required, unload and load passengers, cargo, and crew. These events form the essential parts of the turnaround process of an aircraft. Aircraft depend on GSE to perform the required processes, such as cleaning, maneuvering and refueling. Airports of significant size must have ground handling service provider(s) that can supply the handling of passengers and the servicing, maintaining, and engineering of aircraft.

The turnaround process starts when an aircraft reaches its parking position and lasts until the aircraft is ready to depart. This is the case for flights that are made ready for take-off immediately after arrival. An efficient and reliable aircraft turnaround is an essential component of airline success, which allows them to maintain schedules. The turnaround time has hence become a very important key parameter in determining the profitability of an airline. The activities that are performed by the different GSE types during a turnaround cycle can be visualized in a Gantt-chart, referred to as a turnaround time chart. The logical chain, regulations and restrictions due to limited space around the aircraft leads to a strict chronological order for certain handling operations. These operations form the critical path of the turnaround process, since the minimum necessary turnaround time depends on these.

A classification can be made between GSE dedicated to: 1.) ground power / air conditioning, 2.) aircraft movement, 3.) aircraft servicing, 4.) passenger loading/unloading, and 5.) baggage/cargo handling. It is also possible to make a classification between GSE that 1.) stays at an aircraft stand, 2.) operates between aircraft stands and logistics locations, and 3.) operates between aircraft stands. The first category is often required for a significant part of the turnaround cycle of one aircraft. The second and third category is often required for part of the turnaround cycle. Furthermore, a distinction is made between three parameters that characterize the GSE operation: 1.) operational characteristics, 2.) aircraft characteristics, and 3.) airport infrastructure.

2.2. Electrification

This section discusses the influence of the electrification of GSE compared to conventional GSE. As eGSE can be seen as a subcategory of the Electric Vehicle (EV) category, several influential aspects of EVs that are therefore also applicable to eGSE will be discussed as well. First, Section 2.2.1 outlines the main challenges of EVs. After that, the most important battery characteristics of the batteries that are used in EVs will be discussed in more detail in Section 2.2.2. Then, Section 2.2.3 elaborates on the charging of EVs. After that, the operational influences of eGSE will be discussed in Section 2.2.4. Section 2.2.5 elaborates on a way to gain insight into the energy consumption of eGSE. Finally, Section 2.2.6 provides a summary of this section, together with an answer to SQ 2.

2.2.1. Challenges of Electric Vehicles

In terms of vehicles, electric Ground Support Equipment (eGSE) can be placed in the Electric Vehicle (EV) category. EVs perform better than Internal Combustion Engine Vehicles (ICEVs) in terms of efficiency due to the use of more efficient power trains and electric motors (Yong et al., 2015). Taking the component efficiencies such as the batteries and electric motor, recharging efficiency and regenerative braking (see Section 2.2.3) into account, the total energy efficiency of EVs ranges from 60% to 90% (Dixon, 2010; Li et al., 2019; Young et al., 2012). The efficiency of ICEVs ranges from 15% to 30% (Dixon, 2010; Li et al., 2019; Young et al., 2012). However, besides this great advantage of EVs, major challenges can be found in the limited range, and charging time for an EV, which does not come close to the time required to refuel an ICEV (Boysen et al., 2017). These challenges are the result of limited energy storage and the power capability of the batteries, respectively. They will be discussed in the following subsections.

Limited energy storage

A comparison between gasoline and a Li-ion battery provides insight into the limited energy storage that EVs have to deal with. Although there are other types of batteries, Li-ion batteries are widely used in EVs (W. Chen et al., 2019; Li et al., 2019; M.-K. Song et al., 2013; Stan et al., 2014; Yong et al., 2015; Young et al., 2012; Zakaria et al., 2019). Gasoline has a theoretical specific energy of 10,000 - 13,000 Wh/kg (Dixon, 2010; Young et al., 2012), which is about 65 - 100 times higher than the specific energy of 120 - 200 Wh/kg (Dixon, 2010; M.-K. Song et al., 2013; Young et al., 2012) of typical Li-ion batteries. It is therefore not feasible to have a battery pack with the same amount of energy as a full tank of gasoline with the current technology. However, since the electric propulsion of EVs is much more efficient than that of ICEVs, less energy is needed to propel an EV. Considering the above mentioned efficiency of about 60 - 90% for EVs and 15 - 30% for ICEVs, the total amount of energy stored for an EV can be at least a quarter of what a regular ICEV needs (Young et al., 2012). However, this does not cancel out the difference in specific energy by a factor of 65-100, which results in a limited range of EVs compared to that of ICEVs.

Nevertheless, the batteries that are being used in industrial machines are required to handle high power (up to a hundred kW) and high energy capacity (up to tens of kWh) within a limited space and weight, at an affordable price (Young et al., 2012). To accommodate for these high power requirements, a large number of batteries need to be packaged in serial and parallel to form a battery pack (W. Chen et al., 2019). The performance of these batteries change as their operating conditions (temperature, charging or discharging current, State of Charge (SOC), etc.) and their service time vary (Young et al., 2012). Therefore, a Battery Management System (BMS) is used to control the operational conditions (such as the maximum charge/discharge current) of the batteries to prolong their life and guarantee their safety. Next to that, it also provides an estimation of the State of Charge (SOC) and State of Health (SOH) (Rahimi-Eichi et al., 2013; Young et al., 2012).

Power capability

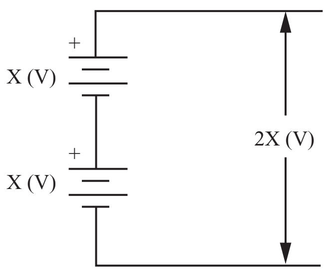
Another challenge with EVs, arises from the power capability. This is the ability of a battery to accept or deliver power at a given time. A high power capability is required for a good acceleration, maximum speed performance, efficient regenerative braking (if applicable), but most importantly fast charging (Zheng et al., 2016). Moreover, things may get worse when the charging current exceeds the battery's design limit, resulting in a high current if the BMS did not set a proper current limit. This may cause thermal issues due to rapid heat generation and temperature rise. It may reduce the battery's lifespan by damaging the internal chemical materials (further). A battery's power capability thus directly affects the safety and reliability. In addition, the technical limitations make that the charging time for an EV does not come close to the time required to refuel an ICEV and is therefore, in addition to the limited range, the second major challenge of EVs (Boysen et al., 2017). Charging is therefore currently a logistical challenge in itself, which will be discussed in Section 2.2.3.

2.2.2. Battery characteristics

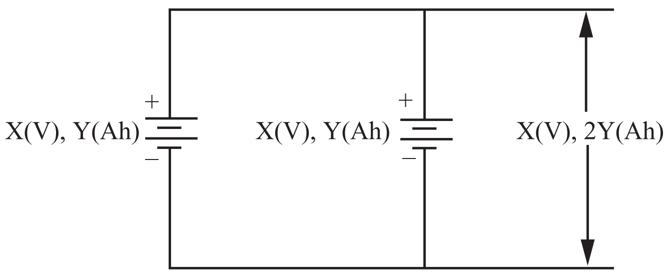
Batteries are chemical circuits that can store the energy resulting from chemical reactions as electrical energy. They consist of cells that contain chemical energy that can be converted into electrical energy. The performance of a battery differs according to its chemical and physical properties (Aktaş & Kirçiçek, 2021). The battery types that are currently suitable for road transportation are discussed in Appendix D.1. Three of the most important battery performance characteristics for this research are the 1.) battery capacity, 2.) State of Charge, and 3.) State of Health. They will be discussed in the following sections. Other battery characteristics are discussed in Appendix D.2.

Battery capacity

A battery is usually formed by a set of cells, which are connected in parallel or series to boost the current or voltage of the battery. A higher voltage can be obtained by connecting the cells in series (see Figure 2.5a), while the required capacity can be obtained by connecting the cells in parallel (see Figure 2.5b) to get the right output current (Abdi et al., 2017). The battery capacity is defined as the total amount of electricity generated due to electrochemical reactions in the battery and is expressed in ampere hours (Ah) (Aktaş & Kirçiçek, 2021). Charge and discharge rates of a battery are governed by C-rates (see Section 2.2.3). The behaviour of cells of different capacities with the same C-rate value is similar for a given cell type. For example, a constant discharge current of 1 C (5 A) can be drawn from a 5 Ah battery for 1 hour. For the same battery a discharge current of 0.1 C (500 mA) can be drawn for 10 hours.



(a) *Series connection of cells (Abdi et al., 2017).*



(b) *Parallel connection of cells (Abdi et al., 2017).*

Figure 2.5: *The required voltage and current levels of a battery can be obtained by the way the cells are connected.*

A battery cell has a specific operating voltage, based on its chemical properties (see Figure 2.6). Based on the State of Charge (SOC) of the cell, the discharge voltage varies slightly, but in the "mid range" it is fairly constant. Considering a battery with 60 1.2 V and 18 Ah cells, with six parallel branches of ten cells in series, therefore has an output voltage of V_{out}= 10 · 1.2 V = 12 V and an output capacity of C_{out} = 6 · 18 Ah = 108 Ah. The maximum energy in the battery can then be calculated as E = 12 V · 108 Ah = 1.3 kWh.

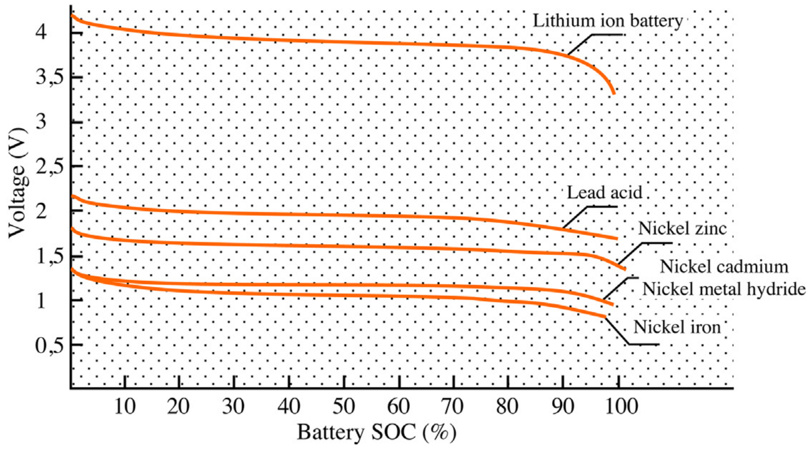


Figure 2.6: *Discharge voltage graphs of rechargeable battery cells (Aktaş & Kirçiçek, 2021).*

State of Charge and State of Health

The State of Charge (SOC) of a battery denotes the capacity that is currently available as a function of the rated, nominal, capacity. The value of the SOC varies between 0% and 100% (Abdi et al., 2017; Sundén, 2019). The preferred SOC reference should be the SOC of the actual battery cell, not the capacity of a new battery cell. As the battery ages, its capacity gradually decreases. For example, when a battery reaches the end of its life, its actual usable capacity is approaching 80%. In this case, even if the battery is fully charged, its nominal SOC capacity will be around 80% (Aktaş & Kirçiçek, 2021). A battery should be operated within a certain SOC range in order for it to be (dis)charged properly. This safe working area varies according to the battery type. The Depth of Discharge (DOD) is used to describe how deeply a battery has been discharged. In most cases it is related to the SOC by DOD = 100% - SOC (Sundén, 2019), and the State of Health (SOH) indicates the remaining battery capacity compared to the capacity of the battery at its "begin of life". The SOH depends on, among others, parameters like the number of charge-discharge cycles, capacity, vehicle usage, battery and cell design, temperature, and the SOC DOD range, and C-rate (see Section 2.2.3) (Sundén, 2019).

Several methods to estimate the SOC have been introduced since the 1980s, however, the most classical method to estimate the SOC is current integration, which expresses the ratio of the available current capacity to the nominal capacity (Hannan et al., 2017; Hou et al., 2017):

$$SOC = \frac{C_{res}}{C_n} = \frac{C_n - C_d}{C_n} = 1 - \frac{C_d}{C_n} = 1 - \frac{\int_t I dt}{C_n}. \tag{2.1}$$

Here, $C_{res} = C_n - C_d$ is the residual capacity, C_n is the nominal capacity, C_d is the drawn capacity, and I is the current drawn from the battery. Since the SOC is a percentage, it can be used to calculate the remaining energy in a battery in, for example, kWh or Ah. Based on the SOH, the nominal capacity C_n can be calculated as:

$$C_n = SOH \cdot C_{new}. \tag{2.2}$$

Here, C_{new} is the capacity of the battery at its "begin of life".

2.2.3. Charging

The considerable charging time and lower range of EVs compared to ICEVs mean that the implementation of these vehicles brings considerably more challenges with it. The time required to charge a vehicle does not exclusively depend on the power capability (see Section 2.2.1) of the vehicle's battery, but also on the characteristics of the charging equipment. Different types of chargers exist, which are discussed in the next subsection. Batteries that are often used for Electric Vehicles are not charged linearly. They are often charged using the Constant Current-Constant Voltage (CC-CV) method. This method is outlined in more detail below. The different charging standards that exist are discussed in Appendix D.3. In addition to charging, Regenerative Braking System (RBS) can also provide energy for vehicles through recovering and storing the kinetic energy of a vehicle when it is decelerating. This principle is explained in more detail below.

"Fast" charging

A charger is required in the EV charging process, because the power grid supply is in the Alternating Current (AC) form, while the battery is in the Direct Current (DC) form. EV chargers are therefore designed to rectify the AC power level from the grid to a suitable DC power level. To this extent, an EV charger is usually constructed as an AC/DC converter or rectifier. In some cases (e.g. fast charging stations) an additional DC/DC converter is included for a better energy conversion (Yong et al., 2015). The transfer of energy from the grid to the battery can take place inside the vehicle using an on-board charger, which restricts it to a low power, or externally through an off-board charger.

A commonly heard commercial term is "fast charging". The nomenclature "fast charging" refers to DC charging and "normal charging" refers to AC charging. In the case of a normal charger, the charging equipment delivers AC current and the on-board charger converts the AC current to its DC equivalent before charging the battery. The power of on-board chargers is limited to a few tens of kilowatts (kW), as it is restricted by the limited space, mass, and cost of a vehicle. In case of an off-board charger, the charging equipment converts AC from the grid to DC. This direct current is directly fed into the battery. An off-board charger is therefore sometimes referred to as a DC charger. Off-board chargers are usually not limited by space or mass, making it possible to reach some hundreds of kilowatts (kW) (Suarez & Martinez, 2019).

Charging rate

The charging rate (C-rate) is defined as the (dis)charge current divided by the battery's capacity to store an electrical charge (Qu et al., 2022). In other words, for a given charging power, the larger the battery capacity, the lower the C-rate for charging (Bhagavathy et al., 2021). A C-rate of 1C means that a battery will be completely charged (or discharged) in 1 hour at that level of current. In the same way, a 2C rate equals a charge of a full battery in half an hour. The (dis)charge C-rate significantly impacts battery degradation (Qu et al., 2022; Wankmüller et al., 2017). A higher C-rate intrinsically results in accelerated capacity fade due to the greater heat release from the battery and the mechanically induced damage to the active battery material. To maintain good battery health, it is therefore important to limit the C-rate. Moreover, optimal management of charging, for example decreasing the C-rate during night recharge could attenuate the effect of aging (Micari et al., 2021) (Contract Manager GSE).

CC-CV charging

In addition to the fact that it is better for the life of a battery to charge it slowly, the SOCs between which this happens are also important for the battery life time (see Section 2.2.2). First of all, fast charging rates are typically only achievable up to a SOC of 80% due to safety issues caused by too much voltage over the battery cells (Tomaszewska et al., 2019). At high SOCs, the current needs to be gradually decreased to avoid exceeding the maximum cell voltage limits, resulting in much longer times to require to charge to full capacity. Various charging methods can be used to charge an EV battery. The conventional charging methods are Constant Current (CC), Constant Voltage (CV), constant power, taper charging, and trickle charging. (Yong et al., 2015). An advanced charging method that combines CC and CV) charging is the CC-CV charging algorithm. It is the favored choice to "fast charge" batteries (Yong et al., 2015), and therefore it is widely adopted in charging lead-acid and lithium-ion batteries (R. Das et al., 2018; Horkos et al., 2015; Shen et al., 2012). During the first stage of the CC-CV charging algorithm, the CC stage, a constant current is applied to charge the battery until the battery voltage rises to a preset voltage, specified by the manufacturer (R. Das et al., 2018; Horkos et al., 2015; Shen et al., 2012). In the second stage, the CV stage, the current decreases exponentially until the charging current reaches a preset small current (Shen et al., 2012). The battery is then fully charged. A typical CC-CV charging curve can be seen in Figure 2.7. Two interesting characteristics can be noted: 1.) The available charge, or SOC, increases non-linearly. As a result, charging from, for example, 0 to 25% is much faster than from 75 to 100%. 2.) Since the charging power is the multiplication of the charge voltage and current, it decreases rapidly in the CV stage, as the charge current decreases. In the CC stage, the voltage increases slightly. This makes that in this stage the charging power increases with the SOC.

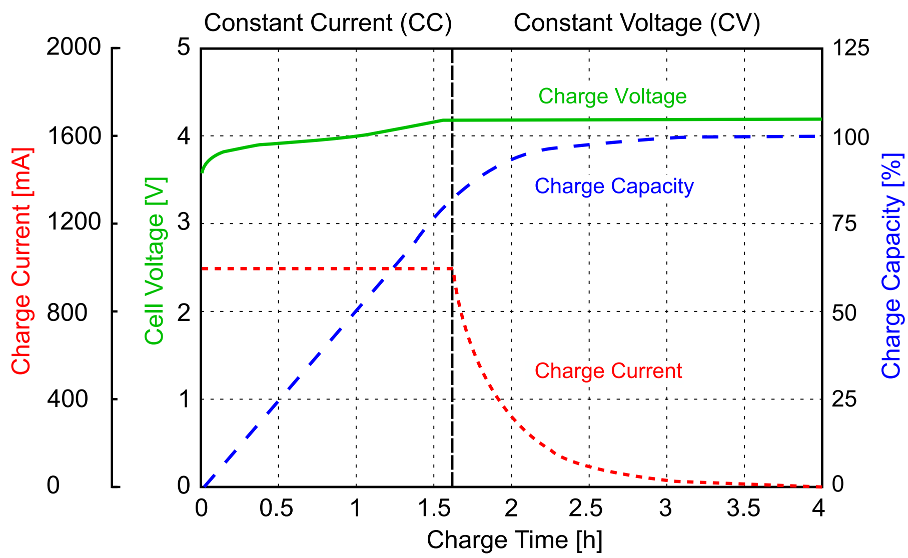


Figure 2.7: *Typical Constant Current (CC)-Constant Voltage (CV) charging profile (adapted from Sony (2001)).*

Regenerative braking

In addition to charging, a Regenerative Braking System (RBS) can provide energy for vehicles through recovering and storing the kinetic energy of a vehicle when it is decelerating. It converts the kinetic energy into electricity by using the driving motor in reverse and operating it as a generator (Wager et al., 2017). Without an RBS, the kinetic energy of the vehicle in the decelerating stage is converted into heat by the mechanical breaking (Hamada & Orhan, 2022; Li et al., 2019; Zheng et al., 2016). Wager et al. (2017) found that the driving range of an EV could be increased by 11% to 22%. However, the energy that can be generated using an RBS largely depends on the vehicle, the route characteristics, and the traffic conditions (Hamada & Orhan, 2022). And as mentioned before, the potency of an RBS also strongly depends on the properties of the battery that is in the vehicle (Dixon, 2010; Zheng et al., 2016). For instance, RBS operations rely on the energy storage capacity (SOC) as well as the maximum permissible charging current that can be withstand. When the SOC of a battery is low (< 10%), or high (> 90%), any incoming charging currents can damage the battery system, resulting in a restricted energy gain from regenerative braking (Hamada & Orhan, 2022).

2.2.4. Operational influence

The introduction of EVs imposes a number of operational challenges. The following sections will elaborate on the challenges regarding commercial EVs and eGSE. Due to the difference in application, both groups have their own challenges.

Challenges of commercial EVs

While the large-scale introduction of EVs and (fast) charging of vehicles is desirable for environmental and operational purposes, the higher power requirement of the charging infrastructure has several drawbacks (H. Das et al., 2020; L. Wang et al., 2021; Xiao et al., 2014; Yong et al., 2015). Firstly, the interconnection of large EV fleets to the power grid will increase the burden on the power system, resulting in greater differences of peak power loading and power demands (H. Das et al., 2020; Yong et al., 2015). Secondly, a bad effect on the reliability of and more difficulty in controlling the power system will arise from the kind of randomness that is imposed by the charging behavior of EVs and its users (Xiao et al., 2014), possibly resulting in system losses, voltage drops, equipment overloading, and stability issues (H. Das et al., 2020; Yong et al., 2015). Xiao et al. (2014) have identified four main factors that influence the load profile of the power grid as EVs are additional loads to be connected: 1.) the number of EVs scale, 2.) the power battery characteristics, 3.) the charging methods, and 4.) the user behavior. According to L. Wang et al. (2021), "fast charging" might create even more severe issues, compared to "slow charging". It shows some different characteristics like the higher charging power, and the more pulsating load as a result of the shorter charging time. Next to that, "fast charging" is mainly applied during daytime, whereas the "slow charging" is mainly applied overnight.

For commercial EVs, the significant duration and the impact on the power grid that comes with the charging of EVs makes that it is useful to think about the moments at which EVs are charged. When it comes to the logistics of charging EVs, two main decision problems can be distinguished (Boysen et al., 2017):

- On an operational level, a short-term vehicle scheduling problem must be solved. Hereby the goal is a sequence of all given transport requests interspersed with recharging events, such that the makespan of the point-to-point transport schedule is minimized and no power breakdown occurs.
- On a strategic level, the locations of charging stations along the area need to be determined. Here, the basic trade-off is to either have more charging stations, which reduces the detours of the vehicles, or to save investment costs by erecting fewer stations for the price of additional vehicle travel.

By solving the daily vehicle scheduling problems, one can quantify whether some location plan is indeed better than another one (Boysen et al., 2017). Next to locating the charging stations, several studies have looked at the influence of the mix of various charger "sizes" (Cui et al., 2018; Y.-W. Wang & Lin, 2013).

Challenges of eGSE

As part of noise abatement, night curfews on aircraft operations exist at many airports throughout the world (Ashford et al., 2013). Consequently, many airports only use (the majority of) GSE during the day, meaning they can and must be charged at night. Compared to commercial EVs, most of the GSE drives relatively short distances. As a result, they accelerate and brake relatively more. Next to that, GSE drives at lower speeds, and a number of GSE types also consume energy while not driving, to perform the service on an aircraft stand. The consumption of and the way in which the small GSE vehicles are used makes it possible to only have to recharge these vehicles at night, as they can be used for a whole day on one full battery charge. And if it turns out to be necessary, opportunity charging can be used during the day (Business Contract Manager GSE I). Other, larger GSE vehicles, must be charged during the day. With these vehicles, the challenge still lies in battery capacity or energy density and the limited space and weight that can be spend on batteries (Contract Manager GSE). These vehicles therefore have a greater downtime than their diesel equivalents (Aviation Sustainability Consultant). Several studies into the implementation of eGSE on airports found that the charging of eGSE fleets might bring challenges like peak grid loads (Gulan et al., 2019; Kirca et al., 2020) (Aviation Sustainability Consultant) or overloading transformers (Rajagopalan et al., 2003) as well. According to Kirca et al. (2020), non-scheduled charging of high number of eGSE may significantly increase both magnitude and duration of peak grid loads. So a challenge at the moment is where and when you charge the vehicles (Airport Planner). This is related to how long the vehicles can remain operational and also dictates how much space you need to reserve to place the vehicles for charging. This can pose challenges at space-constrained airports (Aviation Sustainability Consultant). Another challenge at an operational level lies in maintenance. The lead-acid batteries that are commonly used require a vehicle to be maintained more often (Aviation Sustainability Consultant).

2.2.5. Energy consumption of eGSE

To gain insight into the energy consumption of eGSE, one can look at the power demand for operating the eGSE and the duration of this demand. Kirca et al. (2020) classified the different GSE types into four classes based on power demand. Based on this classification, most of the GSE types in Table 2.1 can be assigned to a power demand class (see Table 2.5). Together with six GSE activity categories (see Table 2.6), a load factor is determined based on the GSE class and activity category (see Table 2.7).

The power demand for a specific activity by a GSE type can be calculated as

$$P_{demand} = \frac{P_{rated} \cdot LF}{\eta_{GSE}}. \tag{2.3}$$

Here, P_{rated} (kW) is the rated power, LF (-) is the load factor based on Table 2.7, and η_{GSE} (-) is the lumped efficiency of the drivetrain. The energy usage can be calculated by integrating the power demand over the time that the power is required. Because the variables in Equation (2.3) are considered constant for an activity category, this can be simplified to multiplication with time:

$$E_{demand} = \frac{\int_0^t P_{demand} \, \mathrm{d}t}{60} = \frac{P_{demand} \cdot t}{60}. \tag{2.4}$$

Here, P_{demand} (kW) is the power demand, and t (min) is the time. By dividing by 60, the energy consumption in kWh is obtained.

Table 2.5: *GSE classes based on power demand (adapted from Kirca et al. (2020)).*

GSE class	Abbreviation	GSE type
A	CPB	Conventional pushback tractor
	TPB	Towbarless pushback tractor
B	CAT	Catering truck
	LAV	Lavatory service
	WAT	Water truck
	FUE	Fuel bowser
	DIS	Fuel dispenser
	CLE	Cabin cleaning van
	BUS	Bus
	BAG	Baggage tug
	CAR	Cargo tug
	ICE	De-icer
C	PAS	Boarding stairs
	BEL	Belt loader
	LDD	Lower-deck loader
	MDL	Main-deck loader
D	GPU	Mobile power unit
	MPA	Mobile pre-conditioned air unit
	ASU	Air starter unit

Table 2.6: *GSE activity categories vs. GSE power-demand mode (Kirca et al., 2020).*

Activity category	GSE activity	GSE power-demand mode
1	Activity	High-auxiliary power demand
2	GSE transit between gate and GSE base (Loaded)	Loaded transit
3	GSE transit between gate and GSE base (Unloaded)	Unloaded transit
4	GSE removal or positioning	Positioning
5	Idle during operation	Idle, cannot be charged
6	Not servicing an aircraft	Idle, can be charged

Table 2.7: *Load factors with respect to GSE activity categories and GSE classes (Kirca et al., 2020).*

		Activity category					
		1	2	3	4	5	6
GSE class	A	0.95	N/A	0.5	N/A	N/A	0
	B	0.3	0.5	0.4	N/A	0	0
	C	0.5	N/A	0.3	0.4	0	0
	D	1	N/A	N/A	N/A	N/A	0

2.2.6. Summary

This section has reviewed the existing relevant literature about (the influence of) the electrification of Ground Support Equipments (GSEs). As eGSE can be seen as a subcategory of the EV category, several influential aspects of EVs that are therefore also applicable to eGSE were therefore discussed to formulate an answer to SQ 2: *"What are the requirements for an electric Ground Support Equipment fleet compared to a conventional GSE fleet?"*.

EVs perform better than Internal Combustion Engine Vehicles (ICEVs) due to the use of more efficient power trains and electric motors. However, besides this advantage of EVs, major challenges can be found in the limited range, and charging time for an EV, which does not come close to the time required to refuel an ICEV. These challenges are the result of the limited energy storage and the power capability of the batteries, respectively. An extra challenge, in addition to this limited energy storage, arises from the power capability, the ability of a battery to accept or deliver power at a given time. A high power capability is required for a good acceleration, maximum speed performance, efficient regenerative braking (if applicable), but most importantly fast charging.

The introduction of eGSEs imposes a number of operational challenges. As a consequence of the night curfews on aircraft operations, many airports only use (the majority of) GSE during the day, requiring nighttime charging. While smaller GSE vehicles can operate for a whole day on a single charge, larger ones face challenges in battery capacity, energy density, and limited space for batteries, resulting in greater downtime compared to diesel equivalents. Charging these GSE fleets may lead to peak grid loads and transformer overloads, emphasizing the need for strategic planning to address when and where to charge the vehicles. Space constraints at airports further complicate this issue. Maintenance is also highlighted as a challenge, particularly with the more frequently serviced lead-acid batteries commonly used in GSE.

2.3. Important variables in operating a GSE fleet

From an airport master planning perspective, a number of important variables can be distinguished when it comes to GSE. In the master planning phase, the first thing that is looked at is the numbers of GSE that are required for the peak moments at an airport (Airport Planner). Based on this, it is determined how much space is needed to park the vehicles and what the capacity of the maintenance facilities and lanes in the road network for GSE should be (Airport Planner, Aviation Sustainability Consultant). In the case of eGSE, the space required for charging, the charging infrastructure itself and the requirements for the power grid also follow from this (Airport Planner). However, many of the variables depend on each other, resulting in an iterative design process. A Causal Loop Diagram (CLD) can be used to gain a better insight into the causal relationships between the different variables. Here, a distinction can be made between endogenous variables, that are inside the system boundary, and exogenous variables that are outside the system boundary (Bala et al., 2017). Using the CLD method, the system behaviour of different scenarios can be illustrated (Dhirasasna & Sahin, 2019).

Figure 2.8 shows the causal relations in airport master planning variables regarding GSE fleets. The number of Air Traffic Movements (ATMs) during the peak, and the number of GSE operations that follow from this are exogenous variables that are defined outside the scope of the system that is being reviewed. They arise from the flight schedule that is used as input for this research. The total number of GSE operations can be translated to the number of GSE, and the parking area that is required (Airport Planner). Next to that, the required energy for the GSE operations can be deduced from it. Although that is also influenced by the average distances that have to be driven between the different locations. Based on the required energy during the ATM peak, together with the distribution of ATMs, the number of chargers can be determined with the use of the average charging time. The charging time and how long the battery lasts dictates how many vehicles will be operational in a day (Aviation Sustainability Consultant). It directly influences the required charging area.

The average charging time is influenced by the charging power that is used. The overall electricity grid requirements are based on the number of chargers in use, and the applied charging power to account for the ATM peak.

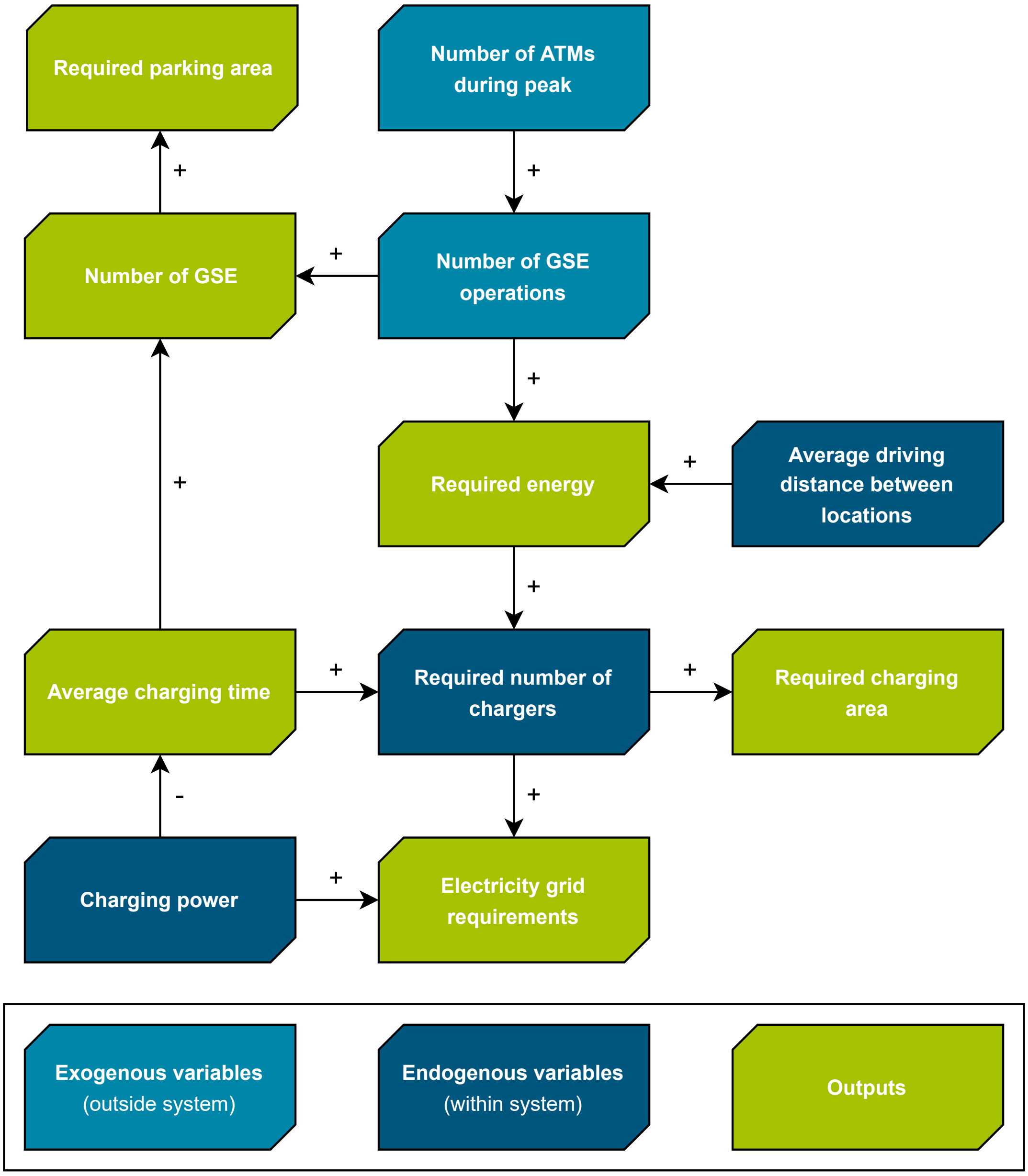


Figure 2.8: *Causal Loop Diagram of the airport master planning outputs regarding GSE fleets.*

2.3.1. Summary

This section has discussed the important variables in operating a GSE fleet from an airport master planning perspective, to formulate an answer to SQ 3: *"What are the KPIs of a Ground Support Equipment fleet and how are they related to the parameters of it?"*.

The airport master planning process for GSE involves considering various variables. Initially, the focus is on determining the number of GSE required during peak moments, which influences the space needed for parking, maintenance facilities, and road network capacity. For eGSE, additional considerations include charging space, infrastructure, and power grid requirements. The interdependence of these variables leads to an iterative design process. A Causal Loop Diagram (CLD) was employed to analyze the relationships between endogenous (inside the system boundary) and exogenous (outside the system boundary) variables. The number of Air Traffic Movements during peak times and ensuing GSE operations are exogenous variables. These operations impact GSE quantity, parking needs, and energy requirements. The energy demand influences the number of chargers and the charging area, with factors like charging time and charging power contributing to the overall electricity grid requirements.

2.4. Existing operations research

This section presents a review of the existing literature on operations research that is considered relevant for this research. Section 2.4.1 discusses different works on the optimization of operations. Next, Section 2.4.2 reviews different works on energy management, including topics like charging (scheduling), and charging infrastructure as well. Most of the works being reviewed focus on GSE. However, some works focusing on (commercial) EVs are included as well. After that, the scope is widened in Section 2.4.3, which looks into other related problems in the aviation industry. Finally, a comparison of the different works and an answer to SQ 4 is provided in Section 2.4.4.

2.4.1. Optimization of operations

Determining how to meet a set of demands, a scheduling problem, is a frequently discussed problem in the literature. When the focus is on scheduling vehicles for specific tasks the problem is often described as a Vehicle Routing Problem (VRP). In this case, the focus is on scheduling GSE, which entails an additional challenge in addition to the optimal allocation of vehicles. Because it is about handling flights (turnarounds), the vehicles are also bound to certain time windows, described in the literature as a Vehicle Routing Problem with Time Windows (VRPTW). Ip et al. (2013) identify the GSE scheduling optimization problem as a VRPTW of multiple non-identical vehicles, but it is not clear which GSE types are included. Next to this, they also consider the assignment of the service jobs to the right crews. Three aspects of optimization problems are distinguished: 1.) assignment optimization for allocating the right service jobs to the right crews, 2.) service sequencing optimization for obliging the tight flight schedule, and 3.) traveling route optimization for reducing noneffective traveling time. Given the large solution space, a Genetic Algorithm (GA) with a hybrid assignment is proposed to solve the problem. Padrón et al. (2016) also treat the GSE scheduling problem as a VRPTW. However, unlike the approach of Ip et al. (2013), they consider a VRPTW per vehicle type instead of one big VRPTW. Decisions made on the routing are propagated to other VRPTWs through reductions in the available time windows to solve the complete problem. In addition, the focus of the optimization is also different, with the following objectives: 1.) minimizing the waiting time before an operation starts and the total reduction of corresponding time windows, and 2.) minimizing the total completion time of the turnarounds. To solve the problem, a combination of Constraint Programming (CP), Large Neighborhood Search (LNS), and Variable Neighborhood Descent (VND) is used. The work was later enhanced by Padrón and Guimarans (2019) to reduce the computional times. Another VRPTW is proposed by S. Wang et al. (2021). They only consider the baggage tugs together with the dollies, with the objective to minimize the total cost, including: 1.) the cost of renting tugs and dollies, and 2.) total fuel (or electricity) power consumption of tugs. The work includes a number of components that are, compared to the other GSE types, characteristic for baggage tugs, such as multitrips, replaceable dollies, and limited baggage waiting time. The problem is formulated as a Mixed-Integer Linear Programming (MILP). Like the work of Ip et al. (2013), the work of Gök et al. (2022) focuses on the scheduling of aircraft turnaround tasks and the routing of involved teams of staff across an apron. The problem is identified as a Resource-Constrained Project Scheduling Problem (RCPSP). The team routing decisions are formulated as a VRPTW, and solved with the use of CP. Simulation is integrated withing the optimization process, following simheuristic techniques, to allow for solving the complex problems with less computational effort than classical optimization methods. Another VRP formulation can be found in the work of Bao et al. (2023). They establish a mixed operation model of fuel and electric aircraft towing tractors with time windows, with the objective function of minimizing the sum of time cost, energy cost, and emission cost. It combines the already existing Electric Vehicle Routing Problem (EVRP) and Heterogenous Vehicle Routing Problem (HVRP), to create a Electric Vehicle Routing Problem with Time Windows and Mixed Fleet (EVRPTWMF). The problem is solved through MILP. Another work that focuses on the dispatching of a fleet of electric aircraft towing tractors is that of Van Oosterom et al. (2023). They propose a two-phased MILP program. The first phase takes care of the routing of the towing tractors. The aircraft are routed to their destination along the shortest paths in the airport taxiway system. In order to ensure that aircraft maintain a minimum separation distance, the velocities with which they are towed are adjusted. The choice of routing them across the shortest path is motivated by the fact that this requires the least energy per towing. In the second phase, the obtained velocities are used to optimally schedule the fleet of towing tractors to either perform aircraft towing tasks or battery recharging.

Other works approach the scheduling of GSE without the use of a VRP. Zhang et al. (2022) argue that dispatching GSE can be done better through a RCPSP, rather than a VRP. They state that in support tasks, facing time windows and resource constraints, consideration should be taken of how to maximize the allocation of existing resources to form the best job scheduling, instead of, for example, guarantying the shortest driving path or time with a limited number of resources. The work differs in more areas, as it focuses on handling military aircraft, and it does not consider time windows. The problem is solved using a GA. Kuhn and Loth (2009) introduce different scheduling algorithms, including one based on solving static vehicle scheduling problems within a moving time window. A novel formulation of such problems is introduced, and complemented by a specially designed branch and bound solution search strategy. Next to that, a GA approach based on research in aircraft arrival scheduling is used. Both approaches are used to solve the MILP that is introduced by the authors, since they found that the brand and bound algorithm caused a significantly bigger computational burden. In the work of S.-T. Chen (2022), creating an automated task allocation optimization mechanism is one of the main goals. It is used to optimally allocate the ground handling tasks to GSE, complying with temporal and operational constraints. An auction mechanism, called adapted TeSSI auction, is implemented to perform the task allocation. Agents use the costs for them to perform a ground handling task as the bid for the TeSSI auction. The bids are generated by modeling the task scheduling for agents as single-vehicle pickup and delivery optimization problems.

As mentioned earlier, VRPs are also widely used in a broader context than GSE. The work of X. Song et al. (2019), for example, includes a VRPTW for routing a number of vehicles to serve a set of customers and determining the best way of loading the goods ordered by customers onto the vehicles used for transportation. The problem is formulated as a MILP with three objectives pertaining to minimisation of total travel distance, number of routes to use, and total number of mixed orders in the same pallet included in one objective function. A Generalised Variable Neighborhood Search (GVNS) algorithm is designed as the search engine to relieve the computational burden inherent to the application of the MILP model. The work of Arias-Melia et al. (2022) describes a Vehicle Sharing and Task Allocation Problem (VSTAP) which is more complex than a regular VRPTW, as it also includes vehicle sharing. The problem is formulated as a Mixed-Integer Programming (MIP) program. To solve larger instances of the problem a heuristic approach is introduced, using the Clarke and Wright Savings (CWS) algorithm and LNS.

2.4.2. Energy management

Multiple works consider the energy management of GSE. The work of Rensen (2013) focuses on the creation of a framework to determine the value for airports regarding the design choices made introducing the Multiple Aircraft Receiving Stand (MARS) concept, proposed by the International Air Transport Association (IATA). This concept provides the possibility of parking either a single Wide-Body (WIBO) aircraft or two Narrow-Body (NABO) aircraft at an aircraft stand simultaneously. The work focuses on the number of GSE required, the distance covered, the operational time, and the energy consumption of the GSE and installations is provided. To determine the required energy, the average power demand of the various GSE is used. It is based on the average horsepower and load factors for driving, and separate calculations for the PCAs and GSE types that include pumps. The work of Gulan et al. (2019) describes a charging algorithm created to service each GSE type efficiently on a fully electrified airport. It proposes an intelligent scheduling algorithm based on variable pricing and required aircraft support at peak and off-peak times. The adjustable parameters of the model include the number of each type of GSE, the number of chargers, charging algorithm weights, and the maximum target load of the airport facility. The algorithm keeps the total electrical load under the maximum target load. The GSE are split into three categories: 1.) typical on-road vehicles that transport fuel, food, and people, 2.) high-powered pushback tugs, and 3.) small, low-power tugs. A ranking system is used to prioritize the charging of certain GSE. GSE with low SOC and availability have charging priority over other vehicles. The availability of a GSE is hereby defined as the number of vehicles in that class that could be used divided by the total number of vehicles in the class. When there are not enough electric vehicles available, the model employs conventional vehicles. In the work of Kirca et al. (2020) a generic Multi-Input Multi-Output Airport Energy Model (MIMO-AEM) is developed to understand eGSE charging requirements and to investigate eGSE charging scheduling for existing turnaround procedures. The model is capable of investigating the trade-off between the number of eGSE required and the number of chargers required for different eGSE battery pack sizes. The model is also capable of sizing battery packs of different GSE types specific to their use case. A methodology is proposed to generate power vs. time duty-cycles for each type of GSE for turnaround services of different aircraft, since standardised or real-world duty cycles for GSE are not available in the reviewed literature. Next to that, an algorithm is developed to distribute aircraft traffic among the minimum possible number of gates and generate a daily gate GSE schedule. The GSE types are categorized into four classes, according to the similarities between their activities. Load factors are assigned as a function of GSE power demand mode and GSE category. The eGSE battery discharge power, eGSE energy usage, and conventional GSE energy usage are estimated for each type of GSE servicing each aircraft covering daily airport traffic. Two electrification scenarios covered in the model are 1.) the case where conventional GSE is replaced with a minimum number of eGSE, and 2.) the case where as many eGSE as required is used to complete assignments in a day with a single full charge. Together with two charging strategies: 1.) overnight charging, and 2.) intermittent opportunity charging, it is possible to evaluate four different cases in the model, based on the four combinations of scenarios and strategies. It is hereby assumed that each GSE in each GSE sub-fleet has a designated charging station.

The challenge that pertains the energy management of EVs is of course also being researched for commercial EVs. The work of Clemente et al. (2014) deals with a problem related to EV charging operations: the integration of EVs with the power distribution problem, including possible electrical grid disruptions due to uncoordinated charging operations. In this work, a mathematical programming approach is considered and a system made up of two interdependent optimization models is introduced in order to identify the optimum spatial and temporal scheduling of EVs charging operations in an urban area served by several charging stations. Moreover, a MILP formulation for the Vehicle-to-Charging Station Assignment Problem (VCSAP) is proposed. The work of Keskin et al. (2021) proposes a Electric Vehicle Routing Problem with Time Windows (EVRPTW) that includes stochastic waiting times. The EVs may wait in queue before the recharging service starts due to the limited number of chargers available. Since the customers and depots are associated with time windows, long waiting times at the stations in addition to the recharging times may cause disruptions in logistics operations. To solve this problem, a two-stage MILP program with a simulation-based heuristic using Adaptive Large Neighborhood Search (ALNS) is presented. In the first stage, a set of routes is determined. In the second stage, each route is executed as planned up to the recharging stations, where the random queuing times are realized. The second stage solution is then constructed by applying the recourse action and correcting the first-stage solution.

2.4.3. Related problems in the aviation industry

There are also various works that include GSE, but do not focus on the optimization of operations or energy management. Francfort et al. (2007) evaluate the costs associated with operating GSE to assist airlines and other stakeholders in future evaluations of deploying GSE. The approach of this study was to compare eGSE to conventional GSE that would be replaced at four different airports in the US. To this extent, data was collected from these airports, and a model was developed. One main finding of the study is that eGSE has lower operating costs than conventional GSE.

The purpose of the study of Hannah et al. (2012) is to provide airport managers with a trade-off analysis for strategies to achieve carbon neutral growth at airports. A decision support tool was developed to create an emissions inventory to model airport operations to evaluate mitigation strategies. The study considers two projections towards 2050, using a 2% and 4% growth rate with 2005 as a baseline. The main finding of the study is that carbon neutral growth is feasible with 2% growth at Dulles Airport, when all design alternatives are combined together. When 4% growth is modeled, this is no longer feasible.

The objective of the study of Van Baaren (2019) is to determine if a fully electric towing system can be a technically and operationally feasible alternative to conventional taxiing operations. The method in this feasibility study consists of three parts: 1.) the conceptual design of a fully electric towing vehicle, 2.) the ground movements simulations, and 3.) a towing vehicle routing problem. The main finding of the study is that the concept of fully electric towing can be technically and operationally feasible, with a large fuel and emissions saving potential. The costs and logistical challenges are the main disadvantages.

Sznajderman et al. (2022) aim to develop an integrated model identifying the required GSE and the gaseous emissions produced by them due to apron traffic and aircraft service. In order to do this, in the case of service, the model proposed considering loading and unloading and dividing them into the following stages: wait, connection, service, and disconnection. The proposed model aims at copying the real movements of GSE according to the aircraft and its corresponding operation (Full-Service, Low-Cost, etc.). To do that, the program discretizes GSE movements into loading and unloading processes through different stages and for circulation where the tool itself sets the parameters of the apron.

The work of Bosma (2022) describes the development of a capacity model that functions as an essential input for airport design related to sustainable aircraft refueling services. The model outputs provide insights in the future fleet mix (conventional and electric) and charging infrastructure requirements on a tactical level to achieve carbon emission goals for refueler fleets. Based on a case study for Hamburg Airport, it was concluded that if targets are set to stabilize future emissions at specific levels, it is not necessary to completely electrify the fleet of refuelers. Next to that, it was concluded that electrified fleets do not necessarily result in higher annual cost compared to conventional fleets, due to the fact that annualised investment costs for electric refuelers and the required charging infrastructure are more than compensated for by lower operational costs.

Van Amstel (2023) and D. Horstmeier (2023) contribute to the field of electric aviation by offering innovative modeling approaches that optimize infrastructure and charging scheduling while minimizing costs. The work of Van Amstel (2023) emphasizes flexibility and renewable energy integration as part of the energy balance, while the work of D. Horstmeier (2023) focuses on different scenarios of electric aviation uptake, aircraft types, charger types, and spatial aspects of charging locations. These works provide an interesting look at the electrification of airports in general from a different perspective.

2.4.4. Summary

This section has reviewed different works that are considered relevant for this research, to formulate an answer to SQ 4: *"How can the existing (Ground Support Equipment operations) models be used?"*.

An overview of the works on GSE, with a comparison on different aspects, is provided in Table 2.8. Here, the focus of the studies is denoted by an icon, referring to "optimization of operations" (), "energy management" (), "operational costs" (), or "environmental impact" (). In addition, a distinction is made between works that consider GSE or not. It stands out that the vast majority of works that consider GSE only look at one or a few GSE types, and in the works that consider several GSE types, the different properties of these GSE types are not taken into account. In some works, several GSE types are divided into a number of categories with similar properties.

The studies that focus on optimizing operations in most cases include the assignment of tasks and the travel time between different locations. In most cases, a VRPTW is also part of the research, which means that the inclusion of time windows is frequently discussed. These are important aspects for a model in which the GSE turnaround operations of different aircraft, with time constraints, must be included. A number of studies also include individual service times, meaning that a distinction is made between the duration of the processes at the locations, depending on the process and the vehicle. The energy consumption of the vehicles is often not included in these works, which makes sense, because the focus is on the optimization of operations. In many of the works, attention is also paid to the computational complexity to solve the problems. In some cases specific algorithms are used here and in other cases simplifications are made.

Logically, the works that focus on energy management have included the energy consumption of the vehicles. Most of the works also include the charging of the vehicles, although in all cases this is not yet done in a "realistic" way, as the increase in SOC over time is considered to be linear, which is not in line with the CC-CV charging algorithm that was discussed in Section 2.2.3. Most works do include the scheduling of charging, be it by solving an optimization problem or using an algorithm that decides on the choices regarding the charging. A number of works also consider mixed fleets, where conventional vehicles are used when the availability of electric vehicles is insufficient.

The other aviation related studies have a varied focus. Some of them are GSE-related and focus on the costs or the environmental impact of GSE. Overall, the works clearly show that there is a lot of improvement to be achieved with the implementation of eGSE. Both the costs and of course also the (local) emissions can be reduced by the implementation of eGSE. Other works are related to the charging of electric aircraft. The fact that charging electric aircraft, unlike many GSE vehicles, cannot necessarily be done at night makes that these works provide an interesting look at the electrification of airports in general.

2.5. Contribution

It has become apparent that there are many differences between the GSE types required for servicing aircraft at an airport. In order to use the model as widely as possible, the model will therefore distinguish between a number of groups with GSE types that share the same properties. The literature research, interviews and observations have revealed a number of essential components that are important when modeling GSE operations at an airport. The literature research shows that there are only a few works that consider multiple GSE types and none of the works that do this do include all details that are assumed to be essential based on the literature research.

The unique way in which GSE is used means that it is not possible to directly adopt the solutions found for commercial EVs when implementing eGSE. The differences in maximum speed, charging options and usage times mean that the smaller GSE types currently do not pose a major challenge in the field of charging. This could possibly be the case in the future for the larger GSE types. Therefore, the model will mainly focus on simulating and optimizing the GSE operations and the associated energy consumption. A follow-up study could then focus on a possible charging strategy based on this energy consumption. The two-phased approach used by Van Oosterom et al. (2023) is an example of this. In the same way, an addition could be made in the future that would allow for including mixed fleets.

Including the above elements results in a contribution as shown in the last column of Table 2.8. Because the literature review also shows that the nature of the operations to be simulated often leads to a computationally complex problem, extensive attention will also be paid to improving and accelerating the solvability during the development of the model.

Table 2.8: *A comparison of different studies that include the modeling of GSE operations.*

	Kuhn and Loth (2009)	Ip et al. (2013)	Padrón et al. (2016)	X. Song et al. (2019)	S. Wang et al. (2021)	Gök et al. (2022)	Zhang et al. (2022)	Arias-Melia et al. (2022)	S.-T. Chen (2022)	Van Oosterom et al. (2023)	Bao et al. (2023)	Rensen (2013)	Clemente et al. (2014)	Gulan et al. (2019)	Kirca et al. (2020)	Keskin et al. (2021)	Francfort et al. (2007)	Hannah et al. (2012)	Van Baaren (2019)	Sznajderman et al. (2022)	Bosma (2022)	This thesis
Focuses on																						
Considers GSE	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
Includes all common GSE types															✓			✓				✓
- Number of GSE types included	1	0	7	0	1	6	3	0	6	1	1	6	0	6	16	0	3	8	1	11	1	16
- Considers GSE types individually	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓					✓		✓	✓	✓	✓
GSE turnaround operations	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Task allocation	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓								✓		✓	✓
- Travel time between locations	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓			✓	✓	✓	✓
- Service time window	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓										✓
- Service time at aircraft stand	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Individual service times	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Energy consumption of vehicles				✓						✓	✓	✓	✓		✓	✓			✓	✓	✓	✓
Considers eGSE										✓	✓	✓		✓	✓		✓	✓	✓		✓	✓
- Considers mixed fleets											✓			✓	✓			✓			✓	
- Charging (scheduling)										✓	✓		✓	✓	✓	✓			✓		✓	
Determines number of vehicles				✓		✓		✓		✓		✓			✓						✓	✓
Number of vehicles as an input	✓	✓	✓		✓		✓		✓		✓			✓				✓	✓	✓		

3
Model development

This chapter focuses on the development of the mathematical model that will be used to model and optimize the GSE operations. This will be done by means of a Task Scheduling Problem, that will be optimized using Mixed-Integer Linear Programming. This, together with the different task types, and model assumptions, is discussed in Section 3.1. Section 3.2 presents the MILP model's mathematical formulation, including its sets, indices, variables, objective function, and constraints. In Section 3.3, different solvability enhancements are discussed. Section 3.4 includes the verification of the model. Finally, Section 3.5 provides a summary of this chapter, together with an answer to SQ 5.

3.1. Model setting

This section describes the setting of the model that is developed to model the GSE operations. For the model, the approach of a Task Scheduling Problem (TSP) has been taken. This will be explained in Section 3.1.1. The TSP is solved using MILP, which is discussed in Section 3.1.2. Section 3.1.3 explains the different task types that are included in the model. To reduce the computional complexity, a rolling horizon is applied, which is explained in Section 3.1.4. The assumptions made in the model are listed in Section 3.1.5.

3.1.1. Task scheduling problem

According to Solomon (1987), a VRP involves the design of a set of minimum-cost vehicle routes, originating and terminating at a central depot, for a fleet of vehicles that services a set of customers with known demands. Each customer is serviced exactly once and all customers must be assigned to vehicles without exceeding vehicle capacities. This formulation can be extended to a Vehicle Routing and Scheduling Problem with Time Windows (VRSPTW), where these issues must be addressed under the added complexity of allowable delivery times, or time windows (Solomon, 1987). By replacing "customers" with "flights", it is this description that pretty much describes the problem at hand.

However, a VRP is primarily concerned with finding optimal routes for vehicles to serve a set of customers. In this case the focus is more on the "scheduling" part, related to assigning vehicles to specific tasks, considering factors such as task durations, vehicle availability, and operational constraints. This makes that the problem at hand will be described as a Task Scheduling Problem (TSP). According to Bunte and Kliewer (2009), an optimal schedule is characterized by minimal fleet size and/or minimal operational costs. These elements are at the heart of the problem. In order to compare and optimize the costs of different scenarios, it was decided to use Mixed-Integer Linear Programming (MILP) for this problem (see Section 3.1.2).

3.1.2. Mixed integer linear programming

In literature, MILP is widely used to solve Task Scheduling Problems and Vehicle Routing Problems with Time Windows (Bao et al., 2023; Clemente et al., 2014; Keskin et al., 2021; Kuhn & Loth, 2009; X. Song et al., 2019; S. Wang et al., 2021). As discussed in Section 2.4.1 Bao et al. (2023), Kuhn and Loth (2009), and S. Wang et al. (2021) even do this for scheduling airport GSE. Its modeling capability and the availability of good solvers make that Mixed-Integer Linear Programming (MILP) is a powerful tool for planning and control problems (Earl & D'Andrea, 2005). Therefore, the problem at hand will also be solved using MILP.

In literature, some works discretize the time so that it can be used as an index (Clemente et al., 2014; Van Amstel, 2023), and in other cases the time is tracked using one or more decision variables (Arias-Melia et al., 2022; Bao et al., 2023; Keskin et al., 2021; Kuhn & Loth, 2009; S. Wang et al., 2021). The use of time discretization imposes the trade-off between increased problem size versus a sparser set of time periods (Ma & Miller, 2006). Given the nature of the problem, a rather dense set of time periods with a step size of a maximum of $\Delta t = 5$ minutes is appropriate, which increases the problem size to an undesirable extent. That is why it was decided to use decision variables to track time in the problem at hand. The exact model formulation, including the decision variables, can be found in Section 3.2.

3.1.3. Task types

Within the model there are 1.) parking tasks, 2.) flight tasks and 3.) logistics tasks. The purpose of these task types is explained below. Each task has the following properties:

- **Task ID:** The task ID is a unique number linked to one task.
- **Task type:** Three task types can be distinguished: 1.) P, for a parking task, 2.) F, for a flight task, and 3.) L, for a logistics task.
- **SBE type:** The SBE type indicates how a task can be used. Three SBE types can be distinguished: 1.) S (start), for the tasks that need to be used as start tasks, 2.) B (between), for the tasks that can be used in between, and 3.) E (end), for the tasks that need to be used as end tasks.
- **Task name:** The task name provides extra information on the task. In the case of flight and logistics tasks, this is based on the flight number.
- **Location ID:** The location ID is used to indicate the location of a task. In contrast to the task IDs, it is possible to have multiple tasks with the same location ID.
- **Location number:** The location numbers are only applicable to the parking tasks. They are used to keep track of and regulate the usage of the parking tasks by the vehicles.
- **Aircraft type:** The aircraft type corresponding to the task, if applicable.
- **Demand (DEM):** The demand of a task indicates what share of the capacity of a vehicle with logistics is required to perform the task. The demands can be expressed as a percentage of a vehicle capacity or as an absolute value.
- **Energy consumption (EC):** The energy consumption of a task indicates the energy that a vehicle requires to perform the task. It is expressed in kWh.
- **Earliest time (ET):** The earliest time is the earliest time at which the task may be executed. It is expressed in minutes, where 0 corresponds to the start of the day and 1440 to the end of the day.
- **Latest time (LT):** The latest time is the latest time at which the task may be executed. It is expressed in minutes, where 0 corresponds to the start of the day and 1440 to the end of the day.
- **Task time (TT):** The task time is the time that is required to execute a task. It is expressed in minutes.

The different types of tasks and task-specific properties are:

- **Parking tasks:** Two parking tasks are defined for each parking location. The parking task from where a vehicle starts (SBE type S) runs from the beginning of the day ($ET = 0$) to the end of the day ($LT = 1440$). This makes it possible for a vehicle to leave a parking location throughout the day. The parking task where a vehicle ends (SBE type E) is defined at the end of the day ($ET = 1439$ to $LT = 1440$). The demand and task time for a parking task are both zero (i.e. $DEM = 0$ and $TT = 0$). A vehicle can therefore be on a parking task between 0 and $LT - ET$ minutes.

- **Flight tasks:** The flight tasks arise from the flight schedule and the turnaround tables of the aircraft types. The earliest time (ET) and latest time (LT) of a flight task define the time window within which the task must be executed. The task time (TT), for a flight task also follows from the turnaround table. It always holds that $TT \leq LT - ET$. The demand (DEM) and energy consumption (EC) of a flight task depend on the aircraft type and the GSE type. One flight may result in multiple flight tasks, based on the required number of vehicles and how long the aircraft is on the ground. The location of a flight task is an aircraft stand. It is therefore possible that there are several flight tasks with the same location if 1.) in the flight schedule several flights are handled on one aircraft stand and/or 2.) several vehicles of one type are required to handle one flight. The exact establishment of the ET, LT, TT, DEM, and EC are further explained in Appendix E.1.

- **Logistics tasks:** The logistics tasks may be used by a vehicle to refill or empty its storage compartment. They are therefore only necessary for GSE types with a so-called logistics function. The logistics tasks are placed prior to a flight task in terms of time window. This makes it possible for a vehicle to go to a logistics task before a flight, or directly to the flight without a stopover. The demand and task time for a logistics task are both zero (i.e. $DEM = 0$ and $TT = 0$). A vehicle can therefore be on a logistics task between 0 and $LT - ET$ minutes. The constraints in the mathematical model (see Section 3.2) oblige a vehicle to spend the time on a logistics task that corresponds to the change in load. The exact establishment of the ET, LT, and TT are further explained in Appendix E.1.

Figure 3.1 shows an example of a small set of tasks with a possible solution. It should be noted that this example task set does not show a realistic scenario in terms of time windows, as it is purely meant for explanatory purposes. It should also be noted that the vehicle stays at A01 and A02 after finishing the task. This is in line with the assumptions that are made in Section 3.1.5. The task set includes four parking tasks (at two parking locations) and two logistics tasks (at one logistics location). There is one flight task at A01 with $ET_7 = 570$ and $LT_7 = 750$, and one flight task at A02 with $ET_8 = 1080$ and $LT_8 = 1320$. The required task times are $TT_7 = 150$ and $TT_8 = 180$ minutes (this can not be seen in the figure). The arrows indicate a possible sequence of tasks that a vehicle could take to handle the flight tasks. The vehicle starts at a parking location and then drives to a logistics location for refilling its storage compartment. After this, the vehicle can perform the first flight task (for 150 minutes) and then continue with the second flight task (for 180 minutes). After that, it will return back to a parking location.

The sequences of tasks performed by the vehicles are optimized based on a predefined objective function. What this optimization problem looks like can be read in Section 3.2. Appendix E.1 provides more information on how the different sets of data are processed to generate the task list and the other data that is used for creating the optimization problem.

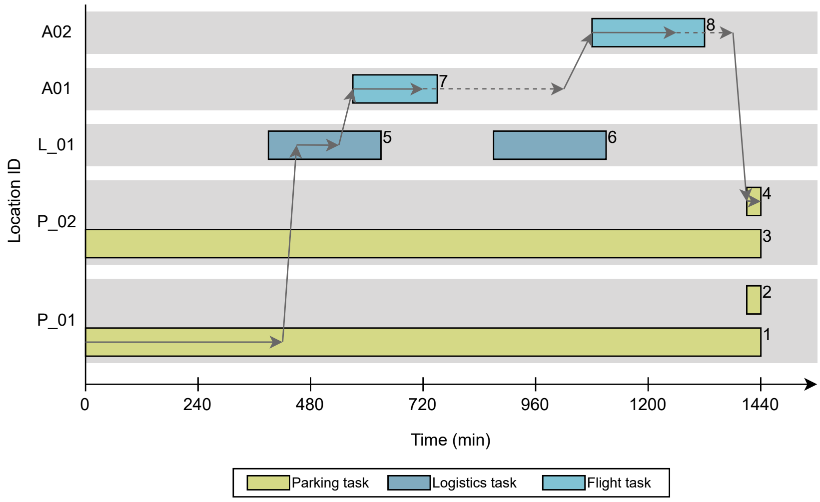


Figure 3.1: *Overview of a small set of tasks with an example of a solution. The task set contains eight tasks, which are located at 5 different locations. The task IDs are displayed next to the task blocks.*

3.1.4. Rolling horizon

Optimization problems with long time horizons are known to be computationally expensive to solve. Fortunately, for many (dynamic) optimization problems, the distant forecasts seem to have a diminishing effect on the initial decisions (Chand et al., 2002). Therefore, to obtain a good quality feasible solution for large scale instances, a rolling horizon approach is often used (Qin et al., 2019). This methodology decomposes the global optimization problem into smaller optimization problems to reduce the computational complexity and handle uncertainties throughout the whole process (Xin et al., 2020). Splitting the optimization problem into smaller ones reduces the number of variables and constraints that need to be considered simultaneously. In most applications, the rolling horizon approach has achieved satisfying performance (Chand et al., 2002), with a significant reduction in computation times (Xin et al., 2020). Next to that, it is shown that with some additional constraints, the quality of the solution of a rolling horizon approach can be guaranteed (Lu et al., 2023). To reduce the computation time for the optimization problem at hand, a rolling horizon will be implemented. Kuhn and Loth (2009) use a rolling horizon for the scheduling of GSE as well.

Figure 3.2 gives a general impression of what the concept of a rolling horizon looks like. Algorithm 1 explains how it will be applied in the context of this research. Here CT is the current time and Π is the set of flight tasks that still need to be assigned. The set of all flight tasks is A. Each iteration set F is defined as the set of flights $i \in \Pi$ that have an earliest time (ET_i) that is within the next $t_{forward}$ minutes from the current time (CT). The optimization problem is then solved, which uses the data from the vehicles $k \in K$ and the flight tasks $i \in F$ to perform the assignment of tasks. The assigned flight tasks with a start time (s_i) that is within the current time and the time step at which the update takes place, t_{update}, are added to set Ω. Here, it holds that $t_{update} \leq t_{forward}$. The execution of the flight tasks in Ω is fixed and removed from set Π. The overall task list is updated and the current time is increased with t_{update}. After this, set F is defined again, based on the new CT. This process repeats until $\Pi = \emptyset$.

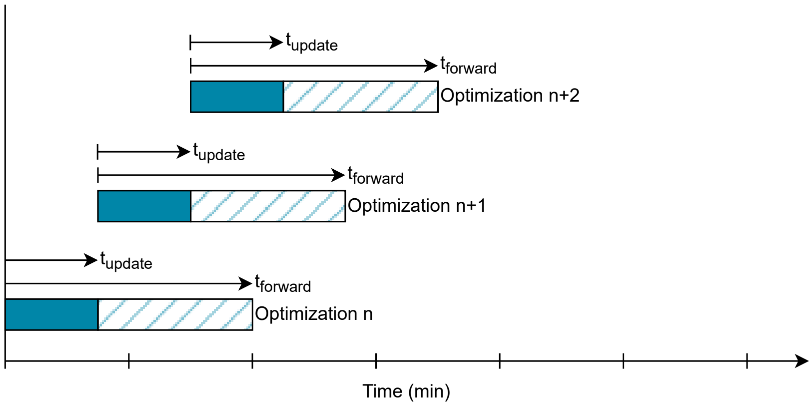


Figure 3.2: *Impression of the rolling horizon concept, including the definition of* $t_{forward}$ *and* t_{update}.

Algorithm 1: Basic principle rolling horizon

$CT \leftarrow 0$
$\Pi \leftarrow A$
while $\Pi \neq \emptyset$ **do**
  $F \leftarrow \{i \in \Pi : ET_i \leq CT + t_{forward}\}$
  Solve: optimization problem using data regarding all $k \in K$ and $i \in F$
  $\Omega \leftarrow \{i \in F : s_i \leq CT + t_{update}\}$
  Assign: all tasks in Ω
  $\Pi \leftarrow \Pi \setminus \Omega$
  Update: overall task list together with vehicles states and SOC
  $CT \leftarrow CT + t_{update}$

3.1.5. Assumptions

Several assumptions are made when creating the model. Some assumptions are of an operational nature, while others are purely intended to increase the solvability. The operational assumptions are based on practical experience:

- Vehicles using a logistics location in the model are not allowed to remain there once they have completed the task. The time the vehicles spend at these locations is therefore part of the objective function.
- It is assumed that a vehicle starts at a parking location at the beginning of the day and ends at one at the end of the day. This does not necessarily have to be the same location.
- It is assumed that between flight tasks the vehicles can remain at the pier where they last performed a task. This means that the model works less realistically for airports where limited space for parking is available in the proximity of or at the aircraft stands.
- If an aircraft is on an aircraft stand for longer than its minimum turnaround time plus 30 minutes, the tasks are split into a separate arrival and departure. When creating the tasks, separate arrivals, separate departures and "full" turnarounds are taken into account.

The assumptions that are made to improve the solvability of the model are:

- Each GSE type is optimized in a separate run.

- The traffic situation (such as congestion) at the airport is not included in the model. If necessary, a correction can be applied to the driving speed.
- Accelerating and braking are not included in the model. A constant average driving speed is assumed.
- A constant average value (in kWh/m) is used for the energy consumption for driving.
- Vehicles that use a logistics location in the model always leave the logistics location with a 100% full load. Vehicles can come to a logistics location if they are not completely empty yet.
- The model formulation that is presented in this chapter can only be used for logistics vehicles that become increasingly empty during flight services.
- A linear time relationship is assumed for refilling a vehicle at a logistics location (e.g. refilling from 0% to 50% takes twice as long as refilling from 75% to 100%). For each type of vehicle, a certain time constant (R) applies, which is multiplied by the quantity of load that is added to a vehicle.
- It is assumed that a vehicle consumes no energy at a logistics location.
- The model does not take into account how many vehicles are at one logistics location at the same time.
- The model does not take into account working hours, breaks and work schedules. However, it is possible to reduce the number of available vehicles to take into account limited staff availability. Yet, this has no influence if the number of vehicles is optimized.
- To reduce the number of possible solutions, the assumption is made that vehicles must be back at the final parking task 1 minute before the end of the day. Until then, the vehicles will remain at the pier during the optimization. This is corrected in the post-processing phase.
- The distances between the locations are based on a predefined table with distances, including one-way traffic routes. The distances in this table are based on the route with the shortest distance. Because the traffic situation is not taken into account, it cannot be guaranteed that this is necessarily the fastest route as well.
- The travel times are calculated based on the predefined distances and the travel speed.
- To limit the size of the table with distances, location groups can be used (e.g. aircraft stands A01, A02 and A03 fall under location group A). The distances between the location groups are used to determine the distances between two locations. A predefined value is used for the distance between two locations within one location group. If desired, it is possible to consider each location individually by making the number of location groups equal to the number of locations.
- The required task time for a flight task depends on the type of aircraft and is based on a ground handler's turnaround table. This means that the task times are equal for multiple aircraft of the same type. However, it is possible that an aircraft type requires multiple vehicles of one GSE type and therefore tasks, each with its own task length.
- The required energy for a flight task depends on the type of aircraft and is based on the task time. This means that the energy consumption is equal for multiple aircraft of the same type. However, it is possible that an aircraft type requires multiple vehicles of one GSE type and therefore tasks, each with its own energy consumption.

- The demand of a flight task is based on the aircraft type. This means that the demands are the same for multiple aircraft of the same type.
- Delays during the execution of a task are not included in the model. However, if necessary, it is possible to adjust the task times.
- Deviations in the flight schedule throughout the day are not included. By using the rolling horizon, only a limited amount of time ($t_{forward}$) can be looked into the future.
- The set of vehicles of one GSE type is considered homogeneous (i.e. all vehicles have the same properties).

3.2. Basic mathematical formulation

This section describes the different parts of the mathematical model. In Section 3.2.1 the sets, indices and parameters are introduced. The decision variables that are used are explained in Section 3.2.2. Section 3.2.3 describes the objective function that is used and finally the constraints are listed in Section 3.2.4.

3.2.1. Sets, indices, and parameters

In the sets used in the model, a distinction is made between numerical sets and modeling sets. The sets can be seen below. For the modeling sets, the model formulation sometimes uses one or more subscripts, which indicate a subset. Three subscripts can be distinguished: 1.) S (start), for the tasks that need to be used as start tasks, 2.) B (between), for the tasks that can be used in between, and 3.) E (end), for the tasks that need to be used as end tasks. For example, P_S is a subset of set P, i.e. $P_S \subset P$, and it contains all task indices of parking tasks that need to be used as start tasks. If no subscript is indicated, the entire set is meant (e.g. $P_{SBE} = P$). As explained in Section 3.1.4, several optimizations are performed as a result of the rolling horizon approach. After each optimization, the modeling sets P, F, L, K_{unused}, K_{used} and $K_{depleted}$ are updated.

<u>Numerical sets</u>

$\mathbb{R}^+$	Set of all positive real numbers	
$\mathbb{R}^+_0$	Set of all positive real numbers including 0	
$\mathbb{N}^+_0$	Set of all positive integers including 0	

<u>Modeling sets</u>

P	Set of parking tasks	
F	Set of flight tasks	
L	Set of logistics tasks	
T	Set of all tasks	$P \cup F \cup L$
K	Set of all vehicles	$K_{unused} \cup K_{used}$
K_{unused}	Set of vehicles that have not been used yet	$K_{unused} \subseteq K$
K_{used}	Set of vehicles that have been used in a previous run	$K_{used} \subseteq K$
$K_{depleted}$	Set of vehicles that are used and depleted	$K_{depleted} \subseteq K_{used}$

Three different indices are used in the model. Some of the parameters depend on one (or more) of these indices, while other parameters have a fixed value. Both the indices and the parameters are listed below.

Indices

i	Index for current task	$i \in T$
j	Index for the next task	$j \in T$
k	Index for vehicle	$k \in K$

Parameters

$ET_i \in \mathbb{R}_0^+$	Earliest time of performing task i	min
$LT_i \in \mathbb{R}^+$	Latest time of performing task i	min
$TT_i \in \mathbb{R}_0^+$	Required time for task i	min
$D_{ij} \in \mathbb{R}_0^+$	Distance between task i and j	m
$V \in \mathbb{R}^+$	Travel speed of vehicles	m/min
$RT_k \in \mathbb{R}_0^+$	Time at which vehicle k becomes ready	min
$ST_k \in T$	Starting task of vehicle k	-
$SL_k \in \mathbb{R}_0^+$	Starting load of vehicle k	-
$EP_k \in P$	Ending parking task of vehicle k in previous run	-
$LOC_i \in \mathbb{N}_0^+$	Location number of task i	-
TN_i	Task name of task i	-
$DEM_i \in \mathbb{R}_0^+$	Demand of task i	-
$C \in \mathbb{N}_0^+$	Capacity of vehicles	-
$R \in \mathbb{R}^+$	Logistics refilling time constant	-
$M = 1560$	Big M for time constraints	min
$Q = C$	Big M for capacity constraints	-

As with the modeling sets, after each optimization during the rolling horizon, a number of parameters are updated based on the previous optimization. This concerns parameters RT_k, ST_k, SL_k, EP_k, and LOC_i.

3.2.2. Decision variables

The model uses three binary variables. Variable x_{ij} forms the basis for the model. This variable keeps track of which combinations of (i, j)-pairs are successively performed. Variables y_i and z_k are therefore dictated by x_{ij}. They are defined for convenience purposes.

Binary variables

$$x_{ij} = \begin{cases} 1, & \text{if a vehicle travels from task } i \text{ to } j \\ 0, & \text{otherwise} \end{cases} \qquad i, j \in T$$

$$y_i = \begin{cases} 1, & \text{if task } i \text{ is visited} \\ 0, & \text{otherwise} \end{cases} \qquad i \in T$$

$$z_k = \begin{cases} 1, & \text{if vehicle } k \text{ is used} \\ 0, & \text{otherwise} \end{cases} \qquad k \in K$$

The model uses three continuous variables. Variables s_i and w_i are used to keep track of time. Variable q_i is used to keep track of a vehicle's load.

Continuous variables

$s_i \in \mathbb{R}_0^+$	Starting time of servicing task i	$i \in T$
$w_i \in \mathbb{R}_0^+$	Waiting time at task i	$i \in T$
$q_i \in \mathbb{N}_0^+$	Load quantity of a vehicle after visiting task i	$i \in T$

3.2.3. Objective function

The objective function consists of five parts: 1.) the total number of vehicles used, 2.) the total distance traveled by all vehicles (in km), 3.) the number of times vehicles went to a logistics task, 4.) the sum of the starting times at the flight tasks and 5.) the total waiting time of vehicles at a logistics task. Objective function components 1 and 2 are used to optimize actual scenarios and components 3, 4 and 5 are used to help the MILP's solver converge to a solution. Depending on the goal of the optimization, the weighting factors λ_1 to λ_5 can be used to determine the proportions of the five objective function components. However, the weighting factors λ_3 to λ_5 must be relatively small so that they do not influence the optimization of the first two objective function components.

$$\min \lambda_1 \underbrace{\left(\sum_{k \in K} z_k \right)}_{\text{obj1}} + \lambda_2 \underbrace{\left(\sum_{i \in T} \sum_{j \in T} \frac{D_{ij}}{1000} x_{ij} \right)}_{\text{obj2}} + \lambda_3 \underbrace{\left(\sum_{i \in F} s_i \right)}_{\text{obj3}} + \lambda_4 \underbrace{\left(\sum_{i \in T \setminus L} \sum_{j \in L} x_{ij} \right)}_{\text{obj4}} + \lambda_5 \underbrace{\left(\sum_{i \in L} w_i \right)}_{\text{obj5}}$$

3.2.4. Constraints

The constraints used are listed below. A number of constraints are general and always apply. Other constraints are specific to the parking, flight, or logistics tasks.

General constraints

G1a: Connect x_{ij} to y_i.

$$y_j = \sum_{i \in T} x_{ij} \qquad \forall j \in T_{BE} \tag{G1a}$$

G1b: Connect x_{ij} to y_i for vehicles that leave their T_S location.

$$y_i = \sum_{j \in T} x_{ij} \qquad \forall i \in T_S \tag{G1b}$$

G2: Ensure that $z_k = 1$ if vehicle k is used for a task in F.

$$z_k \geq y_i \qquad \forall k \in K, \ \ i = ST_k \tag{G2}$$

G3: Flow conservation for tasks in T_B.

$$\sum_{i \in T} x_{ih} = \sum_{j \in T} x_{hj} \qquad \forall h \in T_B \tag{G3}$$

G4a: Task j can only be visited once.

$$\sum_{i \in T} x_{ij} \leq 1 \qquad \forall j \in T \tag{G4a}$$

G4b: Task i can only be left once.

$$\sum_{j \in T} x_{ij} \leq 1 \qquad \forall i \in T \tag{G4b}$$

G5: Ensure that vehicles do not drive from task i to task i.

$$x_{ii} = 0 \qquad \forall i \in T \tag{G5}$$

G6a: A vehicle can not enter a start task.

$$x_{ij} = 0 \qquad \forall i \in T, \ \ j \in T_S \tag{G6a}$$

G6b: A vehicle can not leave an end task.

$$x_{ij} = 0 \qquad \forall i \in T_E, \ \ j \in T \tag{G6b}$$

G7: A vehicle can not travel from a start to an end task.

$$x_{ij} = 0 \qquad \forall i \in T_S, \ \ j \in T_E \tag{G7}$$

G8a: Visiting a task can not start before ET_i.

$$s_i \geq ET_i \qquad \forall i \in T \tag{G8a}$$

G8b: Visiting a task can not start after LT_i.

$$s_i \leq LT_i \qquad \forall i \in T \tag{G8b}$$

G9: A vehicle can not start with task j before arriving at task j.

$$s_j \geq s_i + TT_i + w_i + \frac{D_{ij}}{V} - M\left(1 - x_{ij}\right) \qquad \forall i, j \in T, \ \ i \neq j \tag{G9a}$$

$$s_j \leq s_i + TT_i + w_i + \frac{D_{ij}}{V} + M\left(1 - x_{ij}\right) \qquad \forall i, j \in T, \ \ i \neq j \tag{G9b}$$

G10: Ensure that a vehicle does not start the servicing of task j before it arrives there (when traveling from starting task i).

$$s_j \geq \left(RT_k + \frac{D_{ij}}{V}\right) x_{ij} \qquad \forall j \in T, \ \ i = ST_k, \ \ k = LOC_i \tag{G10}$$

G11: Unused vehicles can only be used if all previously used vehicles are used again.

$$z_k \leq z_l \qquad \forall k \in K_{unused}, \ \ l \in K_{used} \tag{G11}$$

G12: An end parking task can only be used if the vehicle that ended there in a previous run is used in the current run.

$$y_i \leq y_h \qquad \forall k \in K, \ \ i = EP_k, \ \ h = ST_k \tag{G12}$$

G13: Make sure that depleted vehicles are not used.

$$z_k = 0 \qquad \forall k \in K_{depleted} \tag{G13}$$

Flight task constraints

F1: Ensure that all flight tasks are performed.

$$y_i = 1 \qquad \forall i \in F \tag{F1}$$

F2a: Performing task i can not start before ET_i.

$$s_i \geq ET_i \qquad \forall i \in F \tag{F2a}$$

F2b: Performing task i can not end after LT_i.

$$s_i \leq LT_i - TT_i \qquad \forall i \in F \tag{F2b}$$

Logistics task constraints

L1: The load of a vehicle at task j is equal to the load at task i minus the demand of task j.

$$q_j \leq q_i - DEM_j + Q\left(1 - x_{ij}\right) \qquad \forall i \in T, \ \ j \in T \setminus L, \ \ i \neq j \tag{L1a}$$

$$q_j \geq q_i - DEM_j - Q\left(1 - x_{ij}\right) \qquad \forall i \in T, \ \ j \in T \setminus L, \ \ i \neq j \tag{L1b}$$

L2: Each vehicle must leave the logistics task with a full load.

$$q_i \geq C - Q\left(1 - x_{ij}\right) \qquad \forall i \in L, \quad j \in T \setminus L \tag{L2}$$

L3: Vehicle k leaves the starting task with a load of SL_k.

$$q_i \geq SL_k \qquad \forall i \in T_s, \quad k = LOC_i \tag{L3a}$$
$$q_i \leq SL_k \qquad \forall i \in T_s, \quad k = LOC_i \tag{L3b}$$

L4: Ensure that the waiting time at a logistics task is R minutes per load unit that is added.

$$w_j \geq R\left(q_j - q_i\right) - M\left(1 - x_{ij}\right) \qquad \forall i \in T, \quad j \in L \tag{L4}$$

L5: A vehicle should leave a logistics task before LT_i.

$$s_i + w_i \leq LT_i \qquad \forall i \in L \tag{L5}$$

L6: The load of a vehicle can not exceed the vehicle's capacity.

$$q_i \leq C \qquad \forall i \in T \tag{L6}$$

L7: Ensure that vehicles do not drive from one logistics task to another.

$$x_{ij} = 0 \qquad \forall i, j \in L \tag{L7}$$

L8: Ensure that vehicles can only drive from a logistics task to its corresponding flight task.

$$x_{ij} = 0 \qquad \forall i \in L, \quad j \in F, \quad TN_i \neq TN_j \tag{L8}$$

L9: Ensure that vehicles can not drive from a logistics task to a parking task.

$$x_{ij} = 0 \qquad \forall i \in L, \quad j \in P \tag{L9}$$

3.2.5. Conceptual model validation

The theories underlying the conceptual, mathematical model are based on the literature review, interviews and observations. The assumptions that are made in the development of the conceptual model have been partially derived from interviews and observations, and in every instance, they have undergone thorough discussion and validation with the experts supervising and/or collaborating on this project.

3.3. MILP solving performance

Although mathematically correct, the model's solvability can be substantially improved by several measures. Powerful software packages can solve MILP-problems efficiently for problems in which the number of binary variables is of reasonable size (Earl & D'Andrea, 2005). A major disadvantage of MILP is its computational complexity. The NP-complete nature of many scheduling problems, and MILP-models in general, precludes their being solved within a reasonable time (Roslöf et al., 2002). According to Earl and D'Andrea (2005), the computational requirements can grow significantly as the number of binary variables needed to model the problem increases. Darvish et al. (2020) state that the effectiveness of solving optimization problems using a brand-and-bound/cut algorithm relies mainly on its mathematical formulation. Furthermore, according to Roslöf et al. (2002), the complexity can also be simplified by the use of heuristic procedures. Sections 3.3.1 to 3.3.4 therefore discuss improvements in model tightening, model density, model symmetry, and the use of heuristics, respectively.

3.3.1. Model tightness

According to Sherali and Driscoll (2000), the much sought after characteristic of tight models is that they more closely approximate the convex hull of integer feasible solutions, at least in the vicinity of optimal solutions. They also state that adding the "right" type of constraints, even at the expense of increasing the problem size, often enhances rather than inhibits the solvability. The constraints below are mathematically redundant, but improve the solvability by enforcing variable upper bounds on each continuous variable to tighten the feasible region.

Tightening constraints

T1: If a vehicle is used it must start at its start P task at ET.

$$s_i \leq ET_i + M\left(1 - y_i\right) \qquad \forall i \in P_S \tag{T1}$$

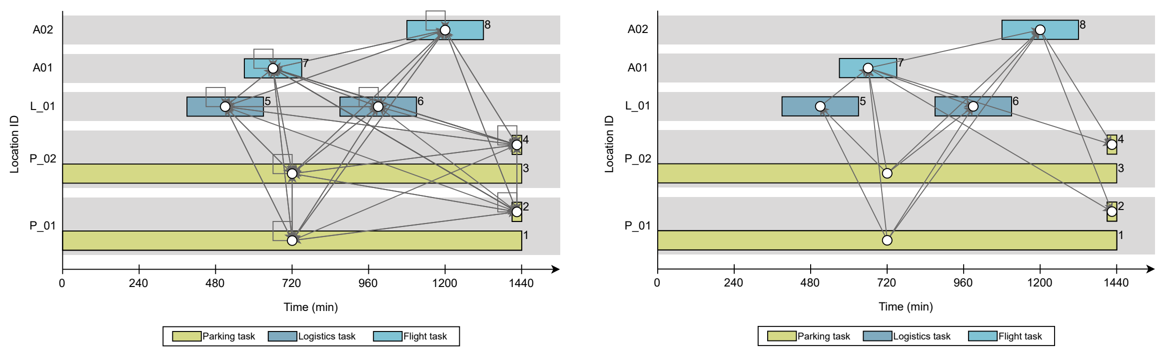
T2: If a vehicle is used it must arrive at its end P task at ET.

$$s_i \leq ET_i + M\left(1 - y_i\right) \qquad \forall i \in P_E \tag{T2}$$

3.3.2. Model density

As mentioned before, the computational requirements can grow significantly as the number of binary variables increases (Earl & D'Andrea, 2005). Although there is nothing wrong with the model formulation from a mathematical point of view, the model does contain a lot of binary variables that could never be part of a feasible solution due to the constraints in the model. This makes that the model is currently quite sparse.

Figure 3.3a shows all the possible (i, j)-pairs included in the model for the example that was already introduced in Figure 3.1. In a similar way to the chain decomposition applied in the work of Hooker and Natraj (1995), by filtering the (i, j)-pairs based on the constraints of the model, it is already possible to omit a large number of (i, j)-pairs from the model in advance. This reduction does not affect the availability of potentially optimal solutions in the model, because only those decisions that are infeasible due to the constraints are omitted from the model. Figure 3.3b illustrates the significant reduction in the number of (i, j)-pairs. In this case it is a reduction of (i, j)-pairs by 75% (from 64 to 16), but for larger examples this reduction can go up to > 85%. The exact steps to reduce the (i, j)-pairs are further explained in Appendix E.2.



(a) *An example of a small set of tasks with all (i, j)-pairs illustrated.* **(b)** *An example of a small set of tasks with the filtered (i, j)-pairs illustrated.*

Figure 3.3: *The reduction of (i, j)-pairs by filtering out infeasible decisions.*

To further reduce the number of variables in the model, logistics tasks are only created for vehicles with a logistics task. For vehicles without a logistics task it holds that $L = \emptyset$. The decision variable q_i and the "logistics task constraints" are also only added to the model if necessary. The above actions result in a lower computational load in two ways: 1.) when creating the model there are fewer constraints and variables that have to be included, and 2.) because the optimization problem is smaller, it can be solved faster.

3.3.3. Model symmetry

With the tightening and reduction of the model variables, a major step has already been taken in improving the problem size. However, another improvement can be made by preventing degeneracy in the model. Degeneracy in MILP problems occurs when the optimal solution to the problem lies at a point where one or more of the binary variables can take on different values while still maintaining the same optimal objective value. In other words, there are multiple feasible solutions that all yield the same objective function value. These solutions are called symmetric. It leads to challenges in solving MILP problems because it can make algorithms used for optimization less efficient. When degeneracy occurs, it means that the search space for finding the optimal integer solution is more complex and may require additional computational effort to explore all possible integer combinations. It has been a topic of interest since the invention of the simplex method (Gamrath et al., 2020).

As an example, the possible solution in Figure 3.4 can be considered. Given that P_01 and P_02 are within the same location group, this solution has exactly the same objective value as the solution in Figure 3.1.

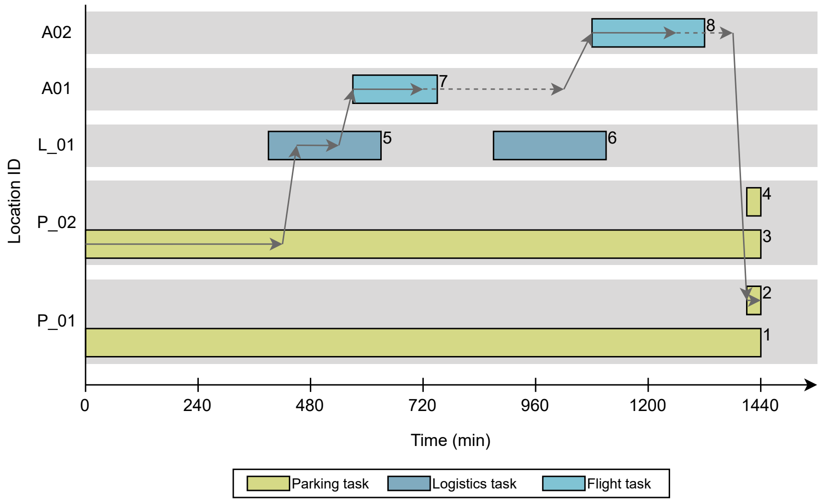


Figure 3.4: *Alternative solution to the small task set that was introduced in Figure 3.1. Both solutions result in the same objective value.*

As a result of these symmetric solutions, the branch-and-bound/cut algorithm that is used in solving of the MILP, can get hopelessly mired by being forced to explore and fathom symmetric reflections of various solutions during the search process. However, by augmenting the model with suitable symmetry-breaking constraints, the structure of the model can be considerably improved by reducing the extent of the feasible region that must be explored (Sherali & Smith, 2001). The example above gives only two different solutions that are symmetrical to each other. However, the number of symmetric solutions can increase rapidly. For a given vehicle set with $|K|$ vehicles, there are

$$C(|K|, N_u) = \binom{|K|}{N_u} = \frac{|K|!}{N_u!\,(|K| - N_u)!}$$

possible options to select N_u vehicles from the fleet. Second, among the selected vehicles, there are $N_u!$ options to allocate the sequences of tasks to the vehicles. Combining both types of symmetry results in

$$\binom{|K|}{N_u} N_u! = \frac{|K|!}{N_u!\,(|K| - N_u)!} N_u! = \frac{|K|!}{(|K| - N_u)!}$$

equivalent solutions. For example, for an instance with a vehicle fleet of $|K| = 5$ vehicles, if 3 vehicles are used, there are $\frac{5!}{(5-3)!} = 60$ equivalent solutions that can be obtained. For a case with $|K| = 10$ vehicles, where 7 vehicles are used, there are already $\frac{10!}{(10-7)!} = 604800$ equivalent solutions. To break the first type of symmetry, a constraint based on the work of Adulyasak et al. (2014) can be used: Constraint S1 ensures that vehicle k can only be used if vehicle $k-1$ is used. To resolve the second symmetry issue, a hierarchical constraint inspired by Darvish et al. (2020) can be used: Constraint S2 ensures that if task $j \in T_B$ is serviced by vehicle k, then at least one other task $j' \in T_B$, with $j' < j$, must be performed by vehicle $k-1$. Both constraints are so-called valid inequalities and strengthen the model formulation.

These constraints can only be used if all vehicles in the fleet are homogeneous and start at the same location. If this is not the case, a more optimal solution could be prevented by one of the symmetry breaking constraints. The constraints are therefore only applied in the model if this is possible without excluding optimal solutions.

Symmetry breaking constraints

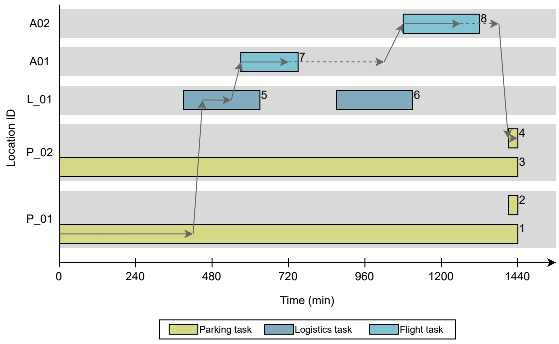
S1: Ensure that vehicle k can only be used if vehicle $k-1$ is used.

$$z_k \leq z_{k-1} \qquad \forall k \in K_{unused} \setminus \min(K_{unused}) \tag{S1}$$

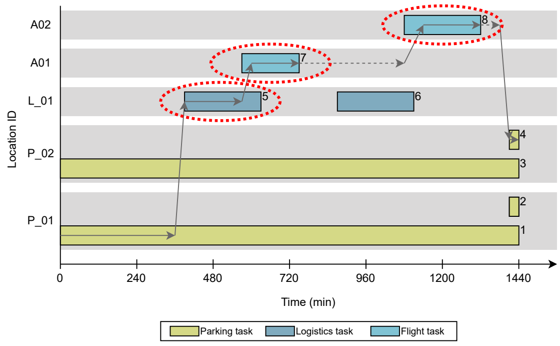
S2: If task j is serviced by vehicle k, then at least one other task j' in T_B, with $j' < j$, must be performed by vehicle $k-1$.

$$x_{ij} \leq \sum_{j'=\min T_B}^{j-1} x_{i'j'} \qquad \forall j \in T_B,\ \ k \in K_{unused} \setminus \min(K_{unused}),\ \ k' \in K_{unused},\ \ k' = k-1,$$
$$i = ST_k,\ \ i' = ST_{k'} \tag{S2}$$

A third form of symmetry that was present in the model has been remedied by adding objectives 3 to 5 in the objective function in Section 3.2.3. This is explained in Figure 3.5. The solution in Figure 3.5a and Figure 3.5b both have the same configuration of x_{ij} and y_i variables. Both solutions would result in the same objective value, if only the first and second part of the objective function were taken into account. By including the third, fourth and fifth part of the objective value, this symmetry is broken. Since the sum of s_i and w_i variables is lower in the solution of Figure 3.5a, this solution is considered better.



(a) *The solution that was introduced in Figure 3.1.*



(b) *Alternative solution to the one that was introduced in Figure 3.1.*

Figure 3.5: *A comparison of two solutions to a small set of tasks. Both solutions would yield the same objective value, if only the first and second part of the objective function were taken into account. By including the third, fourth and fifth part of the objective value, this symmetry is broken.*

3.3.4. Heuristics

According to Roslöf et al. (2002), the solving of a MILP problem can also be simplified by the use of heuristic procedures. These procedures try to make use of some information that is specific to the problem at hand. In this way they orient themselves on finding feasible solutions in a short time. In addition, heuristics also bring some advantages to the optimization process: 1.) They help to prune the search tree by bounding which reduces the work of the branch and bound algorithm, and 2.) the better the heuristic solution is, the more reduced dual reductions can be applied to tighten the formulation (Huang et al., 2021).

In this case, a heuristic built into GUROBI is used. Unlike most heuristics, problem-specific knowledge was not used for the development of this heuristic. The heuristic used is the “NoRel” heuristic, which stands for no relaxation heuristic. Not much has been publicly published about the inner workings of the heuristic, but according to Gurobi Optimization (n.d.), this heuristic attempts to find high-quality solutions without solving the relaxation. Due to the way the heuristic works, the heuristic searches in a more diverse solution space than regular branch-and-cut algorithms. A disadvantage is that the heuristic does not provide an objective bound and therefore no solution quality assessment (Gurobi Optimization, 2020).

The heuristic is only used in the model for GSE types with a logistics function, because only then the model complexity is high enough for the heuristic to provide a benefit. In this way, the objective value is quickly lowered, and most of the solving time is needed to increase the lower bound until the desired gap is met. This is especially useful for quick qualitative solutions, without guarantee of optimality.

3.4. Model verification and explanation

In this section, the model is verified using a scenario that is applied to the geometry of a small regional airport. Due to the small scale of the scenario, it is also suitable to get a better understanding of the working principle of the model. Various tests will be carried out with the model to verify correct operation. To this end, only one aspect at a time will be adjusted, and the expected impact will then be discussed. If the result matches this expectation, the test is considered successful. First, the base scenario will be explained in Section 3.4.1. After that, several tests are performed in Section 3.4.2.

3.4.1. Base scenario

Figure 3.6 shows the layout of Rotterdam The Hague Airport. This is the geometry to which the verification scenario will be applied. It is good to know that the scenario applied to this airport does not necessarily correspond to the working methods of the airport in real life. The airport has twelve aircraft stands, numbered from A1 to D3. In this scenario, the aircraft stands are divided into four location groups, which are represented by the letters A to D. Furthermore, there are three other location groups at the airport (E, F and G) that are used for parking GSE or logistics locations. The arrows between the location groups indicate the possible routes that can be driven. The distances (in meters) between the location groups are shown in the yellow circles on the arrows. It is assumed that the average speed of the GSE vehicles is 15 km/h.

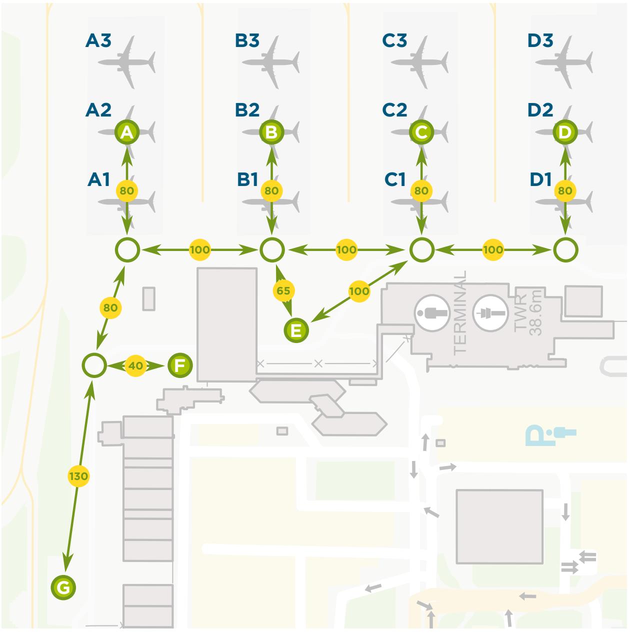


Figure 3.6: *Schematic map of Rotterdam The Hague Airport, including the distances between the location groups (adapted from Roche (2023)).*

In the day of the base scenario there are only six air traffic movements at the airport (see Table 3.1). The flight schedule that will be used for the scenario follows from these air traffic movements (see Table 3.2). How this process works can be read in Appendix E.1. The flight schedule includes three full turnarounds (FT), with three different aircraft types from three different airlines.

Table 3.1: *The air traffic movements data for the base scenario.*

Flight Date	A/D Indicator	Airline	Trip Number	A/C Type	Flight Time	Stand
01/01/2023	A	BA	4457	E90	09:00	A1
01/01/2023	D	BA	4458	E90	10:00	A1
01/01/2023	A	HV	6276	73W	11:00	A2
01/01/2023	D	HV	6275	73W	12:00	A2
01/01/2023	A	OR	1694	73H	12:30	D1
01/01/2023	D	OR	1695	73H	13:30	D1

Table 3.2: *The flight schedule data for the base scenario.*

A/D Indicator	A/D Flight Number	Airline	A/C Type	Stand	SIBT	SOBT
FT	4457_4458	BA	E90	A1	09:00	10:00
FT	6276_6275	HV	73W	A2	11:00	12:00
FT	1694_1695	OR	73H	D1	12:30	13:30

The airport has six belt loaders. These belt loaders can be used for all aircraft types that use the airport. The belt loaders are electric and have a battery capacity of 20 kWh. The belt loaders have an energy consumption of 0.33 kWh per kilometer driven. Furthermore, running the belt for X minutes results in an energy consumption of $\frac{X}{60}$ kWh. All belt loaders are parked at location F. The flight schedule in combination with the GSE fleet results in the task list of Table 3.3. More information on this process can be read in Appendix E.1.

Table 3.3: *The task list for the base scenario.*

Task ID	Task type	SBE type	Task name	Location ID	Location nr.	Aircraft type	DEM	EC	ET	LT	TT
0	P	S	P_BEL_000	P_BEL_000	0	N/A	0	0	0	1560	0
1	P	E	P_BEL_000	P_BEL_000	0	N/A	0	0	1559	1560	0
2	P	S	P_BEL_001	P_BEL_001	1	N/A	0	0	0	1560	0
3	P	E	P_BEL_001	P_BEL_001	1	N/A	0	0	1559	1560	0
4	P	S	P_BEL_002	P_BEL_002	2	N/A	0	0	0	1560	0
5	P	E	P_BEL_002	P_BEL_002	2	N/A	0	0	1559	1560	0
6	P	S	P_BEL_003	P_BEL_003	3	N/A	0	0	0	1560	0
7	P	E	P_BEL_003	P_BEL_003	3	N/A	0	0	1559	1560	0
8	P	S	P_BEL_004	P_BEL_004	4	N/A	0	0	0	1560	0
9	P	E	P_BEL_004	P_BEL_004	4	N/A	0	0	1559	1560	0
10	P	S	P_BEL_005	P_BEL_005	5	N/A	0	0	0	1560	0
11	P	E	P_BEL_005	P_BEL_005	5	N/A	0	0	1559	1560	0
12	F	B	4457_4458_0	A1	0	E90	0	0.48	543	572	29
13	F	B	4457_4458_1	A1	0	E90	0	0.48	543	572	29
14	F	B	6276_6275_0	A2	0	73W	0	0.7	661	703	42
15	F	B	6276_6275_1	A2	0	73W	0	0.7	661	703	42
16	F	B	1694_1695_0	D1	0	73H	0	0.73	751	798	44
17	F	B	1694_1695_1	D1	0	73H	0	0.77	751	798	46

The task list shows that there are two parking tasks per vehicle. One parking task on which a vehicle can start and one parking task on which the vehicle can end. Furthermore, six flight tasks have been created. This is correct because there are three flights and two belt loaders are needed per aircraft. The earliest time, latest time and task time of the flight tasks are determined based on the turnaround tables of the aircraft types.

Based on the distances between the location groups (see Table 3.4), the distances between the individual locations and therefore between the tasks (i.e. task distances) from the task list can also be determined. The distances within location groups A to D are based on the average distance to another aircraft stand within the group, which boils down to 65 meters.

Table 3.4: *The location group distances data for the base scenario.*

		Destination						
		A	B	C	D	E	F	G
Origin	A	65	260	360	460	245	200	290
	B	260	65	260	360	145	300	390
	C	360	260	65	260	180	400	490
	D	460	360	260	65	280	500	590
	E	245	145	180	280	0	285	375
	F	200	300	400	500	285	0	170
	G	290	390	490	590	375	170	0

The task list and the task distances provide the data required to solve the optimization problem. In this case the rolling horizon uses $t_{forward} = 1440$ min and $t_{update} = 1440$ min. So the entire day is considered at once. The optimal solution found by the model is depicted in the post-processed task list in Table 3.5. The following weighting factors have been used for this in the objective function: $\lambda_1 = 500$ and $\lambda_2 = 10$. Thus, in this case the emphasis is on minimizing the number of vehicles. The results show that two belt loaders are used, which is indeed the minimum required number of belt loaders, as two belt loaders are required simultaneously per flight. All tasks are executed within the time windows, i.e. the start time and end time values are between ET and LT. The start and end times also correspond to the distances driven and the speed of the vehicles. A total distance of 2450 meters is driven. With the energy consumption being 0.33 kWh/km, this results in an energy consumption for driving of 0.81 kWh. A total of 3.86 kWh was used to operate the belt of the loader belt, which is correct given the total task time of 232 minutes and the energy consumption of $\frac{X}{60}$ kWh.

Table 3.5: *The post-processed task list for the base scenario.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
10	P	S	P_BEL_005	0	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
12	F	B	A1	0	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
14	F	B	A2	0	661	703	42	0	661	703		0.70	65	0.02	19.43	18.73
17	F	B	D1	0	751	798	46	0	751	797		0.77	460	0.15	18.58	17.81
9	P	E	P_BEL_004	0	1559	1560	0	0	(799)	1560		0.00	500	0.17	17.65	17.65
8	P	S	P_BEL_004	1	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
13	F	B	A1	1	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
15	F	B	A2	1	661	703	42	0	661	703		0.70	65	0.02	19.43	18.73
16	F	B	D1	1	751	798	44	0	751	795		0.73	460	0.15	18.58	17.85
11	P	E	P_BEL_005	1	1559	1560	0	0	(797)	1560		0.00	500	0.17	17.69	17.69
Total				**2**			**232**					**3.86**	**2450**	**0.81**		

3.4.2. Verification tests

This section discusses seven verification tests. For each test, only one element is adjusted compared to the scenario of the previous run. The changes from the previous verification tests are therefore built upon. For each test, the change is first discussed, then the expected impact is discussed and finally the solution found by the model is discussed and compared with the expectation.

Test 1: Moving one flight

Change: For this test, the Transavia (HV) flight will be moved one and a half hour later, so that it coincides with the TUI (OR) flight. This results in an adjusted flight schedule, as can be seen in Table 3.6.

Table 3.6: *The flight schedule data for verification test 1.*

A/D Indicator	A/D Flight Number	Airline	A/C Type	Stand	SIBT	SOBT
FT	4457_4458	BA	E90	A1	09:00	10:00
FT	6276_6275	HV	73W	A2	12:30	13:30
FT	1694_1695	OR	73H	D1	12:30	13:30

Expectation: Because the last two flights in the flight schedule coincide, it is expected that two additional belt loaders will be needed to perform the four flight tasks that coincide. First, two of the four belt loaders can be used to handle the British Airways (BA) flight. After this they can continue with the Transavia (HV) flight. The other two belt loaders can go directly from the parking locations to the TUI (OR) flight and back again.

Outcome: Table 3.7 shows the optimal solution found by the model. As expected, four vehicles are used and two vehicles that serviced the British Airways (BA) flight, continue with the Transavia (HV) flight. Furthermore, the sum of the task times and the energy consumption on the aircraft stands has remained the same. This makes sense, since nothing has changed in the requirements for handling the flights. The distance driven has increased from 2450 to 2930 meters and the driving energy has therefore also increased from 0.81 to 0.97 kWh. The total energy consumption has therefore increased. On the other hand, all belt loaders end up with a SOC that is higher than in the base scenario. This can be explained by the fact that the tasks are divided over more belt loaders.

Table 3.7: *The post-processed task list for verification test 1.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
6	P	S	P_BEL_003	0	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
12	F	B	A1	0	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
15	F	B	A2	0	751	793	42	0	751	793		0.70	65	0.02	19.43	18.73
7	P	E	P_BEL_003	0	1559	1560	0	0	(793.8)	1560		0.00	200	0.07	18.67	18.67
4	P	S	P_BEL_002	1	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
13	F	B	A1	1	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
14	F	B	A2	1	751	793	42	0	751	793		0.70	65	0.02	19.43	18.73
1	P	E	P_BEL_000	1	1559	1560	0	0	(793.8)	1560		0.00	200	0.07	18.67	18.67
0	P	S	P_BEL_000	2	0	1560	0	0	0	749		0.00	0	0.00	20.00	20.00
16	F	B	D1	2	751	798	44	0	751	795		0.73	500	0.17	19.84	19.10
5	P	E	P_BEL_002	2	1559	1560	0	0	(797)	1560		0.00	500	0.17	18.94	18.94
2	P	S	P_BEL_001	3	0	1560	0	0	0	749		0.00	0	0.00	20.00	20.00
17	F	B	D1	3	751	798	46	0	751	797		0.77	500	0.17	19.84	19.07
3	P	E	P_BEL_001	3	1559	1560	0	0	(799)	1560		0.00	500	0.17	18.90	18.90
Total				**4**			**232**					**3.86**	**2930**	**0.97**		

Test 2: Distributing the belt loaders

Change: For this test, the belt loaders are distributed over two starting locations at the airport. Two of the parking spaces will be moved to location group E. The other four parking spaces will remain within location group F. This results in the distribution shown in Table 3.8.

Table 3.8: *The GSE location group distribution for verification test 2.*

Location	Location group
P_BEL_000	E
P_BEL_001	E
P_BEL_002	F
P_BEL_003	F
P_BEL_004	F
P_BEL_005	F

Expectation: Because nothing has changed in the flight schedule, it is expected that four belt loaders will be used again. However, due to the distribution of the belt loaders across the airport, it is now expected that the belt loaders parked at location group F will perform the flight tasks on aircraft stands A1 and A2 and the belt loaders parked at location group E will perform the flight tasks on aircraft stand D1. This is due to minimizing the distance to be traveled.

Outcome: Table 3.9 shows the optimal solution found by the model. As expected, four belt loaders are still used. It can be seen that the belt loaders that perform the flight tasks on aircraft stands A1 and A2 start at P_BEL_002 and P_BEL_003. These are located in location group F (see Table 3.8). The belt loaders that perform the flight tasks on aircraft stand D1 come from P_BEL_001 and P_BEL_000. These are located in location group E (see Table 3.8). This can be explained by the fact that the distance to aircraft stand D1 is shorter from location group E. By distributing the vehicles differently across the airport, the traveled distance is reduced from 2930 to 2050 meters.

Table 3.9: *The post-processed task list for verification test 2.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
4	P	S	P_BEL_002	0	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
12	F	B	A1	0	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
15	F	B	A2	0	751	793	42	0	751	793		0.70	65	0.02	19.43	18.73
5	P	E	P_BEL_002	0	1559	1560	0	0	(793.8)	1560		0.00	200	0.07	18.67	18.67
6	P	S	P_BEL_003	1	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
13	F	B	A1	1	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
14	F	B	A2	1	751	793	42	0	751	793		0.70	65	0.02	19.43	18.73
7	P	E	P_BEL_003	1	1559	1560	0	0	(793.8)	1560		0.00	200	0.07	18.67	18.67
2	P	S	P_BEL_001	2	0	1560	0	0	0	749.88		0.00	0	0.00	20.00	20.00
16	F	B	D1	2	751	798	44	0	751	795		0.73	280	0.09	19.91	19.18
1	P	E	P_BEL_000	2	1559	1560	0	0	(796.12)	1560		0.00	280	0.09	19.09	19.09
0	P	S	P_BEL_000	3	0	1560	0	0	0	749.88		0.00	0	0.00	20.00	20.00
17	F	B	D1	3	751	798	46	0	751	797		0.77	280	0.09	19.91	19.14
3	P	E	P_BEL_001	3	1559	1560	0	0	(798.12)	1560		0.00	280	0.09	19.05	19.05
Total				**4**			**232**					**3.86**	**2050**	**0.68**		

Test 3: Moving one flight

Change: For this test, the Transavia (HV) flight will be moved, so that it coincides with the British Airways (BA) flight. This results in an adjusted flight schedule, as can be seen in Table 3.10.

Table 3.10: *The flight schedule data for verification test 3.*

A/D Indicator	A/D Flight Number	Airline	A/C Type	Stand	SIBT	SOBT
FT	4457_4458	BA	E90	A1	09:00	10:00
FT	6276_6275	HV	73W	A2	09:00	10:00
FT	1694_1695	OR	73H	D1	12:30	13:30

Expectation: Because the first two flights in the flight schedule coincide, it is expected that four belt loaders will be used again. First, the four belt loaders can be used to handle the simultaneous flights at A1 and A2. After this two of them can continue with the TUI (OR) flight. (Because all four belt loaders must come from location group A, it does not matter for the distance which vehicles are going to D1. Without the use of location groups, these would be the two belt loaders on stand A1.) The other two belt loaders can return to the parking area. Because the distance from D1 to location group E is 220 meters shorter than to location group F, it is expected that the two vehicles going to D1 will park at location group E when they are finished. This is only possible if two vehicles have also left here.

Outcome: Table 3.11 shows the optimal solution found by the model. As expected, four vehicles are used again and two vehicles travel from location group A to D1 to continue with the TUI (OR) flight. In this case these are belt loaders 0 and 2, but this could also have been a different combination without affecting the total distance traveled. The total traveled distance has increased from 2050 to 2770 meters.

Table 3.11: *The post-processed task list for verification test 3.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
2	P	S	P_BEL_001	0	0	1560	0	0	0	540.02		0.00	0	0.00	20.00	20.00
12	F	B	A2	0	541	583	42	0	541	583		0.70	245	0.08	19.92	19.22
17	F	B	D1	0	751	798	46	0	751	797		0.77	460	0.15	19.07	18.30
1	P	E	P_BEL_000	0	1559	1560	0	0	(798.12)	1560		0.00	280	0.09	18.20	18.20
10	P	S	P_BEL_005	1	0	1560	0	0	0	540.2		0.00	0	0.00	20.00	20.00
13	F	B	A2	1	541	583	42	0	541	583		0.70	200	0.07	19.93	19.23
9	P	E	P_BEL_004	1	1559	1560	0	0	(583.8)	1560		0.00	200	0.07	19.17	19.17
8	P	S	P_BEL_004	2	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
14	F	B	A1	2	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
16	F	B	D1	2	751	798	44	0	751	795		0.73	460	0.15	19.30	18.57
3	P	E	P_BEL_001	2	1559	1560	0	0	(796.12)	1560		0.00	280	0.09	18.48	18.48
0	P	S	P_BEL_000	3	0	1560	0	0	0	542.02		0.00	0	0.00	20.00	20.00
15	F	B	A1	3	543	572	29	0	543	572		0.48	245	0.08	19.92	19.44
11	P	E	P_BEL_005	3	1559	1560	0	0	(572.8)	1560		0.00	200	0.07	19.37	19.37
Total				**4**			**232**					**3.86**	**2770**	**0.91**		

Test 4: Changing the objective function

Change: For this test, the values of the parameters λ_1 and λ_2 are changed to $\lambda_1 = 10$ and $\lambda_2 = 500$. Thus, in this case the emphasis is on minimizing the total traveled distance.

Expectation: If there is a solution that leads to a lower total traveled distance, then more than four vehicles should be used for this, because the solution with the minimum number of vehicles was also (to a lesser extent) optimized for the distance.

Outcome: Table 3.12 shows the optimal solution found by the model. A solution has been found with a lower total traveled distance. The reduction in the total traveled distance in the solution is 50 meters. However, two additional vehicles are required. As a result, one vehicle is now used per flight task.

Table 3.12: *The post-processed task list for verification test 4.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
8	P	S	P_BEL_004	0	0	1560	0	0	0	540.2		0.00	0	0.00	20.00	20.00
12	F	B	A2	0	541	583	42	0	541	583		0.70	200	0.07	19.93	19.23
11	P	E	P_BEL_005	0	1559	1560	0	0	(583.8)	1560		0.00	200	0.07	19.17	19.17
6	P	S	P_BEL_003	1	0	1560	0	0	0	540.2		0.00	0	0.00	20.00	20.00
13	F	B	A2	1	541	583	42	0	541	583		0.70	200	0.07	19.93	19.23
9	P	E	P_BEL_004	1	1559	1560	0	0	(583.8)	1560		0.00	200	0.07	19.17	19.17
4	P	S	P_BEL_002	2	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
14	F	B	A1	2	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
7	P	E	P_BEL_003	2	1559	1560	0	0	(572.8)	1560		0.00	200	0.07	19.39	19.39
10	P	S	P_BEL_005	3	0	1560	0	0	0	542.2		0.00	0	0.00	20.00	20.00
15	F	B	A1	3	543	572	29	0	543	572		0.48	200	0.07	19.93	19.45
5	P	E	P_BEL_002	3	1559	1560	0	0	(572.8)	1560		0.00	200	0.07	19.39	19.39
2	P	S	P_BEL_001	4	0	1560	0	0	0	749.88		0.00	0	0.00	20.00	20.00
16	F	B	D1	4	751	798	44	0	751	795		0.73	280	0.09	19.91	19.18
3	P	E	P_BEL_001	4	1559	1560	0	0	(796.12)	1560		0.00	280	0.09	19.09	19.09
0	P	S	P_BEL_000	5	0	1560	0	0	0	749.88		0.00	0	0.00	20.00	20.00
17	F	B	D1	5	751	798	46	0	751	797		0.77	280	0.09	19.91	19.14
1	P	E	P_BEL_000	5	1559	1560	0	0	(798.12)	1560		0.00	280	0.09	19.05	19.05
Total				**6**			**232**					**3.86**	**2720**	**0.90**		

Test 5: Changing to a GSE type with a logistics function

Change: For this test, the belt loaders are replaced by two water trucks. At the start of the day, the water trucks are parked without water at location group E. The logistics location to refill the water trucks is located at location group G. A water truck can carry 1500 liters of water and can be filled at a rate of 220 L/min. The three flights in the flight schedule require 61, 63 and 65 liters of water respectively. The water truck requires 5 minutes and 0.01 kWh for these amounts. Driving requires 1.33 kWh/km. The water trucks have a battery capacity of 40 kWh.

Table 3.13 shows the three new locations with their location groups. The task list for this verification test is shown in Table 3.14. The three logistics tasks that are linked to the three flight tasks have been added.

Table 3.13: *The GSE location group distribution for verification test 5.*

Location	Location group
P_WAT_000	E
P_WAT_001	E
L_WAT_000	G

Table 3.14: *The task list for verification test 5.*

Task ID	Task type	SBE type	Task name	Location ID	Location nr.	Aircraft type	DEM	EC	ET	LT	TT
0	P	S	P_WAT_000	P_WAT_000	0	N/A	0	0	0	1560	0
1	P	E	P_WAT_000	P_WAT_000	0	N/A	0	0	1559	1560	0
2	P	S	P_WAT_001	P_WAT_001	1	N/A	0	0	0	1560	0
3	P	E	P_WAT_001	P_WAT_001	1	N/A	0	0	1559	1560	0
4	L	B	4457_4458_0	L_WAT_000	0	N/A	0	0	531	555	0
5	L	B	6276_6275_0	L_WAT_000	0	N/A	0	0	531	570	0
6	L	B	1694_1695_0	L_WAT_000	0	N/A	0	0	741	785	0
7	F	B	4457_4458_0	A1	0	E90	61	0.01	541	560	5
8	F	B	6276_6275_0	A2	0	73W	63	0.01	541	575	5
9	F	B	1694_1695_0	D1	0	73H	65	0.01	751	790	5

Expectation: Considering the time windows of the flight tasks in Table 3.14, it is possible to do all flight tasks with only one vehicle. Due to the large distance to location group G, it is expected that this will also happen. The water truck is therefore expected to first go to the logistics location to collect water. After this, the flight tasks will be completed one by one. In contrast to the previous scenarios, it will no longer be possible to execute all flight tasks at the start (ET) of the time window.

Outcome: Table 3.15 shows the optimal solution found by the model. As expected, one vehicle is indeed used. This vehicle first goes to a logistics location to collect water. Due to the assumption made during the development of the model (see Section 3.1.5), the water truck is filled until it is completely full. The water truck then completes all flight tasks one by one. The flight task on aircraft stand A2 is executed just over 5 minutes after the start of the time window. This can be explained because the water truck first carries out the flight task on aircraft stand A1. In the "load" column it can be seen that the water truck is becoming increasingly empty. In the end, there are still 1311 liters of water left when it has finished the three flight tasks.

Table 3.15: *The post-processed task list for verification test 5.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
0	P	S	P_WAT_000	0	0	1560	0	0	0	531.59		0	0	0.00	40.00	40.00
4	L	B	L_WAT_000	0	531	555	0	0	533.09	539.84	1500	0	375	0.50	39.50	39.50
7	F	B	A1	0	541	560	5	61	541	546	1439	0.01	290	0.39	39.12	39.11
8	F	B	A2	0	541	575	5	63	546.26	551.26	1376	0.01	65	0.09	39.02	39.01
9	F	B	D1	0	751	790	5	65	751	756	1311	0.01	460	0.61	38.40	38.39
1	P	E	P_WAT_000	0	1559	1560	0	0	(757.12)	1560	1311	0	280	0.37	38.01	38.01
Total				**1**				**189**				**0.03**	**1470**	**1.96**		

Test 6: Changing the rolling horizon parameters

Change: For this test, the values of the parameters $t_{forward}$ and t_{update} are changed to $t_{forward}$ = 120 min and t_{update} = 30 min. Given the time between the first two flights and the third flight (3.5 hours), the third flight is not included in the optimization run with the first two flights.

Expectation: Due to the value of $t_{forward}$, the flight tasks on aircraft stands A1 and A2 will already be assigned before the flight task on aircraft stand D1 "becomes known". The moment the flight task at aircraft stand D1 is assigned, the water truck "starts" in location group A, because it ended there earlier. From here it is shorter in terms of distance to drive to aircraft stand D1 and then return to the parking area (740 meters), than for a new vehicle to depart from location group E, to get water at location group G, go to aircraft stand D1, and then go back to the parking area at location group E. This route would be 1245 meters long. In this case, no difference is expected in the solution, because the vehicle continues straight from location group A to aircraft stand D1, since this yields the shortest total traveled distance.

Outcome: Table 3.16 shows the optimal solution found by the model. The distance driven and the number of vehicles used have remained the same as expected. The model has chosen to perform the flight task on aircraft stand A2 first this time. This does not matter for the end result.

Table 3.16: *The post-processed task list for verification test 6.*

Task ID	Task type	SBE type	Location ID	Vehicle	ET	LT	TT	DEM	Start time	End time	Load	Task EC	Distance	Driving EC	Start SOC	End SOC
0	P	S	P_WAT_000	0	0	1560	0	0	0	531.59		0	0	0.00	40.00	40.00
5	L	B	L_WAT_000	0	531	570	0	0	533.09	539.84	1500	0	375	0.50	39.50	39.50
8	F	B	A2	0	541	575	5	63	541	546	1437	0.01	290	0.39	39.12	39.11
7	F	B	A1	0	541	560	5	61	546.26	551.26	1376	0.01	65	0.09	39.02	39.01
9	F	B	D1	0	751	790	5	65	751	756	1311	0.01	460	0.61	38.40	38.39
1	P	E	P_WAT_000	0	1559	1560	0	0	(757.12)	1560	1311	0	280	0.37	38.01	38.01
Total				**1**				**189**				**0.03**	**1470**	**1.96**		

Test 7: Moving the logistics location

Change: For this test, the logistics location is moved from location group G to E. Table 3.17 shows the three new locations with their location groups.

Table 3.17: *The GSE location group distribution for verification test 7.*

Location	Location group
P_WAT_000	E
P_WAT_001	E
L_WAT_000	E

Expectation: The change implemented for this verification test creates a combination of circumstances that will demonstrate that overall optimality cannot be guaranteed when using the rolling horizon. Just like in the previous verification test, a water truck will end up at location group A before it becomes known to the model that there will be a third flight task on aircraft stand D1. Because the focus for optimization is on minimizing the distance, a suboptimal decision is expected for executing the flight task on aircraft stand D1. Now that the logistics location has been moved to location group E, it is better in terms of distance to have a new vehicle drive from location group E to D1. This route (E-D-E) is 560 meters in total, while the alternative route (A-D-E) would be 740 meters.

Outcome: Table 3.18 shows the optimal solution found by the model. As expected, an additional vehicle is used to perform the flight task on aircraft task D1. The total traveled distance is 1115 meters. In an overall optimal solution the shortest route (E-A1-A2-D-E) would be 1050 meters. This would also eliminate the need for the additional vehicle. However, because the model does not know halfway through the rolling horizon whether new flight tasks are coming up, the distance from location group A back to the parking area at location group E is not included. The result is that a solution has now been generated that has a higher total traveled distance and it uses an extra vehicle.

Note: It is important to note that a sub-optimal solution such as this will not occur quickly. It requires a number of decisions that would not be made in a realistic scenario. For example, with a flight schedule of this size, a rolling horizon with these parameters would not be realistic. In addition, in reality it will not often happen that there is such a strong focus on minimizing the distance, without taking into account the number of vehicles used. Nevertheless, when using the rolling horizon, it is important to keep in mind that the overall solution may not be optimal.

Table 3.18: *The post-processed task list for verification test 7.*

Task ID	**Task type**	**SBE type**	**Location ID**	**Vehicle**	**ET**	**LT**	**TT**	**DEM**	**Start time**	**End time**	**Load**	**Task EC**	**Distance**	**Driving EC**	**Start SOC**	**End SOC**
0	P	S	P_WAT_000	0	0	1560	0	0	0	533.27		0	0	0.00	40.00	40.00
4	L	B	L_WAT_000	0	531	555	0	0	533.27	540.02	1500	0	0	0.00	40.00	40.00
7	F	B	A1	0	541	560	5	61	541	546	1439	0.01	245	0.33	39.67	39.66
8	F	B	A2	0	541	575	5	63	546.26	551.26	1376	0.01	65	0.09	39.58	39.57
1	P	E	P_WAT_000	0	1559	1560	0	0	(552.24)	1560	1376	0	245	0.33	39.24	39.24
2	P	S	P_WAT_001	1	0	1560	0	0	0	743.13		0	0	0.00	40.00	40.00
6	L	B	L_WAT_000	1	741	785	0	0	743.13	749.88	1500	0	0	0.00	40.00	40.00
9	F	B	D1	1	751	790	5	65	751	756	1435	0.01	280	0.37	39.63	39.62
3	P	E	P_WAT_001	1	1559	1560	0	0	(757.12)	1560	1435	0	280	0.37	39.25	39.25
Total				**2**				**189**				**0.03**	**1115**	**1.48**		

3.4.3. Conclusion

In all verification tests, the results were consistent with the expectations. The tests that have been carried out have tested and verified the operation of all important elements of the model. The verification of the computerized model is therefore considered successful.

3.5. Summary

This chapter has discussed the development of the mathematical that can be used to model and optimize GSE operations. This allows for the answering of SQ 5: *"How can the Ground Support Equipment operations be modeled?"*.

A Task Scheduling Problem (TSP) was employed, distinguishing three types of tasks: 1.) parking tasks, 2.) flight tasks, and 3.) logistics tasks. Logistics tasks are exclusively utilized by GSE types that also operate at logistics locations. The TSP is solved using Mixed-Integer Linear Programming (MILP). To achieve this, a multi-objective function is employed, encompassing the total number of vehicles used and the total distance traveled by these vehicles. A rolling horizon approach, together with additional solvability improvements, is utilized to obtain high-quality, feasible solutions for large-scale instances. Post-processing is applied to determine the energy consumption by the vehicles after each run as part of the rolling horizon approach. This facilitates the removal of vehicles from the operation during the day if they have a depleted battery. The conceptual model has been validated and the correct implementation of it has been verified. The operational validation will be performed in Chapter 4.

4
Case study

This chapter includes the case study that is conducted at Amsterdam Airport Schiphol (AAS), based on KLM's GSE fleet. First, the relevant details about AAS will be explained in Section 4.1. After that, Section 4.2 contains the details about KLM Ground Services. The model input that is used for the case study is explained in Section 4.3. After that, the developed model is validated for non-logistics, and logistcs GSE types in Section 4.4 and Section 4.5, respectively. Finally, Section 4.6 provides a summary of this chapter, together with an answer to SQ 6.

4.1. Amsterdam Airport Schiphol

This section provides an introduction to Amsterdam Airport Schiphol (AAS). First, the history and an overview of AAS is provided in Section 4.1.1. After that, Section 4.1.2 elaborates on the infrastructure and layout of AAS. The traffic demand at AAS, together with the underlying details, will be explained in Section 4.1.3.

4.1.1. History and overview of Amsterdam Airport Schiphol

Amsterdam Airport Schiphol is one of the oldest international airports in the world. It started over 100 years ago, on 19 September 1916, when the first aircraft, a military plane, landed in the polder of the drained Haarlemmermeer (Lake Haarlem). It marked the start of AAS's service as a military airfield (Royal Schiphol Group, n.d.-b). The Royal Dutch Airlines (KLM) was founded on 7 October 1919. The first KLM flight is operated with a leased aircraft from London to Amsterdam Airport Schiphol. On board are 2 journalists, a letter from the Mayor of London to his Amsterdam counterpart, and a stack of newspapers (KLM Royal Dutch Airlines, n.d.-b). In August 1920, KLM purchases two aircraft, a Fokker F-II and F-III (Royal Schiphol Group, n.d.-b), and after a winter break, KLM resumes its service with its own pilots and aircraft on 4 April 1921 (KLM Royal Dutch Airlines, n.d.-b). At the end of its first few years, AAS still has no paved runways, which is a problem, because the groundwater level is high, and aircraft are becoming heavier (Royal Schiphol Group, n.d.-b).

As of 1 April 1926, AAS belongs to the municipality of Amsterdam. Until this moment, the airport was still the property of the Ministry of War. It marks the start of the high-speed development of the airport. The field and the access roads are improved, a new concrete platform is poured and the first terminal is built, together with an air traffic control tower. During the Second World War, several strategic targets, including AAS, are bombed. The Germans quickly repair the damage and the airport becomes a German air force base. Because AAS is now a key airport for the Germans, 200 American bombers target the airport on 13 December 1943. A completely destroyed airport is what remains at the end of the Second World War. However, the airport is rebuild in a few months, and on 8 July 1945 the first plane lands at a resurrected AAS (Royal Schiphol Group, n.d.-b).

In 1949, airport manager Jan Dellaert presents his plans for the expansion of AAS. His plan (see Figure 4.1) is based on a tangential runway system with a central terminal building, and it forms the basis for AAS as it is know nowadays. The aim of the design is to ensure that flights can always land, despite the notoriously shifting winds over the Netherlands. In 1967, the renewed AAS opens. It is smaller than planned by Dellaert, but the main thoughts have remained (Royal Schiphol Group, n.d.-b). Passenger and ground handling are now separated from one another, with passengers leaving the aircraft via the Passenger Boarding Bridge (PBB), while ground handling takes place down below (KLM Royal Dutch Airlines, n.d.-b).

Figure 4.1: *Jan Dellaert presenting his design (Royal Schiphol Group, n.d.-b).*

Figure 4.2: *The new terminal building that is opened in 1975 (Royal Schiphol Group, n.d.-b).*

In the meantime, jet engines are introduced and in January 1971, KLM's first Boeing 747 arrives at AAS, marking the start of the Wide-Body age at KLM (KLM Royal Dutch Airlines, n.d.-b). The volume of air traffic increases dramatically, and in 1975 a new terminal building, twice the size of the one it is replacing, is opened to facilitate the jumbo jets (see Figure 4.2) (Royal Schiphol Group, n.d.-b). In the next decade, the hub-and-spoke concept becomes more and more the standard and AAS becomes one of the largest European hub airports. Nowadays, the airport is still developing. According to Royal Schiphol Group (n.d.-c), the ambition is to become "the world's most sustainable, high quality airport, that allows international trade, tourism and knowledge exchange to flourish by providing top-quality aviation infrastructure and air transport facilities for passengers and cargo".

4.1.2. Airport infrastructure and layout

This section discusses the locations and the layout of AAS relevant to this study. First the different aprons and their application will be discussed. After that, the GSE's logistics locations will be discussed. Finally, the road network will be discussed.

Aprons

There are different types of aprons at AAS (see Figure 4.3). Most aprons are aimed at passenger aircraft, but there are also aprons specifically for cargo aircraft. There are also differences within the group of aprons for passenger aircraft. A distinction can be made between aprons with connected, semi-connected and remote aircraft stands. The connected stands are contact stands and therefore equipped with a PBB. The semi-connected stands do not have a PBB, but do have a staircase that leads directly into the terminal building. Passengers must therefore exit the plane via stairs and walk a short distance to the stairs of the terminal. The remote stands are located further away from the terminal building and require buses to transport passengers between the stand and the terminal. A number of aprons are used for remote handling, but there are also aprons that only have a buffer function. Here, aircraft can be parked temporarily.

Apart from the different use cases of the aircraft stands, there are also differences that influence the required GSE. Fixed GPUs are currently installed on the north side of the D-pier and the F-, G- and E-piers. Mobile GPUs are required on the other piers. The first electric GPUs are used on the inside of the D-pier. This has to do with the wind and particulate matter at this location (Business Contract Manager GSE I). In addition, the E- and F-pier have electric ACUs. Electric ACUs can also be used on the D-pier. There are mobile diesel units on the A-platform that can be placed at the aircraft stand on request (Business Contract Manager GSE I). The availability of fuel hydrants also varies. The aprons around the terminal building are all equipped with fuel hydrants, except for the A- and G-platforms. And due to the absence of fixed infrastructure on the A-platform, there are two strips with power-in power-out stands, so no pushback tug is required there (Business Contract Manager GSE II).

Figure 4.3: *Different aprons and piers at AAS (Royal Schiphol Group, 2023b) (adapted from Royal Schiphol Group (n.d.-a)).*

Logistics locations

Figure 4.4 shows the logistics locations for the different GSE types at AAS. The three-letter codes correspond to the abbreviations as introduced in Table 2.1. The following locations can be distinguished:

- There is a gas station at the G-pier where the GSE that runs on diesel can refuel. With a few exceptions, all motorized diesel equipment refuels here. A number of vehicles and the diesel GPUs are refuelled by a fuel truck.The fuel bowsers for the aircraft are refueled in their own area (Business Contract Manager GSE II).
- A number of locations with bus gates are distributed throughout the terminal area. In the figure only the groups of bus gates are indicated. Which bus gate is used depends, among other things, on the distinction between Schengen and non-Schengen flights. This process is further explained in Section 4.1.3.

- The point where the water trucks can refill the water and discharge the drain water is located below the F-pier building.
- At AAS there are three basements where baggage is processed. There is one basement located between the C- and D-pier. Many European flights are handled in the basement under the D-pier and the basement where all intercontinental flights are handled is located under the entire E-pier. The figure only indicates the location of the basements. There are different entrances and exits for the GSE per basement (Business Contract Manager GSE II). These are not indicated in the figure.
- The building where the catering trucks are emptied and supplied is located between the A- and B-piers. Unloading takes place on the landside side and loading takes place on the airside side of the facility.
- Next to the A-platform is the cargo handling facility. Pallets and ULDs are brought and collected here.
- On the side of the A-platform is the location where the lavatory service vehicles can be emptied and filled with cleaning fluids and water.
- On the side of the S-platform is the location where the fuel bowsers are refilled with kerosene and where they are refueled themselves. These fuel bowsers are only needed in places where no fuel hydrants are installed in the apron.

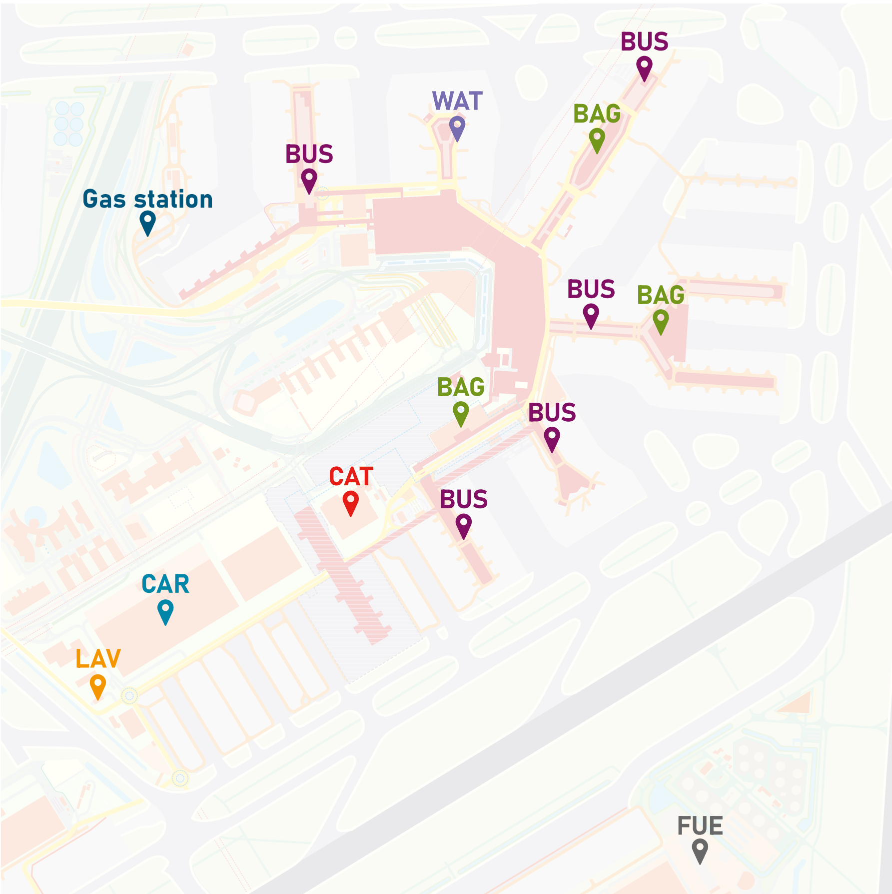


Figure 4.4: *An overview of the logistics locations for GSE at AAS (adapted from Royal Schiphol Group (n.d.-a)).*

Road network

At AAS, every platform or pier can be reached via the ring road (the Rinse Hofstraweg) that runs along the edge of the main terminal building. There are also roads along the contours of the piers that make it possible to reach the aircraft stands. A maximum speed of 30 km/h applies on these roads (Business Contract Manager GSE I). There is also a road across the apron towards the buffer (D/E-platform in Figure 4.3). This road may only be used if you have to go to or leave the buffer.

Driving on the aircraft stands themselves is only permitted if you need to be on the aircraft stand itself. The roads must therefore be used to drive from aircraft stand to aircraft stand, except if you need to be at the adjacent aircraft stand. There is no absolute maximum speed on the aircraft stands. The rule that is adhered to is that you drive at a walking pace. In the case of KLM this boils down to 11 km/h (Business Contract Manager GSE I).

The parking and charging places for electric vehicles are currently the same at AAS (Business Contract Manager GSE I). There are parking spaces for smaller (electric) vehicles along the piers. At other dedicated locations there is parking space for larger vehicles. Vehicles that run on diesel can choose their own parking space. The electric vehicles must be parked in a parking lot that is equipped with the right type of charger. A number of GSE types are excepted and have their own specific loading or tank position (Business Contract Manager GSE I).

4.1.3. Traffic demand

As an airport, AAS has a hub function in a network of destinations. This is reflected in the statistics regarding passengers and air traffic movements. This section discusses the development of these numbers over the years. In addition, attention is paid to the operational impact that the hub function entails and the way in which aircraft stand allocation on AAS is arranged.

Passengers and Air Traffic Movements

AAS has been growing almost ceaselessly in terms of passengers and ATMs for the past decades. The attacks on 9/11 in the United States, the economic crisis in the period 2007-2009 and in particular the COVID-19 pandemic were three causes that temporarily halted growth, as can be seen in Figure 4.5. With 71,706,999 passengers, the record for handled passengers on AAS was broken in 2019. The number of ATMs also increased up to that point. Now, after the COVID-19 pandemic, the numbers are rapidly returning to their previous levels. However, at the time of writing, there is intense debate about the number of ATMs on AAS. In a letter to the House of Representatives in June 2022, the Ministry of Infrastructure and Water Management explained that it wanted to reduce the maximum number of ATMs from 500,000 to 440,000 (Government of the Netherlands, 2022). In September 2023 it became clear that the reduction to 440,000 might be changed to 452,500 (Government of the Netherlands, 2023a). It was later announced in November 2023 that the reduction of ATMs at AAS would not proceed at all for the time being, following the stance taken by the European Commission, the United States and Canada (Government of the Netherlands, 2023b).

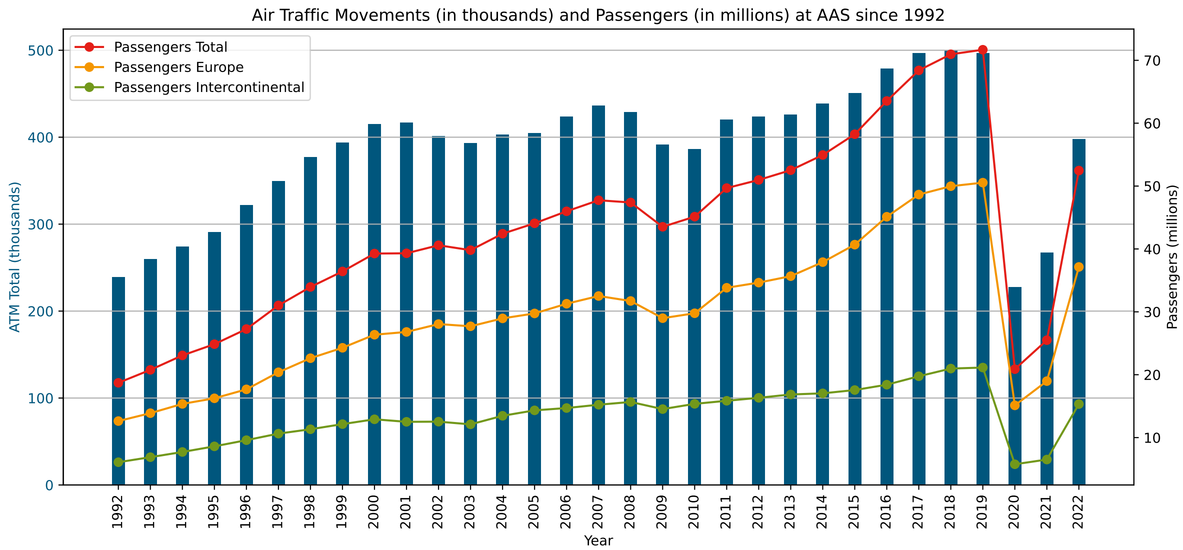


Figure 4.5: *Air traffic movements and passengers at AAS since 1992 (Royal Schiphol Group, 2023a).*

AAS uses a summer and winter schedule. The summer schedule is effective from the last Sunday of March until the last Sunday of October, and the winter schedule is effective from the last Sunday of October until the last Sunday of March (Royal Schiphol Group, 2022b). Figure 4.6 clearly shows that the number of ATMs in the summer period is much higher than in the winter period.

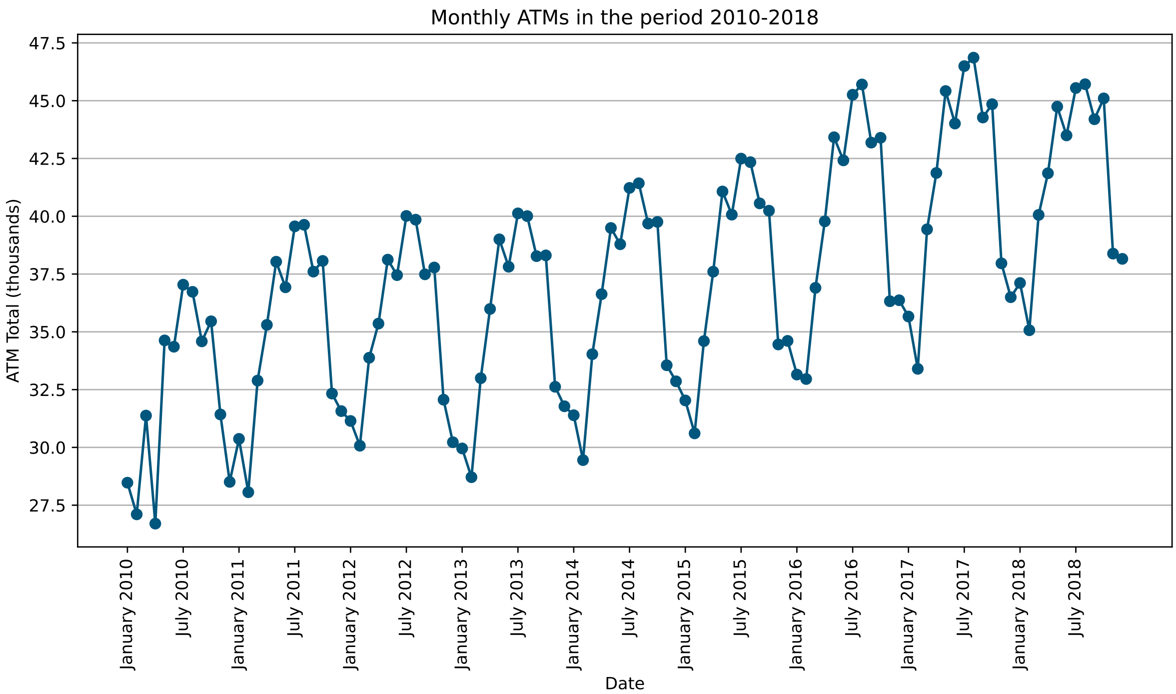


Figure 4.6: *Monthly air traffic movements at AAS between 2010 and 2018 (Royal Schiphol Group, 2023a).*

Hub function

In 2022, 36.7% of the passengers at AAS were transfer passengers (Royal Schiphol Group, 2022a). This is the result of AAS being the hub airport in the hub-and-spoke network of KLM and SkyTeam-partners such as Air France and Delta Airlines. Worldwide, AAS ranked third in terms of hub connectivity in 2022 (Royal Schiphol Group, 2022a). To optimize the transfer opportunities at AAS, KLM implemented inbound and outbound waves in the 1990's. Each wave consists of a sequential arrival of intercontinental and European flights, the departure of European flights, and finally the departure of intercontinental flights (Troquete, 2020). Seven of these waves can be distinguished, as shown in Figure 4.7. Because of these waves, there is a continuous alternation of busy and more quiet periods at AAS throughout the day.

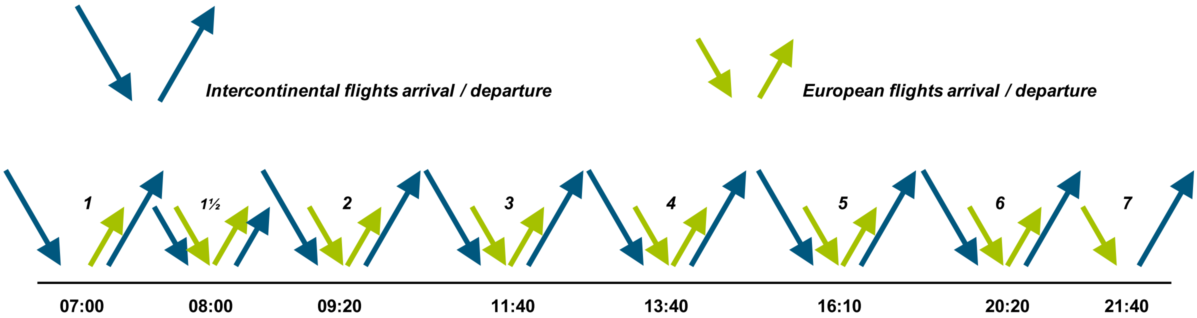


Figure 4.7: *KLM's in- and outbound peaks at AAS (adapted from Troquete (2020)).*

Stand allocation

At AAS, the "Regulation Aircraft Stand Allocation Schiphol (RASAS)" is used to assign the flights to the aircraft stands/gates. According to Royal Schiphol Group (2022b), the allocation process is subject to the following four restrictions:

1. Physical restrictions: AAS has aircraft stands of different dimensions, in categories from 1 to 10. This categorisation specifies each aircraft stand and aircraft separately. In addition to the physical restrictions, certain aircraft cannot be handled using aircraft stands for technical or safety reasons. AAS draws up an aircraft stand table that indicates the highest possible category for each stand and any handling restrictions applicable to certain stands.

   In practice, the A-platform is used by the Embraer fleet of KLM Cityhopper. Only NABO aircraft are handled on the B-, C- and H-piers. A mix of NABO and WIBO aircraft are handled on the D-pier, and the E-, F- and G-piers are primarily reserved for WIBO aircraft.

2. Borders and security: In accordance with the agreements between the Dutch State and foreign governmental authorities concerning the free movement of goods and persons, the terminal of AAS has been divided into zones. These zones distinguish between Schengen passengers (who are exempt from border control when travelling between Schengen countries) and non-Schengen passengers. In addition, within the non-Schengen area, there is a distinction between passengers from screened or unscreened airports/countries. Figure 4.3. shows which aprons are used for Schengen, non-Schengen or mixed operations.

3. Customs: Dutch customs has different types of checks that can be performed upon arriving at a gate at AAS. The applicable kind of check is based on either the origin of a flight or instructions from the Dutch government. These flights can only arrive at E17, E19, E22, E24, G05 and G08. Remote handling for these flights is not allowed.

4. Works: Due to projects, maintenance and (technical) failure stands can be U/S (Under Service), which could lead to less capacity.

4.1.4. Ground handling services

At AAS, six parties provide ground handling services for scheduled flights, which is, compared to other similar airports, quite a lot. They are Menzies, Aviapartner, Swissport, Viggo, Dnata and KLM. The first five parties only perform ground handling for third parties, while KLM is both a self-handler and it provides these services to third parties. In cargo and mail handling, five parties are active: WFS, Menzies World Cargo, Swissport Cargo, Dnata and Freshport. (Behrens et al., 2023).

Next to the above-mentioned companies, more companies at AAS can be considered as ground handlers, in other areas such as cleaning, catering, de-icing, and line maintenance. Some ground handlers also focus specifically on handling non-scheduled flights, such as private aircraft and small business traffic. In total, including the aforementioned, there are approximately 45 companies involved in various aspects of ground handling at AAS (Behrens et al., 2023).

The ground handlers for apron and baggage handling individually serve a minimum of four and a maximum of about twenty airlines. Behrens et al. (2023) found that KLM as a self-handler handles approximately 50% of the total number of passengers at AAS. This means that the other part of the 72 million passengers (as of 2019) is handled by the third-party handlers (Behrens et al., 2023).

Every ground handler at AAS must have a Licence to Operate (LtO). This LtO sets standards to create a safe, healthy working environment and ensure reliable, high-quality and sustainable ground handling. The ground handlers are obligated through the LtO to participate in a workgroup, leading to equipment pooling (Royal Schiphol Group, 2022c). It involves sharing the equipment needed by ground handlers to deliver ground handling services. KLM Ground Services and Viggo have made such an agreement on equipment pooling. Under equipment pooling, the equipment is leased from a third party, which is TCR at AAS. TCR ensures that the equipment is available to the ground handlers at the right time in return for a fee for this service. The idea behind equipment pooling is that it leads to more standardised operations. Furthermore, equipment pooling reduces the traffic on the apron. Figure 4.8 shows an eGPU that is part of the Schiphol Ground Power Unit Pool.

Figure 4.8: *An eGPU at AAS that is part of the Schiphol Ground Power Unit Pool.*

AAS is one of the users of the A-CDM concept (see Appendix B). The aim of A-CDM at AAS is to optimize the turnaround process in order to assure the best possible coordination of resources (Royal Schiphol Group, 2019). According to Royal Schiphol Group (2019), the Main Ground Handling Agency (MGHA) is responsible to make sure that ground handling processes are finished at TOBT and to keep the TOBT accurate during the turnaround process. This means that the MGHA must update the TOBT to reflect when all ground handling processes are expected to be ready, within a minimal accuracy of +/- 5 minutes. This includes processes for which the MGHA hired a subcontractor.

4.2. KLM Ground Services

KLM Ground Services is the main ground handler at AAS. This section contains information about the GSE fleet of KLM Ground Services, since the model will be applied to their GSE fleet in this case study. Section 4.2.1 discusses the current status regarding the electrification of the GSE fleet. Section 4.2.2 explains how the GSE is used and finally, Section 4.2.3 explains how the charging of eGSE is handled at KLM Ground Services.

4.2.1. KLM's GSE fleet

KLM Ground Services has a GSE fleet that can handle every part of an aircraft's turnaround cycle (i.e. no other ground handlers are needed to service airlines that have a contract with KLM Ground Services) (Business Contract Manager GSE I). One exception to this are the buses for passenger transport, which are owned by AAS. Not all GSE vehicles can be used for all aircraft. For example, three types of belt loaders are used at KLM. One type for the WIBOs, one type for the Boeing 737 and similar and one type for the Embraer fleet. The same principle applies to the pushback tugs that are used. There are also different sizes of these, suitable for different sizes of aircraft (Business Contract Manager GSE II).

A large part of KLM's GSE is already electric. At the time of writing, electric pushback tugs for smaller aircraft and a number of electric water and toilet trucks have recently come into use. Other vehicles such as belt loaders, baggage tugs, "semi-wide" deck loaders and about 50% of the passenger cars have been electric for some time. Vehicles such as fuel bowsers, dispenser trucks, "wide" deck-loaders, pallet transporters, larger aircraft tugs and cargo tugs currently still run on diesel, but are scheduled to be electrified. This is currently being worked on for the "wide" deckloaders and cargo tugs (Contract Manager GSE).

Part of the GSE used by KLM Ground Services is part of an equipment pool with Viggo. This pool includes several loader-transporters, deck loaders, cargo transporters, belt loaders and stairs. Viggo can therefore also use this equipment to handle airlines with which they have a contract.

4.2.2. KLM's GSE operations

At KLM, the crew members are assigned to a flight for handling. For this purpose, there are people in the office per department (baggage, pushback, etc.) who have an overview of the range of flights, the work schedules and the availability of everyone. A number of types of vehicles may be used "freely" by the persons assigned to a flight and other vehicles are linked to a person during his shift (Business Contract Manager GSE I). This concerns all services that are directly required in the turnaround process of the aircraft. In addition, there is equipment in use for the additional tasks needed to keep the operation running. For example, on every pier there is someone ("bovenrijder") with a tug who can do the "fast" actions such as moving stairs, GPUs, PCAs and the like. Another process that requires "extra" equipment is the towing of aircraft to buffer stands or MRO locations.

In principle, the Ground Operations Manual Schiphol (GOMS) is used to service a flight. This is the turnaround table (per aircraft type) in which the standard times per process for handling a flight are included. A distinction is made between "separate arrivals", "separate departures" and "full turnarounds". It has also been determined for a number of GSE types how many are required for a flight, based on the number of passengers or pieces of baggage. However, there are several scenarios in which these pre-established protocols are deviated from:

- Some processes can and are carried out in a flexible manner by KLM. This is especially possible if an aircraft is on the ground for longer than its minimum turnaround time. For example, it is possible to refuel an aircraft well before departure, or to collect the remaining catering from an aircraft later. There are also processes that can sometimes be skipped, such as topping up water, if it turns out that there is still enough of it in the aircraft to carry out another flight.
- As a result of the efficient utilization of the available resources, certain services may not be performed or may be performed with less equipment. It is also possible that an aircraft, for example, is supplied with more water than is needed for the flight, so that it can perform another flight afterwards.
- The baggage process has an extremely large number of variables, compared to the variability in the other processes. If there are passengers on a flight with a short connection time (less than 70 minutes) to the next flight, "tail-to-tail" baggage tugs are used to transfer the baggage directly to the next aircraft. Sometimes up to six of these are needed on one flight. In addition, there is always one tug for baggage of the passengers that leave the airport and one for the regular transfer baggage. And there is also a lot of variability in the choice of which baggage basement is used. A lot of strategic choices are made for this, which are purely based on turnaround times and capacity availability of the basements (Business Contract Manager GSE II).

4.2.3. Charging of equipment

All eGSE used by KLM is fully charged overnight in any case. In principle, most vehicles should be able to last a full day on a full battery, but if it turns out to be necessary, opportunity charging can still be used during the day. The vehicles are then charged when there is time to do so. The belt loaders are the most critical here (Business Contract Manager GSE I). Around 90% of the eGSE fleet runs on lead-acid batteries and those batteries have been sized in such a way that it can easily last two shifts in a row. This is different for the next group of GSE that is being electrified: those vehicles require lithium-ion batteries, because lead-acid becomes too large and too heavy. These vehicles will have to be fast-charged (Contract Manager GSE). A number of vehicles are also equipped with a system of indication lights. At a battery percentage of 20% or lower, an orange light will illuminate. The vehicle then slows down and the task must be completed. As soon as the percentage falls below 10%, it can only be driven and the other functions are disabled. It will still have enough energy to drive to a charging point. For safety reasons, the 10% stated here is in fact 20% of the battery pack's capacity (Business Contract Manager GSE I).

It is not the case that every vehicle can use every charger. Each group of vehicles has its own type of charger. KLM has provided each type of vehicle with its own plug shape, so that the wrong charger cannot accidentally be connected to a vehicle. The maximum time is used for charging the vehicles with lead-acid batteries. The charging speed is tailored to the eight hours available at night. This is done to minimize the wear on the batteries as much as possible. This is also the aim for new vehicles with lithium-ion batteries, but charging will also have to take place during the day (Contract Manager GSE). For some vehicles, the charging areas are centered in one location. For other vehicles, the charging areas are spread throughout the airport.

4.3. Model input for the case study

This section elaborates on the input data that is used for the case study. Details on the flight schedule that will be used are provided in Section 4.3.1. The location groups and the definition of distances are discussed in Section 4.3.2.

4.3.1. Used flight schedule

The flight schedule used for the case study is determined based on the IATA Busy Day definition. As stated by IATA (2022), this can be done based on the monthly passengers or movements:

> *"This methodology defines the design day, or busy day, as the second busiest day in an average week during the peak month. To determine the average week, the monthly passengers or movements are divided by the number of weeks in the peak month, or are divided by the number of days of the month and multiplied by seven. The seven-day period (Monday through Sunday) that is closest to an average week is selected and the second busiest day of the week during that period is identified."*

Due to the nature of the research, in this case a day was selected based on the number of movements. Based on this definition, KLM has selected July 13, 2023 as IATA Busy Day. After this, the airlines handled by KLM Ground Services were first filtered, because only this data is relevant to this case study. This resulted in a flight schedule with a total of 735 ATMs. The graphs below only include these filtered flight movements. Figure 4.9 shows the number of ATMs in half-hour blocks. The peaks in arrival and departure movements, as explained in Section 4.1.3, become clear from this.

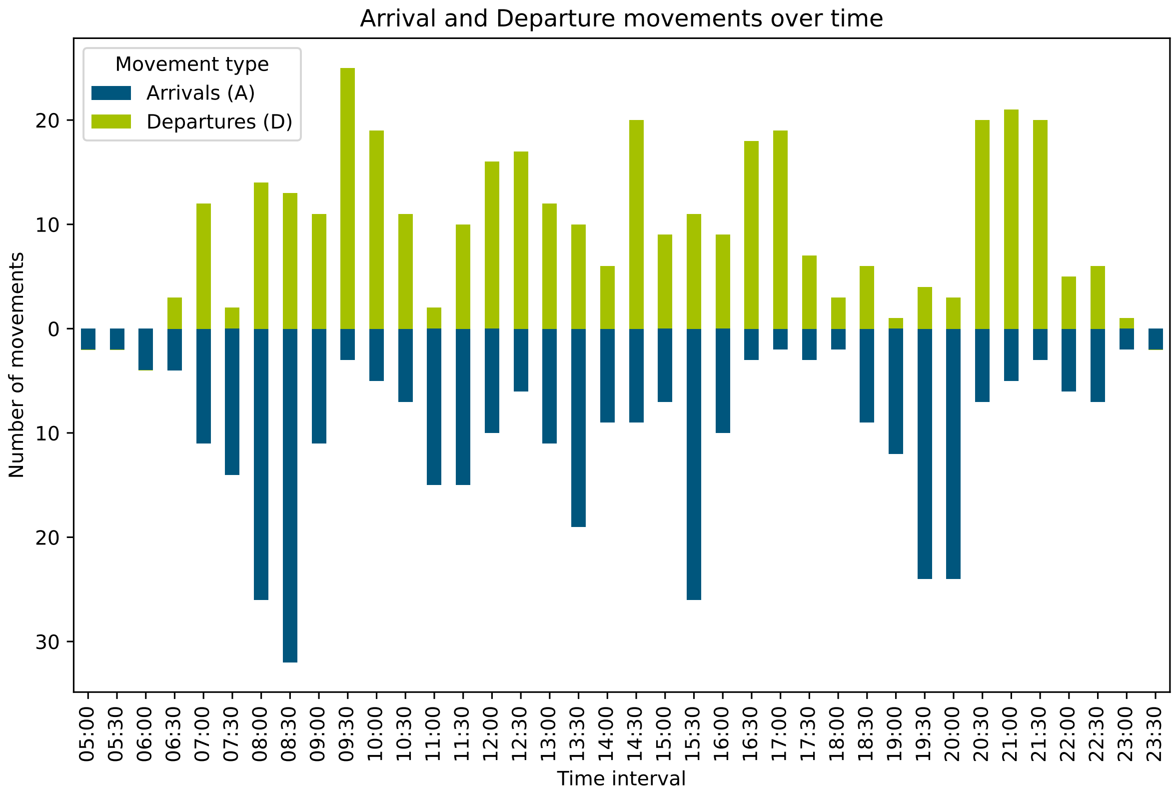


Figure 4.9: *An overview of the arrival and departure movement quantities at AAS on July 13, 2023.*

The ATMs are matched with each other to create a flight schedule. More information about this process can be found in Appendix E.1. The generated flight schedule distinguishes between separate arrivals, separate departures and full turnarounds. The numbers of these are 194, 191 and 175, respectively. A total of fourteen different aircraft types can be found in the flight schedule. Figure 4.10 shows the distribution of the aircraft types across the aprons. The Embraers have been removed from the NABO category, because different GSE is used for these aircraft than for the other NABOs, depending on the GSE type. In this way it also becomes clearer how the distribution of the Embraers compared to the other NABOs is across the airport. The figure also makes it clear that there are far fewer flights with WIBOs in one day, while KLM owns more WIBO than NABO and Embreaer aircraft. This is explained by the fact that these aircraft make longer flights and are therefore less often on AAS. It is also noticeable that there are only a few flights handled by KLM at the G-pier. The H-pier is completely missing from the figure, because it is only used by low-cost carriers and KLM does not handle any of these low-cost carriers.

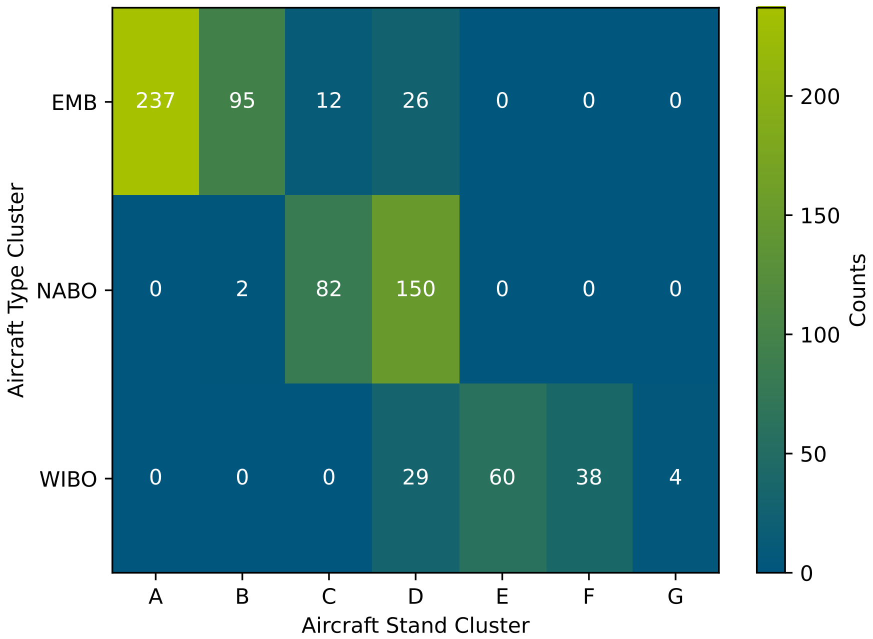


Figure 4.10: *An overview of the distribution of ATMs per aircraft size over the aprons at AAS on July 13, 2023.*

4.3.2. Location groups and distances

For the case study at AAS, the various locations such as aircraft stands, parking locations and logistics locations are divided over 35 location groups (see Figure 4.11). These location groups are based on a document used by KLM (see Figure F.1). The same document also includes the distances between the location groups and based on this the shortest distance between all combinations of location groups are calculated. Because the locations used are defined on the roads along the piers, 50 meters have been added to each distance to correct for the distances from the road to the center of the aircraft stands and vice versa. The distribution of aircraft stands across the location groups can be found in Appendix F.1.

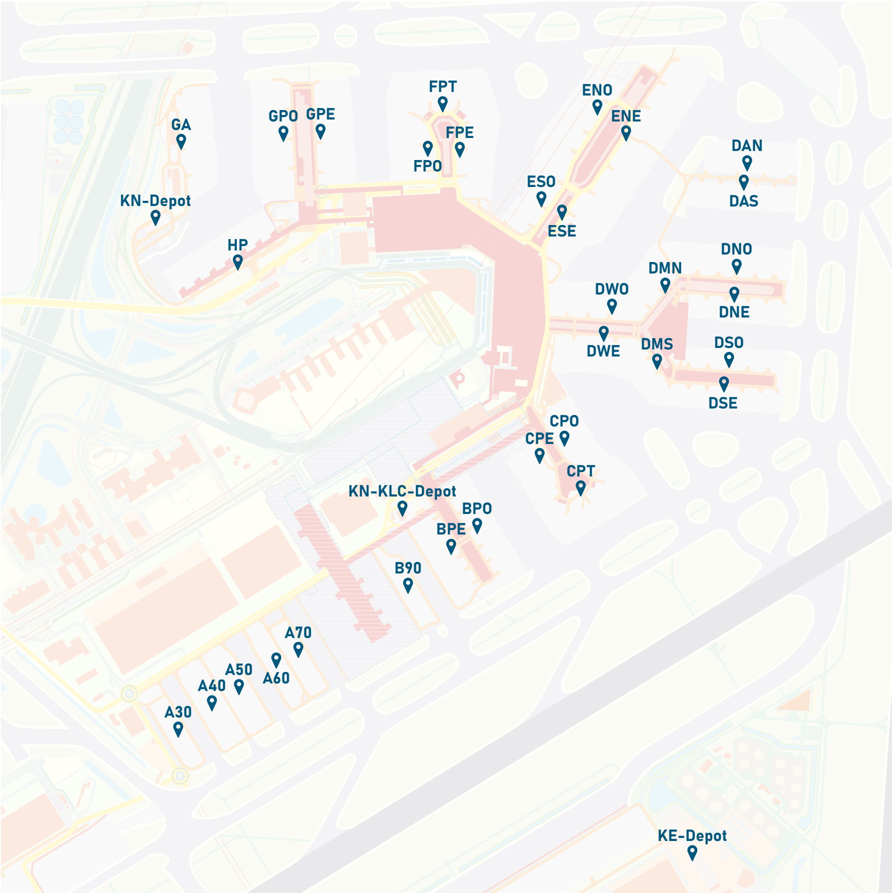


Figure 4.11: *An overview of the location groups that are used for the case study at AAS.*

4.4. Validation on non-logistics GSE type

For the model validation on a GSE type without a logistics function, one of the three types of belt loaders used by KLM is used. Section 4.4.1 provides some information that is specific to this vehicle. A sensitivity analysis is performed and discussed in Section 4.4.2. In Section 4.4.3, one of the solutions found during the sensitivity analysis is chosen and discussed for the model validation. The validation itself is included in Section 4.4.4. Finally, Section 4.4.5 includes a scenario where a fixed set of vehicles can be used, without additional costs if an additional vehicle is used.

4.4.1. Vehicle-specific information

KLM Ground Services is in possession of 65 units of the type of belt loader being considered. Currently, 55 units are available. The vehicles are spread across the location groups, as shown in Table 4.1. These locations are determined based on the locations of the chargers along the piers.

Table 4.1: *The distribution of belt loaders over the location groups at AAS.*

Quantity	Location nr.	Location group
5	0-4	BPE
9	5-13	CPE
10	14-23	CPO
11	24-34	DWE
7	35-41	DNO
12	42-53	DMN
1	54	DAN

The chassis of the belt loader is that of the TLD NBL-E. The vehicle has a rated power of 22 kW and a battery capacity of 33.6 kWh, according to the spec sheet of TLD (2023). The power of the motor to rotate the belt is not mentioned in the spec sheet and therefore a value from the spec sheet for a comparable belt loader from another manufacturer, Charlatte (2017), is used. Based on this, the rated motor power for belt rotation is assumed to be 1.5 kW. For both motors an engine efficiency of 75% is assumed, based on the values discussed in Section 2.2.1. The energy consumption of the vehicle is calculated using the method introduced in Section 2.2.5. Based on this, it can be determined that for driving (activity category 3 and GSE class C), the power demand is

$$P_{demand} = \frac{P_{rated} \cdot LF}{\eta_{GSE}} = \frac{22 \text{ kW} \cdot 0.3}{0.75} = 8.8 \text{ kW}.$$

An average speed of 15 km/h is assumed, based on the values that KLM itself uses for comparable models. This can be used to calculate that driving requires an energy consumption of 0.59 kWh/km. For the movement of the conveyor belt (activity category 1 and GSE class C), the power demand is

$$P_{demand} = \frac{P_{rated} \cdot LF}{\eta_{GSE}} = \frac{1.5 \text{ kW} \cdot 0.5}{0.75} = 1 \text{ kW}.$$

4.4.2. Sensitivity analysis

For the sensitivity analysis, the objective function as discussed in Section 3.2.3 is first normalized. In this way, the sensitivity analysis is performed across the relevant range of the objective values. Only the first two sub-objectives are considered, which focus on minimizing the number of vehicles used and the distance driven. To this extent, the model is run once with the weighting factors $\lambda_1 = 500$ and $\lambda_2 = 0.001$ and once with $\lambda_1 = 0.001$ and $\lambda_2 = 500$. The results of this are shown in Table 4.2. Because $\lambda = 0$ results in an unbounded sub-objective, $\lambda = 0.001$ is used for the sensitivity analysis. The columns “Avg. obj1” and “Avg. obj2” show the average value of the sub-objectives, calculated over all optimization runs with $|F| > 0$. These averages will be used for the normalization of the objective function. To this extent, 81 optimization problems have been solved as part of the rolling horizon approach ($t_{forward} = 120$ min and $t_{update} = 15$ min). The threshold based on which it is determined whether a vehicle can be used in the next optimization run is 30% of the battery capacity.

Table 4.2: *Sub-objective values for the scenarios that are used for the normalization of the objective function.*

λ_1	λ_2	Avg. obj1		Avg. obj2	
500	0.001	17	vehicles	8.479	km
0.001	500	25	vehicles	4.825	km
Absolute difference		8	vehicles	3.654	km

The objective function can be adjusted based on the ranges found. During the sensitivity analysis, the values of λ_1 and λ_2 will be varied, where it must always hold that $\lambda_1 + \lambda_2 = 1$. The value of $\lambda_3 = 0.001$. $\lambda_4 = 0$ and $\lambda_5 = 0$, because this vehicle does not use logistics tasks. The first two sub-objectives are scaled by a factor of 10^4 to make them dominant over the other sub-objectives and to achieve objective values in the order of 10^4, which is optimal for GUROBI. Based on these adjustments, the following objective function is obtained:

$$\min \frac{\lambda_1}{8}\cdot 10^4 \cdot \underbrace{\left(\sum_{k\in K} z_k\right)}_{\text{obj1}} + \frac{\lambda_2}{3.654\ \text{km}}\cdot 10^4 \cdot \underbrace{\left(\sum_{i\in T}\sum_{j\in T}\frac{D_{ij}}{1000}x_{ij}\right)}_{\text{obj2}} + \lambda_3 \underbrace{\left(\sum_{i\in F} s_i\right)}_{\text{obj3}} + \lambda_4 \underbrace{\left(\sum_{i\in T\setminus L}\sum_{j\in L} x_{ij}\right)}_{\text{obj4}} + \lambda_5 \underbrace{\left(\sum_{i\in L} w_i\right)}_{\text{obj5}}$$

Figure 4.12 shows the results of the sensitivity analysis. A distinction is made between the total number of vehicles used in a day and the maximum number of vehicles required within a 30-minute time window. Initially, step sizes of 0.1 were used for the values of λ_1 and λ_2. Later, step sizes of 0.05 were also applied between $\lambda_1 = 0.90$ and $\lambda_1 = 0.20$, because clear changes in the solutions could be observed in this region. The values of all solutions are shown in Table F.2. A number of interesting solutions are:

- Solution 6 with $(\lambda_1, \lambda_2) = (0.70, 0.30)$: This is the solution that requires the least number of vehicles, with the lowest total traveled distance (48.773 km) based on this number of vehicles. In this case, a total of 37 vehicles are used during the day. These vehicles are also all needed at the peak time.
- Solution 10 with $(\lambda_1, \lambda_2) = (0.50, 0.50)$: This solution shows that with 37 vehicles during the peak a lower total traveled distance of 40.733 km can also be achieved. A total of 41 vehicles is used during the day.
- Solution 18 with $(\lambda_1, \lambda_2) = (0.001, 1.00)$: This is the solution with the lowest total traveled distance (24.620 km). This requires a total of 52 vehicles. During the peak, 41 of these vehicles are used.

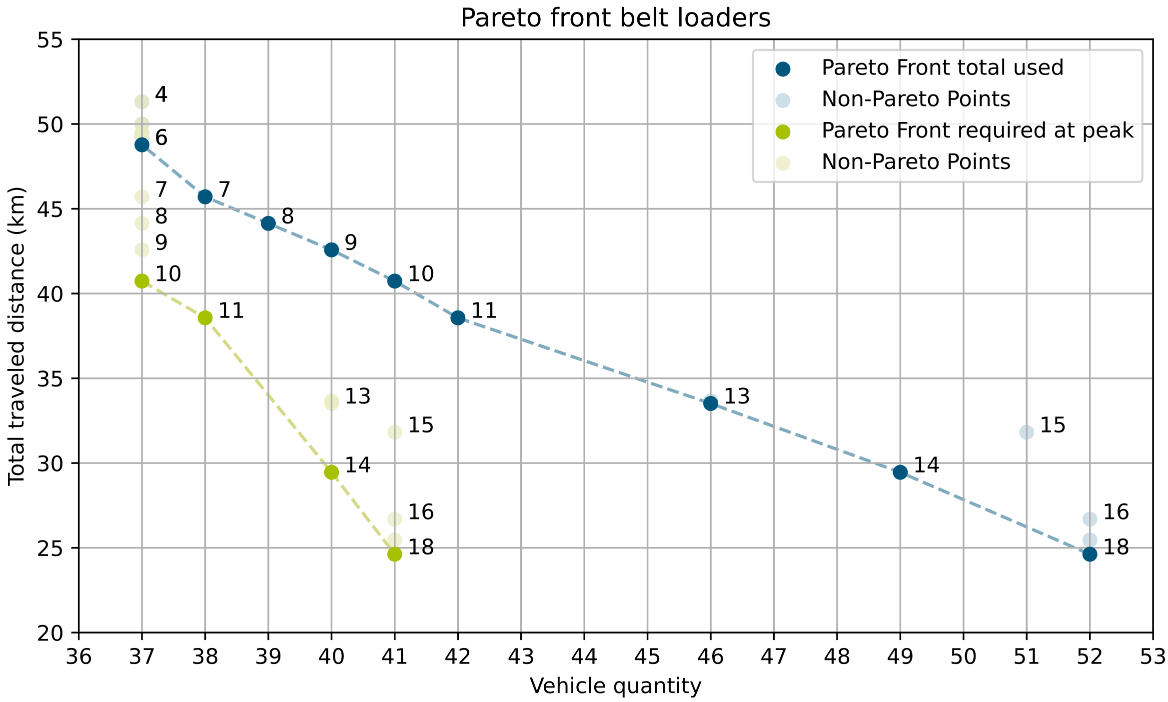


Figure 4.12: *Two Pareto-fronts for the sensitivity analysis of the multi-objective optimization for the belt loader operations. The numbered labels next to the data points correspond to a combination of λ_1 and λ_2. The values of all solutions are shown in Table F.2.*

In general, there is a trend that shows that the use of more vehicles results in a lower total traveled distance. Because this type of belt loader is used for flights at a limited number of piers, the vehicles can often remain idle nearby. The parking areas where the vehicles start and end the day are located at the same piers, which means that often relatively short distances are driven. The figure also includes solutions that are not in the Pareto front. Analysis of the results has shown that these solutions include inefficiencies that arise from the use of the rolling horizon approach. In these scenarios, a "choice" is made for certain vehicles in one optimization run that is optimal at that moment. However, this choice appears to be generally not optimal in the optimization runs in the remainder of the rolling horizon approach. This is in line with the statement about overall optimality that is discussed as part of the verification in Section 3.4.

4.4.3. Chosen solution

Solution 6 with $(\lambda_1, \lambda_2) = (0.70, 0.30)$ from Figure 4.12 is used for the model validation. This solution uses the minimum number of vehicles required and has the lowest total traveled distance given this number of vehicles. The task schedule that follows from the model for this solution is shown in Figure 4.13. The figure shows how the flight tasks are performed and distributed by the 37 belt loaders used. The white space between the blocks consists of waiting before starting the next task and driving to the next task.

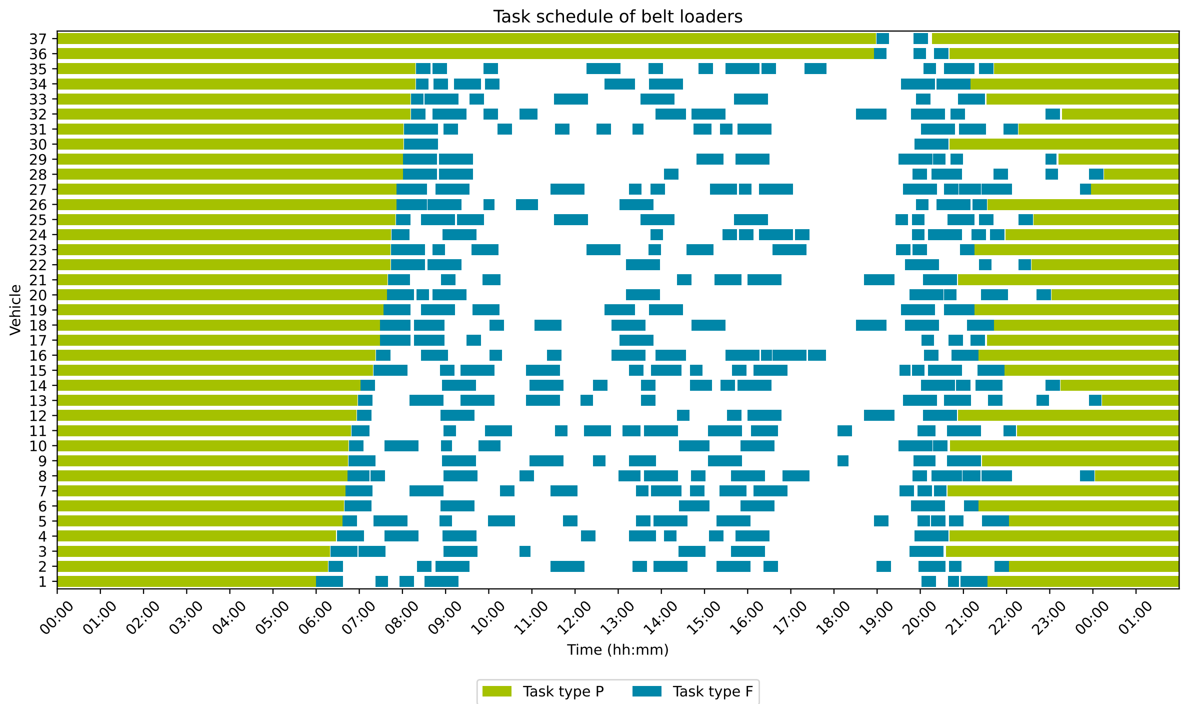


Figure 4.13: *The task schedule of the belt loaders for the selected solution.*

The density of the blocks in Figure 4.13 shows that at some times it is significantly busier than at other times. Therefore, 37 vehicles are not needed all day long. Figure 4.14 shows how many vehicles are needed at each time of the day. In fact, at the quietest time of the day only two vehicles are needed, but there is also a relatively long period when fewer than 15 vehicles are needed.

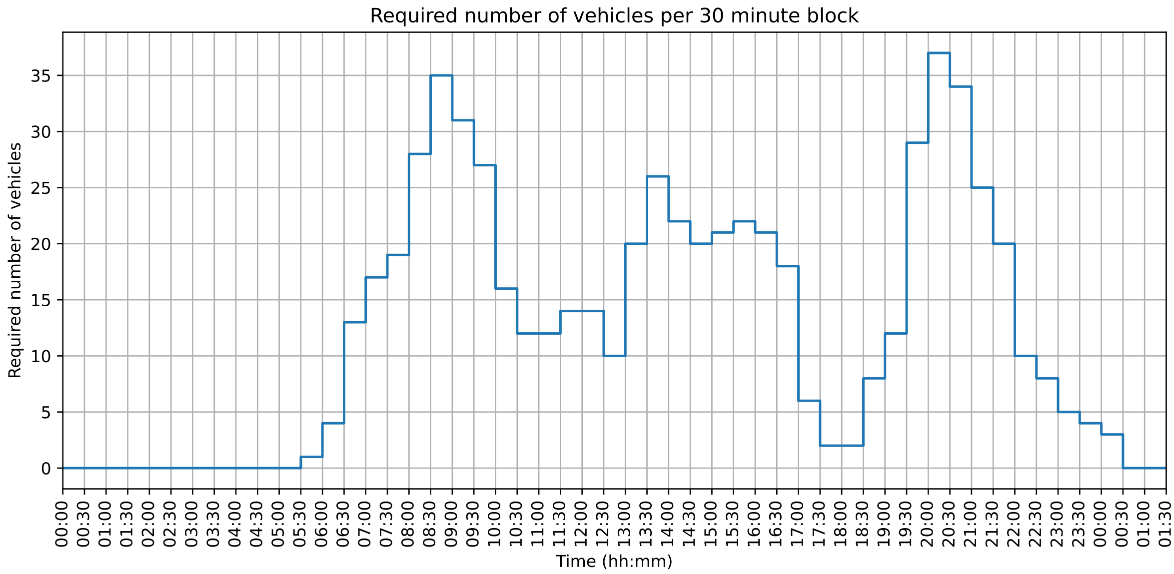


Figure 4.14: *The required number of belt loaders per 30 minute block.*

Figure 4.13 showed that there are a number of vehicles that only perform a few tasks in one day and Figure 4.14 showed that at some times less than half of the vehicle fleet is needed. It is therefore interesting to look at the share of each vehicle in the overall operation. Figure 4.15 therefore shows the utilization rate of the fleet. The utilization rate is calculated as the total time that a vehicle is busy with (driving to) a task, divided by the time in one day (24 hours). The average utilization rate is approximately 21%. Most vehicles have a utilization rate that is above this. However, there are 5 vehicles that have an utilization rate of less than 15%.

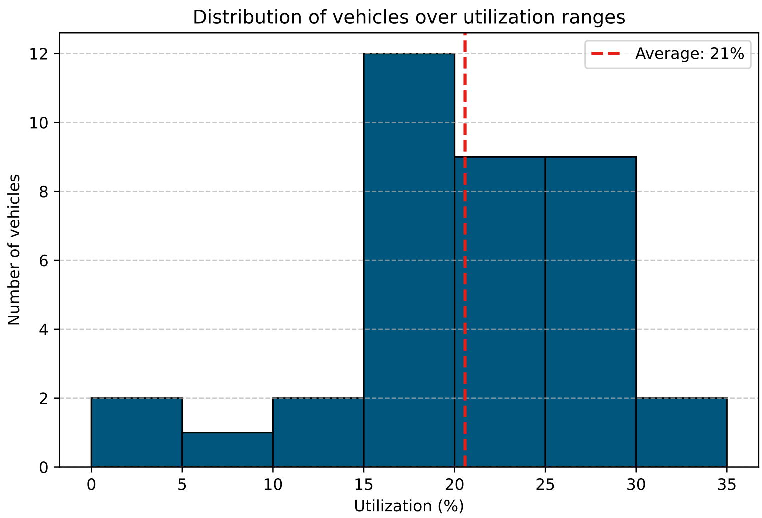


Figure 4.15: *An overview of the utilization rates across the belt loader fleet.*

A total of 210 kWh was used to execute the task schedule in Figure 4.13. Of this, 181 kWh (86%) was used to perform the tasks on the aircraft stands, i.e. running the conveyor belt, and 29 kWh (14%) was used for driving a total distance of 48.773 km. This makes clear that most of the energy consumption for the belt loaders cannot be optimized, because the flight tasks have to be carried out anyway. If desired, the 29 kWh can be reduced by using more vehicles, as can be seen in Figure 4.12. Figure 4.16 shows the SOC progression for each belt loader. None of the belt loaders have a depleted battery at the end of the day. The average energy consumption per belt loader is 5.7 kWh. The belt loader with the highest consumption used 8.5 kWh.

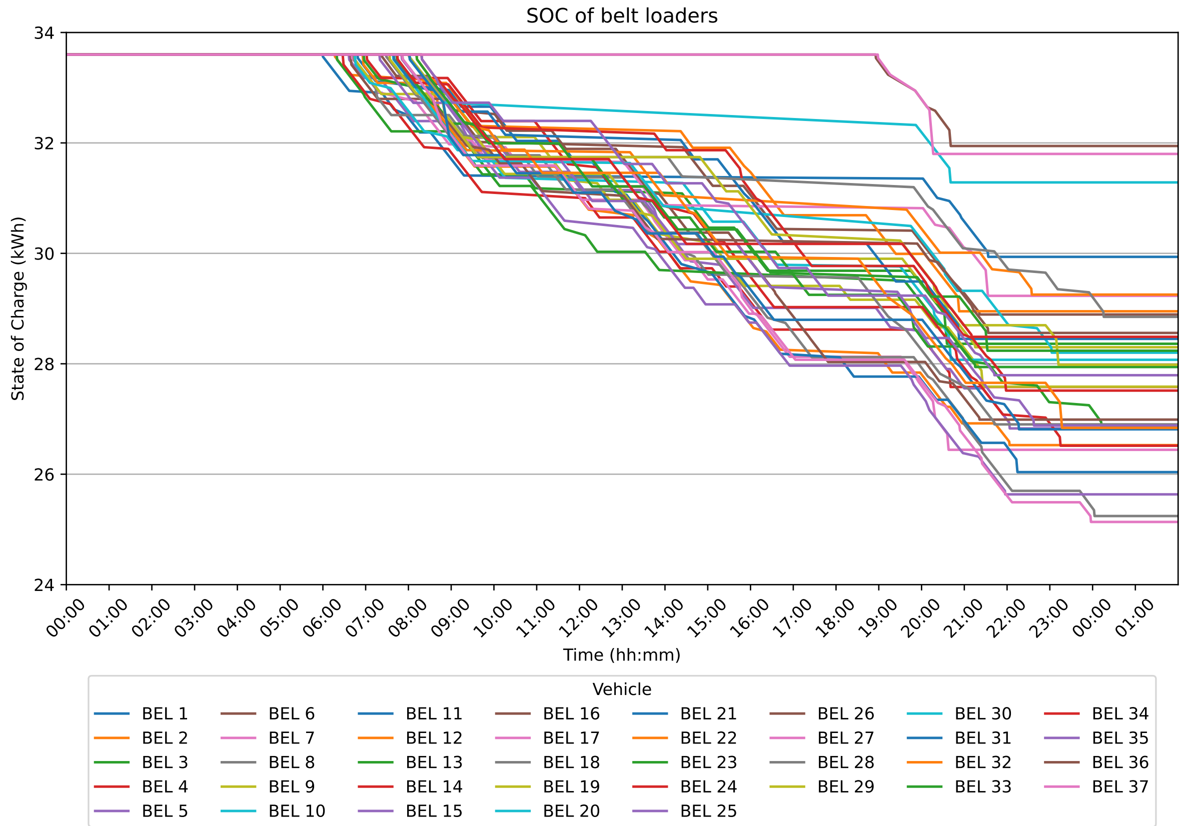


Figure 4.16: *An overview of the SOCs of the belt loader fleet.*

4.4.4. Validation

The data available at KLM shows that 31 belt loaders were in use on the IATA Busy Day. This is therefore less than the minimum number (37) determined by the model. This difference can be explained by the fact that in the model two belt loaders are used for each flight. Conversations with KLM employees show that it often happens that only one belt loader is sent to an aircraft stand. This may be because 1.) it is known that one belt loader is sufficient based on the amount of baggage on board, or 2.) as a result of the efficient utilization of the available resources. Analysis of the historical data for the IATA Busy Day shows that KLM used an average of 1.4 belt loaders that day to handle the flights handled by the type of belt loader discussed. Based on this, it is likely that it was possible to handle the flights with 31 belt loaders.

The conversations with KLM also revealed that it is usually not necessary to charge the belt loaders during the day. This is confirmed by the solution of the model. The vehicles were originally purchased with a battery capacity that should last two shifts to be able to operate a full day, but due to degeneration there are many batteries that have a SOH that is significantly lower than the 100% used in this model.

Based on the outcome of the model, in combination with the above statements, it is assumed that the operation of the model for vehicles without a logistics function has been validated. Given the average number of belt loaders deployed by KLM of 1.4 on the IATA Busy Day, it is likely that a solution with even fewer than 31 belt loaders could be obtained. However, it should be noted that the outcome of the model assumes the most efficient scenario in terms of routes driven. Disruptions in the flight schedule, the availability of vehicles and staff, and inefficiencies in the process are factors that make it necessary to always apply a buffer to the value found by the model.

4.4.5. Using a fixed set of vehicles

In the solution used for validation on the belt loaders, 37 belt loaders were used. Due to the rolling horizon approach, a series of optimizations were solved for this, whereby the objective value was minimized each time. This means that every optimization used as few vehicles as possible. This offers the opportunity to take personnel planning into account, because the number of people required changes throughout the day. However, the total number of vehicles required for the day will remain 37.

In this section, the scenario is analyzed where it is specified in advance that these 37 vehicles may be used, without additional costs being applied to the objective function if an additional vehicle is used. This allows the 37 vehicles to be used “free of charge” in all optimization runs, which may result in a better total traveled distance.

Figure 4.17 shows how many vehicles are needed at each time of the day for this specific scenario. The maximum number of vehicles required is indeed still 37. However, the total traveled distance is 45.504 km, compared to the previously found 48.773 km. The results are also better than the distance in solution 7 $(\lambda_1, \lambda_2) = (0.65, 0.35)$ in Figure 4.12, where 38 vehicles were required. Compared to Figure 4.14, there are some time blocks in which more vehicles are now used, but also some in which fewer are used. Overall, however, the area under the graph is now slightly higher, meaning that there are slightly more “vehicle-hours” required.

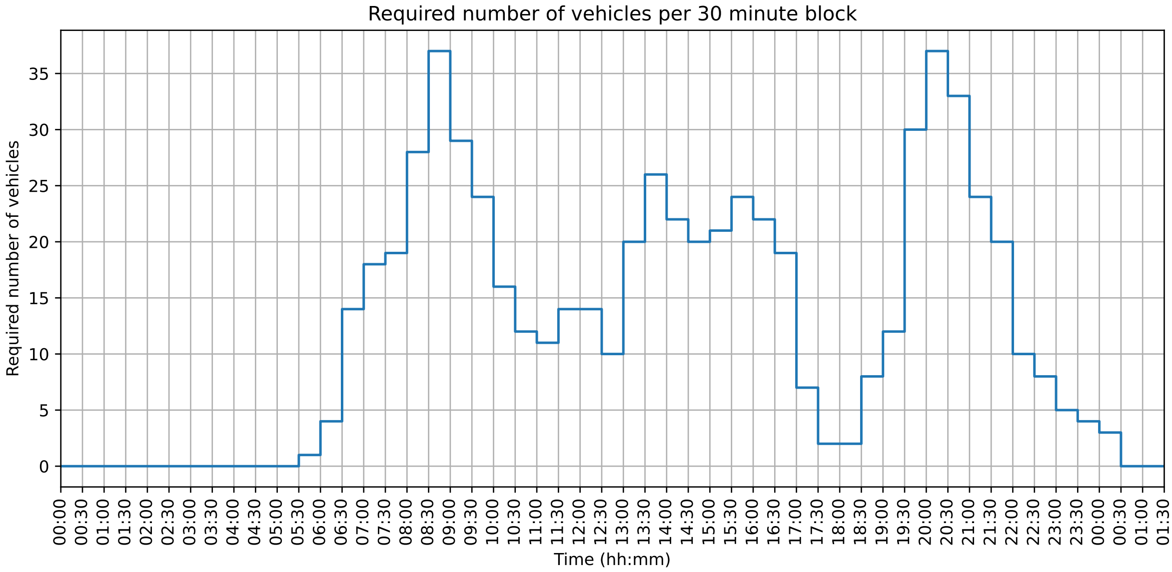


Figure 4.17: *The required number of belt loaders per 30 minute block, when using a fixed set of 37 vehicles.*

Figure 4.18 shows the utilization rate of the fleet. The comparison with Figure 4.15 shows that the average utilization rate has remained the same. Since the tasks and the number of vehicles have remained the same, no major changes were expected here. However, it is noticeable that there are now more vehicles with a more average utilization rate. This corresponds to the adjustment of the optimization objective, whereby more vehicles can be used without additional costs.

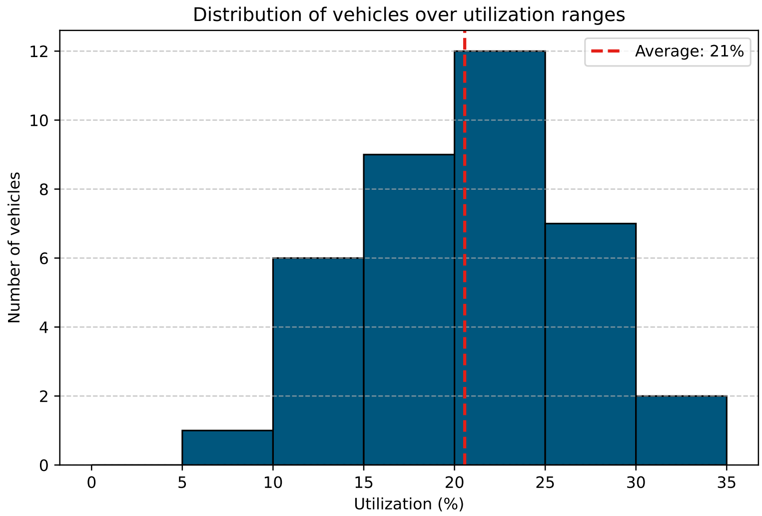


Figure 4.18: *An overview of the utilization rates across the belt loader fleet, when using a fixed set of 37 vehicles.*

It can be concluded that it is possible to further improve the total traveled distance for a scenario with a given number of vehicles. This results in lower energy consumption, but at the expense of the number of staff hours required. A trade-off must be made here.

4.5. Validation on logistics GSE type

For the model validation on a GSE type with a logistics function, the water trucks are used. They are used for handling all aircraft types. Section 4.5.1 provides some information that is specific to this vehicle. A sensitivity analysis is performed and discussed in Section 4.5.2. In Section 4.5.3, one of the solutions found during the sensitivity analysis is chosen and discussed for the model validation. The validation itself is included in Section 4.5.4.

4.5.1. Vehicle-specific information

KLM Ground Services is in possession of 11 water trucks. Currently, 8 units are available. All vehicles are located in location group ENE. The logistics location for this GSE type is located in location group FPE, as can be seen in Figure 4.4 and Figure 4.11. The first electric water trucks were recently put into operation at KLM. The chassis of the water truck is that of the Vestergaard e (electrical chassis) (Vestergaard, 2023), with a battery capacity of 70 kWh. The power of the motor is not mentioned in the spec sheet and therefore a value from the spec sheet for a comparable water truck from another manufacturer, Orientitan Ground Support Equipment (n.d.-b), is used. Based on this, the rated motor power is assumed to be 140 kW. An engine efficiency of 75% is assumed, based on the values discussed in Section 2.2.1. The energy consumption of the vehicle is calculated using the method introduced in Section 2.2.5. Based on this, it can be determined that for driving (activity category 2 and GSE class B), the power demand is

$$P_{demand} = \frac{P_{rated} \cdot LF}{\eta_{GSE}} = \frac{140 \ \text{kW} \cdot 0.5}{0.75} = 93 \ \text{kW}.$$

An average speed of 15 km/h is assumed, based on the values that KLM itself uses for comparable models. This can be used to calculate that driving requires an energy consumption of 6.22 kWh/km. The logistics capacity for water is 3300 L, and 100% refilling of the truck takes 15 minutes. Filling the aircraft takes place at an average of 80 L/min. The power of the pump is not mentioned in the spec sheet, but based on the technical specifications that are provided by Orientitan Ground Support Equipment (n.d.-b), it can be calculated that

$$P_{demand} = \frac{\Delta P \cdot Q}{\eta} = \frac{0.4 \cdot 10^6 \ \text{Pa} \cdot 1.33 \cdot 10^{-3} \ \text{m}^3/\text{s}}{0.75} = 0.711 \ \text{kW}.$$

For the water demand per aircraft type, the historical data with filling quantities per flight of KLM was analyzed from January 1, 2023 to September 20, 2023. Based on this, the average amount of water that was refilled per aircraft type was determined. Only quantities of 15 liters or more have been included. The values between the 95% and 5% quantiles are considered, to avoid outliers. The average values found per aircraft type were used to determine the demand for the tasks. For the energy consumption by the pump, only 75% of the defined task time is used in this case study, as the "pumping" is only part of the total water service procedure.

4.5.2. Sensitivity analysis

For the sensitivity analysis, the objective function as discussed in Section 3.2.3 is first normalized. In this way, the sensitivity analysis is performed across the relevant range of the objective values. Only the first two sub-objectives are considered, which focus on minimizing the number of vehicles used and the distance driven. To this extent, the model is run once with the weighting factors $\lambda_1 = 500$ and $\lambda_2 = 0.001$ and once with $\lambda_1 = 0.001$ and $\lambda_2 = 500$. The results of this are shown in Table 4.3. Because $\lambda = 0$ results in an unbounded sub-objective, $\lambda = 0.001$ is used for the sensitivity analysis. The columns "Avg. obj1" and "Avg. obj2" show the average value of the sub-objectives, calculated over all optimization runs with $|F| > 0$. These averages will be used for the normalization of the objective function. To this extent, 76 optimization problems have been solved as part of the rolling horizon approach ($t_{forward} = 120$ min and $t_{update} = 15$ min). The threshold based on which it is determined whether a vehicle can be used in the next optimization run is 30% of the battery capacity.

Table 4.3: *Sub-objective values for the scenarios that are used for the normalization of the objective function.*

λ_1	λ_2	**Avg. obj1**		**Avg. obj2**	
500	0.001	5	vehicles	25.143	km
0.001	500	7	vehicles	16.199	km
Absolute difference		2	vehicles	8.944	km

Due to the long MIP gap closing time, it is decided to focus on lowering the upper bound using the heuristic discussed in Section 3.3.4. The time that may be used per optimization run by the heuristic to improve the upper bound, is aligned with $|F|$. Because the MILP solving is not continued towards an MIP gap of 0%, optimality cannot be guaranteed. However, practice has shown that the upper bound found by the heuristic is rarely improved by the branch-and-bound algorithm. In addition, the run with $(\lambda_1, \lambda_2) = (500, 0.001)$ showed that the water trucks cannot last a whole day on one full battery charge, so the vehicles are depleted during the day. To give the model the opportunity to use new vehicles to replace these depleted vehicles, a vehicle set of 35 water trucks is used. However, KLM does not have 35 vehicles available and to prevent these from being used by the model as soon as the total traveled distance is optimized, an additional constraint has been added to the MILP model that allows the use of a maximum of 13 vehicles per optimization run. This number is based on the maximum number of vehicles needed per 30 minutes in the run with $(\lambda_1, \lambda_2) = (500, 0.001)$.

The objective function can be adjusted based on the ranges found. During the sensitivity analysis, the values of λ_1 and λ_2 will be varied, where it must always hold that $\lambda_1 + \lambda_2 = 1$. The value of $\lambda_3 = 0.001$, and $\lambda_4 = 0.001$ and $\lambda_5 = 0.001$. The first two sub-objectives are scaled by a factor of 10^4 to make them dominant over the other sub-objectives and to achieve objective values in the order of 10^4, which is optimal for Gurobi. Based on these adjustments, the following objective function is obtained:

$$\min \frac{\lambda_1}{2}\cdot 10^4 \cdot \underbrace{\left(\sum_{k\in K} z_k\right)}_{\text{obj1}} + \frac{\lambda_2}{8.944\ \text{km}}\cdot 10^4 \cdot \underbrace{\left(\sum_{i\in T}\sum_{j\in T}\frac{D_{ij}}{1000}x_{ij}\right)}_{\text{obj2}} + \lambda_3 \underbrace{\left(\sum_{i\in F} s_i\right)}_{\text{obj3}} + \lambda_4 \underbrace{\left(\sum_{i\in T\setminus L}\sum_{j\in L} x_{ij}\right)}_{\text{obj4}} + \lambda_5 \underbrace{\left(\sum_{i\in L} w_i\right)}_{\text{obj5}}$$

Figure 4.19 shows the results of the sensitivity analysis. A distinction is made between the total number of vehicles used in a day and the maximum number of vehicles required within a 30-minute time window. Step sizes of 0.1 were used for the values of λ_1 and λ_2. The values of all solutions are shown in Table F.3.

It is noticeable that the two Pareto fronts are very small. The vast majority of solutions are not part of the Pareto front. A trend that can be deduced from this is that a minimization of total traveled distance in this case also results in a minimization of the number of vehicles required. Because the water trucks first have to go to the logistics location to collect water, a relatively high initial "fixed" distance is required to put a new vehicle into use. In addition, it is a relatively small group of vehicles, which operates throughout the airport. At the end, a vehicle sometimes has to drive a long way back to the parking area, since there is only one parking zone for this type of equipment.

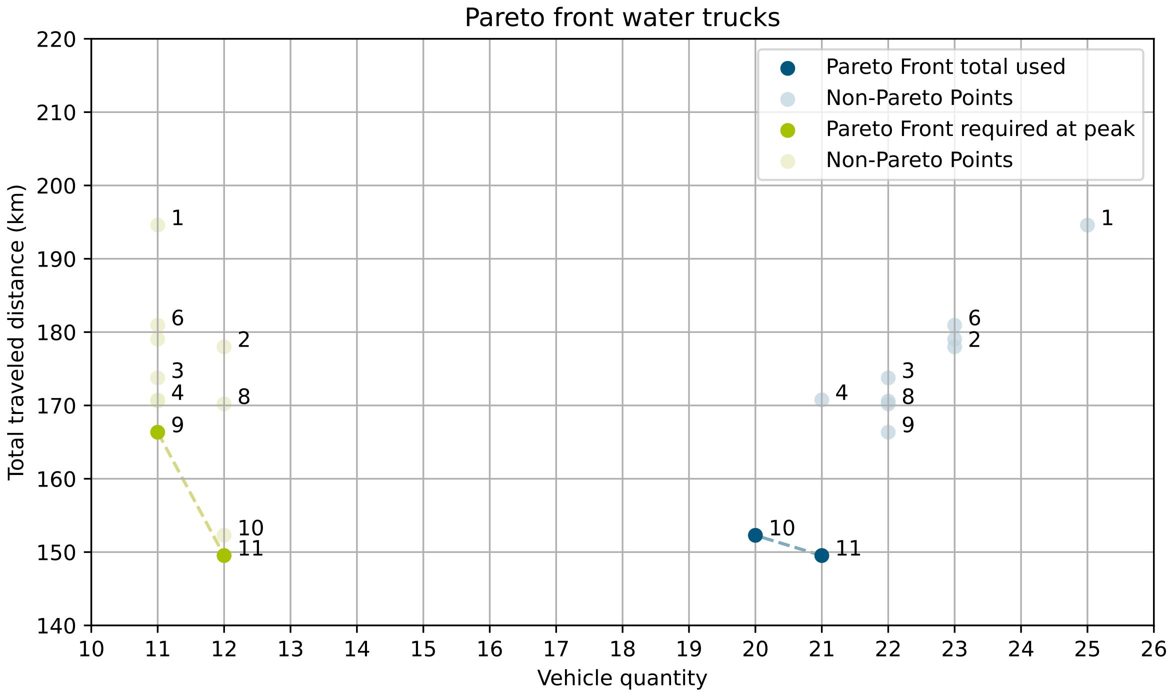


Figure 4.19: *Two Pareto-fronts for the sensitivity analysis of the multi-objective optimization for the water truck operations. The numbered labels next to the data points correspond to a combination of λ_1 and λ_2. The values of all solutions are shown in Table F.3.*

4.5.3. Chosen solution

Solution 10 with $(\lambda_1, \lambda_2) = (0.10, 0.90)$ from Figure 4.19 is used for the model validation. This solution uses the minimum number of vehicles required and has the lowest total traveled distance given this number of vehicles. The task schedule that follows from the model for this solution is shown in Figure 4.20. The figure shows how the flight tasks are performed and distributed by the 20 water trucks used. The white space between the blocks consists of waiting before starting the next task and driving to the next task. The figure also shows when the vehicles went to a logistics location to refill water. New vehicles are added gradually during the day, because other vehicles get depleted.

For many vehicles, a time window can be identified in which it would be possible to use opportunity charging. This would result in fewer vehicles needed in total. However, it is difficult to estimate how many vehicles could exactly be saved this way. Newly used vehicles must first be refilled with water. Because the depleted vehicles do not necessarily end up with an empty water tank, water is collected from the logistics location too often.

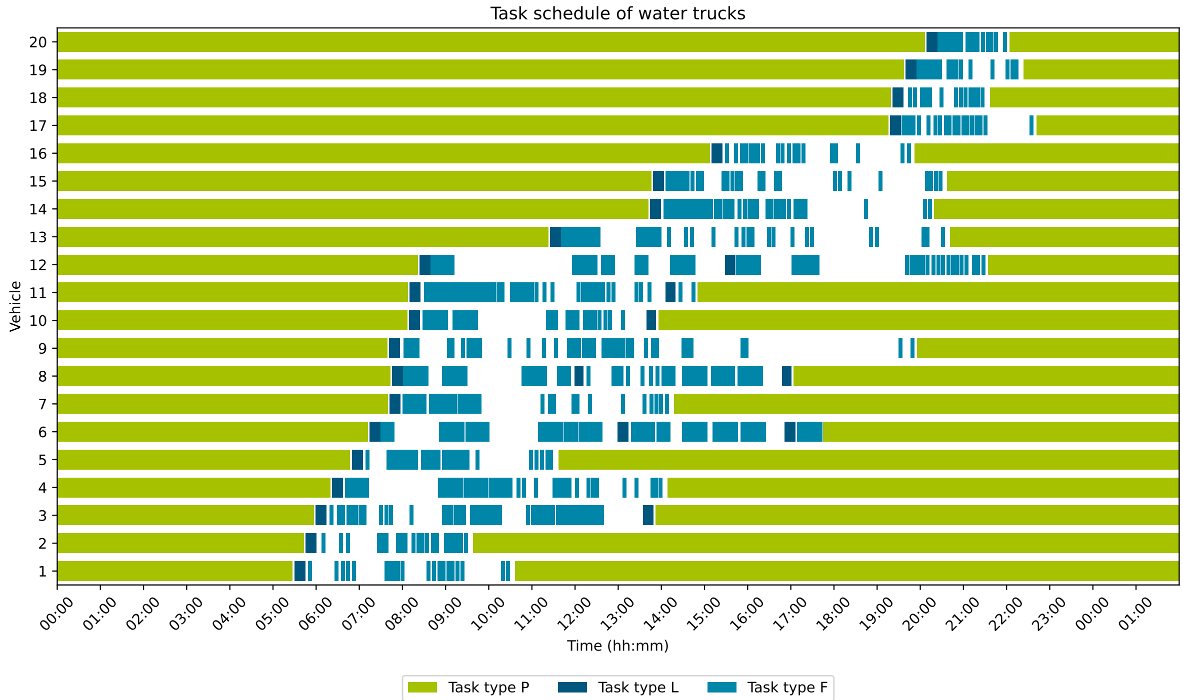


Figure 4.20: *The task schedule of the water trucks for the selected solution.*

Figure 4.21 shows how many vehicles are needed at each time of the day. In fact, at the quietest time of the day only two vehicles are needed, but there is also a relatively long period when fewer than 9 vehicles are needed.

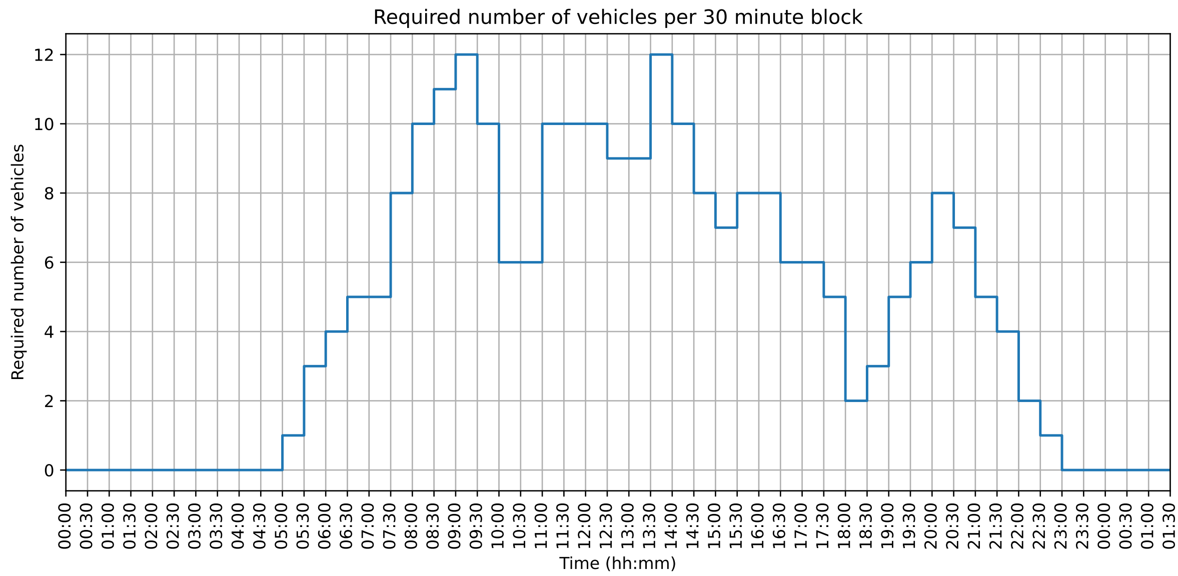


Figure 4.21: *The required number of water trucks per 30 minute block.*

Figure 4.22 shows the utilization rate of the fleet. The utilization rate is calculated as the total time that a vehicle is busy with (driving to) a task, divided by the time in one day (24 hours). The average utilization rate is approximately 15%. However, it should be noted that a higher utilization rate could be achieved if the vehicles are charged when possible and therefore no new vehicles need to be put into use.

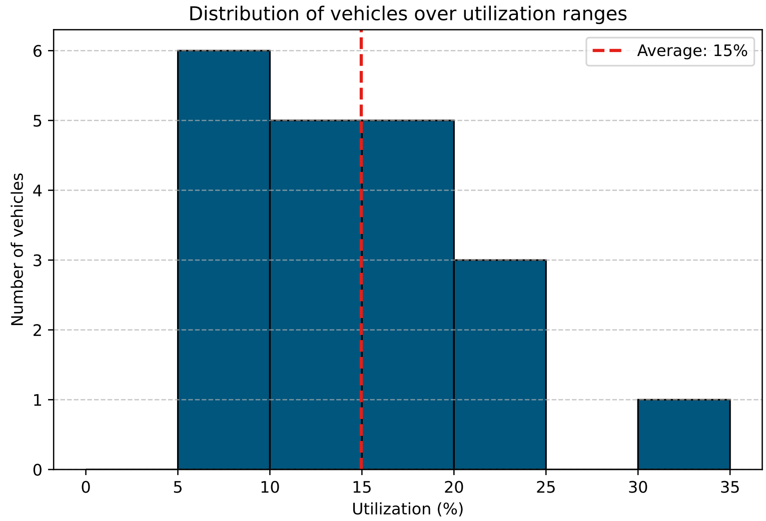


Figure 4.22: *An overview of the utilization rates across the water truck fleet.*

A total of 977 kWh was used to execute the task schedule in Figure 4.20. Of this, 30 kWh (3%) was used to perform the tasks on the aircraft stands, i.e. operating the pump, and 947 kWh (97%) was used for driving a total distance of 152.283 km. This makes clear that most of the energy can be optimized, by minimizing the total traveled distance. Figure 4.23 shows the SOC progression for each water truck. The batteries of 16 water trucks were eventually depleted ($SOC < 30\%$).

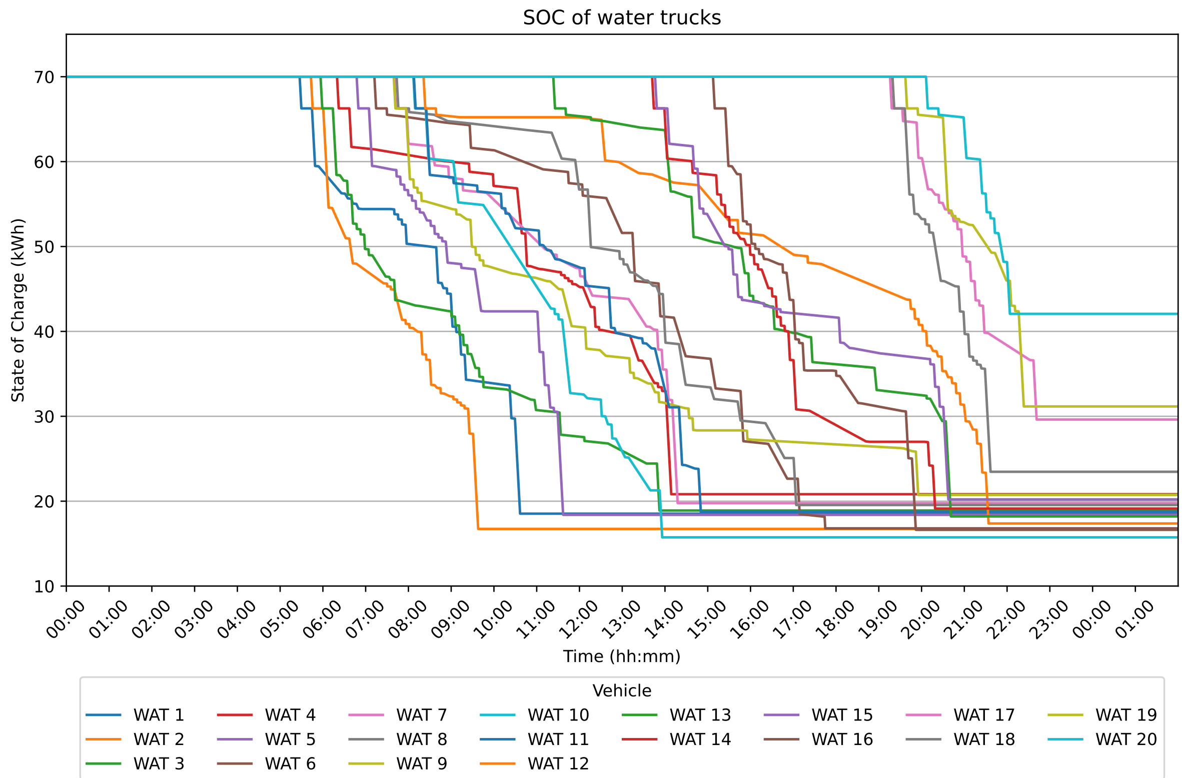


Figure 4.23: *An overview of the SOCs of the water truck fleet.*

4.5.4. Model validation

Although KLM only has eight water trucks available, the model shows that twelve are needed simultaneously and a total of twenty is needed during the day (without charging them). Conversations with KLM show that there are two possible causes for this: 1.) sometimes the computer system indicates that no service needs to be performed on an aircraft, because this aircraft can do a multistretch. This means that an aircraft makes several flights before it is serviced again, and 2.), as a result of the utilization of the available resources it may occur that not all flights that should have water service receive it. This, unintentionally, also results in a "multistretch".

In the model, a task for the water trucks is assigned to each flight. As a result, more services are already being performed in the model than (should be) in reality. In addition, in the model all water service tasks are performed during separate departures and full turnarounds. In reality, it is also possible to perform the water service when an aircraft arrives and remains on the ground for a longer period of time. This allows for a more efficient distribution of tasks. Analysis of the area under the graph in Figure 4.21 shows that 90% of the "vehicle-hours" in the model could be performed with eight water trucks. Based on the arguments that were discussed above, it is likely that it is possible to handle the flights with eight water trucks.

The conversations with KLM also revealed that it is generally necessary to charge the water trucks during the day. This is also proven by the model results. KLM does not (yet) have exact data about the SOC of the water trucks during the day, but the results seem to be in the right order of magnitude.

In combination with the above statements, it is assumed that the number of required vehicles, as determined by the model, is feasible. The operation of the model for vehicles with a logistics function is therefore considered validated. However, the reliability of the model could be improved if it is taken into account that aircraft can also be serviced at a separate arrival, as this may smooth out the peaks in tasks. However, if the choice between servicing as soon as an aircraft arrives or shortly before it departs becomes part of the optimization, a TSP is no longer solved, but the generation of tasks also becomes an optimization problem.

4.6. Summary

This chapter has discussed the validation of the model on a non-logistics and a logistics GSE type, based on a case study for KLM's GSE fleet at AAS. To this extent, a sensitivity analysis was performed. This allows for the answering of SQ 6: *"What are the implications of the different scenarios in the developed model with regard to the KPIs?"*.

Depending on the type of GSE and the method of use, a different pattern can be discovered in the interdependence of the KPIs. The case study for the belt loaders makes it clear that the total traveled distance decreases as the number of vehicles used increases. This GSE type only operates on the aircraft stands and because the specific type of belt loader is only used for a limited set of aircraft, it is possible for this type of vehicle to remain close to the same aircraft stands. The energy for driving therefore only has a small share in the total energy consumption. However, the case study for the water trucks shows the opposite. A higher number of vehicles also results in a higher total traveled distance. This is explained on the one hand by the fact that these vehicles have to cover a "high" initial distance because they first have to collect water at the logistics location and on the other hand, these vehicles are used for all aircraft types, which means they are needed throughout AAS. Because there is only one area where they can park, this sometimes entails long distances to drive at the start and end of the day. The energy for driving has a large share in the total energy consumption. The energy consumption of the water trucks also results in the vehicles having a depleted battery halfway through the day. These vehicles therefore need to be charged in between to use them all day long. Although the case study was carried out for two GSE types, it can be expected that these properties and relationships will also apply to other GSE types.

5
Conclusion

This chapter will formulate an answer to the Research Question. This will be done in Section 5.1. This is followed by a discussion on the research, methods and assumptions in Section 5.2. After that, recommendations for further research are discussed in Section 5.3. Finally, some recommendations for NACO and KLM are provided in Section 5.4.

5.1. Conclusion

The motivation for this research was formed by the environmental impact that is caused by the aviation sector. In 2017, the aviation sector was the second most important source of GHG emissions in the transport sector after road traffic (European Commission, 2021), and it seems that these environmental problems will continue, as the current traffic growth is outpacing fuel efficiency improvements and reductions of emissions from other sectors (European Union Aviation Safety Agency, 2022). To mitigate climate change and control temperature rise, the aviation sector needs to reduce GHG emissions, like CO_2, and the emission of air pollutants from fossil fuels. Ground Support Equipment (GSE), which supports the turnaround process of aircraft, also has a share in these emissions (Kirca et al., 2020). Hence, to reduce both carbon and air pollutant emissions from GSE, airports and airlines are examining and committing to the electrification of GSE (Francfort et al., 2007; Kirca et al., 2020).

A number of challenges arise as a fully electrified fleet of GSE is realized. The two main challenges pertain the significantly longer charging time compared to refueling conventional fossil-fueled vehicles and the increased burden on the electric grid (Gulan et al., 2019). Electric versions already exist for a number of (especially smaller) GSE types, but these are still being developed for other larger vehicles (Aviation Sustainability Consultant). For the early stage decision making of different stakeholders, such as 1.) airport operators, 2.) ground service providers, and 3.) airline companies, it is therefore important to be able to estimate the required quantity of electric Ground Support Equipment (eGSE), the charging requirements of eGSE, the change of airport electricity requirements, and the scheduling possibilities of eGSE charging for the existing turnaround procedures. This work therefore aimed to answer the following Research Question that was formulated:

What is the impact of the implementation of electric Ground Support Equipment when optimizing the capacity and demand of GSE fleets?

To this extent, (literature) research was conducted about airport operations, the influence of eGSE compared to the conventional non-electric GSE, and the modeling of GSE. Already during the literature research phase it became clear that charging for smaller GSE vehicles does not currently pose a major challenge, because they can often be charged overnight. This is different for larger vehicles. While there are relatively few of them on the market, interviews with KLM already made it clear that it is necessary to charge these vehicles during the daytime. To get insight into the required number of vehicles and the energy consumption, a model was developed to simulate and optimize the GSE operations at airports. This was done by means of a Task Scheduling Problem, that is optimized using Mixed-Integer Linear Programming. Based on the results of this model, an answer to the Research Question can be formulated.

From the results of the case study, it can be concluded that the impact of implementing eGSE on the capacity and demand of a GSE fleet depends on the type of GSE. For GSE types that can last an entire day on a single battery charge, there is no difference in the capacity that can be achieved. These vehicles can therefore be directly replaced one-to-one compared to their conventional counterparts. This primarily applies to smaller vehicles under the condition that the vehicles are not needed at night, so that they can be charged again. Due to nighttime curfews, this is possible at many airports.

However, there is also a group of GSE types where the model results show that the vehicles become depleted before the end of the day. To maintain the capacity of these GSE types, it is necessary to either 1.) use more of these vehicles, 2.) charge the vehicles during the day, 3.) use batteries with a higher capacity, or 4.) use vehicles with a better efficiency. However, it should be noted that charging the vehicles during the day does not necessarily results in a maintained capacity, as this is depending on the possibility to charge. This is related to the distribution of the tasks over the day. Using the developed model, it is possible to determine how many additional vehicles are needed when there is no daytime charging. For interim charging, an estimate can be made based on the model results and the concept of opportunity charging. The flight schedule and the task list for the vehicles can be used to determine when there is time to charge during the day. However, optimality is not guaranteed in this case. Therefore, additional research is required for these vehicles, including the development of a charging strategy as part of the scope.

5.2. Discussion

Based on the literature review, it had already been established that there are many differences between the GSE types required for servicing aircraft at an airport. Based on this, the decision was made to differentiate certain groups of GSE types in the model that share similar characteristics, so that the model can be broadly applied. This decision was made because the literature review also revealed that there are few works that encompass all GSE types in the research. The results obtained from the model provide a good indication of the required number of vehicles, energy consumption, and the possibility of optimization. However, the validation of the model, in particular, shows that despite distinguishing between certain groups of GSE, there are still differences in the operation and performance of each individual GSE type that affect the results. This is where the desired application of the model becomes relevant. Making a distinction between a strategic and operational application of the model and the associated choices allows for an interpretation of the choices and assumptions that emerged in the review of the existing works and the contributions and limitations of this research.

The results of the model developed in this research show that the model can be used for making strategic decisions. The vehicle quantities generated by the model are in the right order of magnitude, and the total energy consumption provides sufficient insight for making decisions at a strategic level. This aligns with the parameters used by a company like NACO at an airport master planning level. An advantage of the application at a strategic level is that it requires less detail, enabling a less complex model. An example of this is the use of location groups in this research, which generalize multiple locations into one location. Similar choices were made in works such as that of Padrón et al. (2016), Gök et al. (2022), and Kirca et al. (2020), which makes that the results of these works are also suitable for decision making at a strategic level. For use at a strategic level, it is also questionable whether the current level of accuracy is required. For example, consideration could be given to formulating the problem as an assignment problem instead of a TSP, as it has sufficient accuracy for this level and the complexity of the problem can be reduced by discretizing the time.

By including all the components that were assumed to be essential for modeling GSE operations based on the literature review, interviews, and observations, the current model can already be used at an operational decision level more effectively than comparable works that have made more simplifications and assumptions at this level. In the developed model, there is the possibility to incorporate the distances between each individual location by increasing the number of location groups. Additionally, it is possible to have each vehicle start at a desired location, and individual aircraft types are taken into account for task duration, time windows, and energy consumption.

However, to improve the accuracy of the model for an operational level, it would be necessary to look even further into each individual GSE type in addition to the GSE groups with similar characteristics. For example, the case study for KLM revealed that the procedures used for each GSE type differ to such an extent that it is not possible to make generic assumptions at an operational level. From the interview with Business Contract Manager GSE II, it became even clear that modeling the baggage process is particularly challenging when the model is intended to work for multiple GSE types. This also explains why works such as that of Bao et al. (2023), Bosma (2022), and S. Wang et al. (2021) focus on only one GSE type, justifying the contributions of these works at an operational level. For a better operational approach, it would also be necessary to consider disruptions in the operation, such as changes in the flight schedule and the availability of GSE and staff. In addition, the case study now used the flight schedule of the IATA Busy Day. For operational use it is of course possible to use a flight schedule of any day. It is possible that fewer vehicles will be needed, but this does not have to be the case. For example, if peak times remain just as busy, the same number of vehicles will still be needed at that time. Between those peak moments, there could be more room for charging, which improves the possibilities for opportunity charging. This would strengthen the assumption that vehicles can charge during the day. There is something else to take into account for operational use of the model. For airports that do not use piers with PBBs and power-in push-out stands, it is necessary to adapt the model. Currently the model assumes that vehicles can wait/park along the pier. In the case of power-in power-out stands, this results in an unrealistic approach because vehicles in the model then remain "on the stand".

Based on interviews and observations, the decision was made to focus on simulating and optimizing GSE operations and their associated energy consumption while excluding the charging of eGSE in this research. This decision was made because the smaller GSE types currently available in electric versions do not pose major challenges in the field of charging. Based on the results from the model, this decision does not appear to have a significant impact on smaller GSE types. However, interviews and the results of the validation study for water trucks do indicate that daytime charging will become relevant for larger GSE types that are now emerging in the market. For this reason, it was already decided to include energy consumption in this study. The developed model removes vehicles from the operation when they are depleted. The threshold for considering vehicles as depleted is now on the conservative side. Because the SOC is determined via post-processing, it must be determined before a new optimization run whether a vehicle can last another run or not. Because the depleted vehicles are removed from the operation, a larger set of vehicles is provided to the model so that the depleted vehicles can be replaced. However, as soon as the focus on optimization shifts to the traveled distance, these "replacement" vehicles are used as well. Therefore, a limit to the number of simultaneously used vehicles must be set here. Removing vehicles from the operation when they are depleted, on the other hand, does provide the opportunity to estimate the need for additional vehicles or required charging opportunities and times, but this is not part of the optimization. A relatively simple extension to the model towards "opportunity charging" would be an improvement in this regard. Nevertheless, for an overall optimized operation of larger eGSE types, it is inevitable to include charging as part of the optimization equation and consider a charging strategy instead of just "opportunity charging".

5.3. Recommendations for future research

This research has resulted in a model to optimize the GSE operations at an airport. However, this does not necessarily mean the end of the research. In addition to the possible improvements already discussed in the previous section, there are a number of other recommendations to be made for future research. The recommendations for the scope, the model and the application of the research itself are discussed below.

Scope recommendations:

- This study only looked at fully electric GSE fleets. The way the model works allows the model to also be used for vehicles that use a different energy source such as diesel or hydrogen. Of course, it is necessary to adjust the parameters in such cases. Additionally, it is important to verify whether the functioning of the model remains valid in these scenarios. In the same way it would also be possible to consider mixed-fleets.

- In this research, the results are examined from the perspective of modeling one type of GSE at a time. In this approach, it is assumed that there is a flight schedule with flights that need to be serviced by a GSE fleet. One could revert this perspective and consider the requirements for each aircraft handling. This way, requirements in terms of equipment, energy, and time can be established per ATM. This approach could be valuable for a more generic application in strategic decision-making, such as airport master planning.

- Based on the interviews, it appears that there is still a lot of uncertainty regarding the possibilities for charging larger eGSE types. Therefore, as mentioned above, it is advisable to extend this research to establish a charging strategy for this more energy-demanding equipment.

- The scenarios in the case study show that there are large differences in the shares of energy consumption due to driving and the performance of flight tasks themselves. In the latter case, there is little room for optimization, because the flights from a flight schedule will always have to be serviced. However, for energy consumption by driving, there is room for optimization and research into different scenarios with regard to starting locations, the road network and the assignment of tasks to vehicles. For a follow-up to this research, it is therefore particularly interesting to look at the group of vehicles that cover greater distances.

- Since this study examines the operation for each GSE type individually, it does not take into account the interactions between different GSE types. Therefore, it would be interesting for future research to explore multiple GSE types simultaneously. The advantage of this approach is that dependencies on each other can be considered, such as physical constraints on the aircraft stand and the use of parking locations by only one vehicle at a time. However, it should be carefully considered how to do this without making the computational complexity too high.

- For future research, further investigation can be conducted into the aspects listed in Section 1.5 as being outside the scope of this study.

Model improvement recommendations:

- In the current model, a new vehicle is used to replace a depleted vehicle during the day. As a result, generally, more vehicles are used in the model than would be necessary if the vehicles were charged. There are two recommendations on how to improve this:

  - One way to include the charging of vehicles is to add the principle of opportunity charging. Because charging is not part of the optimization problem, the possibility of charging between each optimization can be considered as part of the rolling horizon approach. Like with the task allocation of the vehicles, overall optimality of the charging is therefore not guaranteed. If the post-processing shows that the SOC of a vehicle falls below a certain threshold, it can then be decided to charge the vehicle in the next optimization block. In that case, the vehicle can not be used to perform tasks in the next block. After t_{update} minutes, the SOC can be recalculated based on the time the vehicle has been able to charge. For the simplest implementation, the increase in the SOC during charging can be considered linear based on the charging rate and a predefined threshold SOC can be used to decide when the vehicle can be used again. For a better application, the CC-CV (see Section 2.2.3) charging algorithm should be included and, based on the tasks expected in the future, it can be determined whether a vehicle can still be charged or should be used again after t_{update} minutes of charging.
  - A charging strategy is required to properly plan the charging of the vehicles. This can be rule-based, using pre-determined rules that look at future tasks and the expected SOC of the vehicles throughout the day. Yet, this can also be based on an optimization problem, where it is possible to minimize the grid load and the number of times that a vehicle needs to charge. Both the rule-based and the optimization approach can be applied as part of the rolling horizon approach, but it is also possible to make the optimization part of the existing optimization problem with the TSP. However, this makes the complexity of the problem much greater, because the charging also becomes part of the objective function and also requires the "calculation" of the SOC in the MILP problem. It is therefore recommended to keep the charging strategy separated from the TSP. Between two optimizations in the rolling horizon approach, the decisions that are made by the charging strategy can be applied for the next optimization block and the newly obtained SOC can be fed to the charging strategy. For the simplest implementation, the increase in the SOC during charging can be considered linear based on the charging rate. For a better application, the CC-CV (see Section 2.2.3) charging algorithm should be included. The work of Van Oosterom et al. (2023) provides a nice example of a method for routing the vehicles and scheduling them to either perform flight tasks or battery recharging. In this work the CC-CV curve is also approximated.

- The solving performance of the model can be notably improved for GSE types with a logistical function and a wide time window within which flight tasks can be performed. This results in a large number of possible solutions. The MILP solver has no trouble with quickly finding good solutions, but closing the MIP gap by increasing the lower bound can take a lot of time. Therefore, there is room for improvement in this aspect in future research.

- While the location groups used in the model are intended to make it easier for the user to set up a scenario, it is not necessarily guaranteed that this is also better for computational complexity. Using more location groups introduces greater variability in distances between locations, which might make it easier for a MILP solver to converge to a solution. This is something to consider in a follow-up to this research.

- Because the model is structured as a TSP, the tasks are predefined, and then the execution of these tasks is optimized. For aircraft that spend more time on the ground, the model currently handles separate arrival and departure movements, unlike aircraft with short turnaround times. Some GSE types are not tied to both an arrival and a departure movement (such as belt loaders) but can be performed at either one of the two. Examples of this are the water service and refuelling service. In the current model, these tasks are always defined for the time of departure. For future research, it is recommended to explore whether a more accurate approach can be applied in such cases. The challenge here is that determining whether a task should be performed upon arrival or departure of an aircraft creates an optimization problem in itself, next to the TSP.

- In addition to the various filters already applied to reduce the number of (i, j)-pairs, it is also possible to explore the impact of a filter based on the maximum distance for a vehicle. If it is known for a specific GSE type that it is not likely that it will travel more than a certain distance, then all (i, j)-combinations with a distance that does not meet this criterion can be filtered out.

- The model formulation that is presented in this report can only be used for logistics vehicles that become increasingly empty during flight services. For vehicles that are becoming increasingly full, the logistics tasks must be placed after the flight tasks and a number of logistics constraints in the MILP must be reversed. The logistics tasks are then used to empty a vehicle instead of filling it. This adjustment is necessary to model a GSE type like the lavatory service vehicle and should be considered when using the model.

- To make the model more suitable for strategic-level decision-making, it could be considered to model the problem as an assignment problem instead of a TSP. An assignment problem has sufficient accuracy for this level and by using a time discretization (e.g. 5 or 10 minutes), the complexity of the problem can be improved.

- To make the model more suitable for operational-level decision-making, it could be considered to use a flight-specific dataset with aircraft data instead of a generic one. This would allow the model to adapt the number of vehicles and the required demand per flight.

- To make the model more suitable for operational-level decision-making, it could be considered to distinguish between vehicles of the same type. This can be done, for example, based on State of Health (SOH) and logistics capacity. However, the latter requires the addition of k as an index of decision variable q_i and parameter C, which makes the problem more complex.

- To make the model more suitable for operational-level decision-making, it could be considered to incorporate changes in the flight schedule throughout the day. The rolling horizon approach that is already used in the model could be used for this purpose. After each t_{update} minutes, the task list can be updated based on the latest flight schedule information. Another option is to generate the complete task list every t_{update} minutes for the next $t_{forward}$ minutes. The task list is therefore not adjusted, but generated throughout the day. Changes that occur during the optimization of the next t_{update} minutes cannot be included. By making t_{update} lower, more short-term changes can be included in the optimization, but this does result in more optimization blocks that need to be solved.

- Currently the model assumes that vehicles can wait/park along the pier. In the case of power-in power-out stands, this results in an unrealistic approach because vehicles in the model remain "on the stand". It poses a problem for airports that do not use piers with PBBs and power-in push-out stands. It is therefore recommended to make a change for these airports whereby the vehicles return to a dedicated parking area between flight tasks on the aircraft stands. One way this could be done is by adding more parking tasks and a constraint that prevents a vehicle from staying at a flight task for longer than the task time, forcing the vehicle to then move on to the next flight task or to a parking task. A disadvantage of this is that it significantly increases the number of tasks in the problem, and therefore also the problem complexity. Another solution is to simulate this intermediate parking by means of constraints that include the time a vehicle requires to go to and from a parking area in the time constraints. In the post-processing of the model, it would then be possible to determine what the route of a vehicle looked like.

- In the current model, all flights are serviced. The minimum number of vehicles is also based on this. For scenarios where the GSE fleet is known in advance, it would therefore be interesting to add the possibility that not all flight tasks are serviced, but that flights are also not serviced or are serviced too late. This makes it possible to use fewer vehicles. For this purpose, an additional variable could be added to the MILP model that indicates whether a flight is not serviced or is serviced too late. By providing the related constraints with this variable in combination with a Big M cost value, insight could be gained into the trade-off between the number of vehicles and the flights that are serviced. Conversely, it is also possible to determine in advance which flights will be skipped. This could, for example, be based on a percentage that is applied if the number of flights in a certain time exceeds a threshold.

Application recommendations:

- Despite the fact that the developed model is intended for modeling GSE operations at airports, a part of the model can also be effectively used for other applications. The core of the model, the mathematical formulation for the optimization problem, can be used generically for a TSP. Therefore, this formulation can be applied, with possibly some adjustments, for modeling similar logistics problems, such as material handling systems and VRPs.

- The steps taken to reduce the computational complexity can also be used for other logistics optimization problems with such a mathematical model.

5.4. Recommendations for NACO and KLM

This section includes some recommendations that are specific to NACO and KLM.

Recommendations for NACO:

- As NACO is involved in projects where the layout of an airport still needs to be determined, it is of interest to NACO to use the model with as few input parameters as possible. Therefore, it is recommended for NACO to assess the impact of reducing the number of location groups. Additionally, an examination of the influence of aircraft data could be valuable. It is possible that generalizing to one NABO and one WIBO type of aircraft might yield results that are still sufficiently accurate.

- To use more accurate input parameters, NACO could first apply the model to a few projects it has had in the past. By comparing the model's outcomes with the knowledge and data that NACO has from a project, potential improvements can be identified and implemented. In addition, the results can be compared with the results of the simulation software that is already used by NACO.

- It is recommended to use the model for use cases where the simulation software currently in use falls short. This model makes it possible to track individual vehicles during a day. In addition, this model makes it possible to gain insight into the energy consumption for eGSE, where this is not possible with the current software. Another advantage of the model is the possibility to make a trade-off between numbers of vehicles and distance driven.
- The software that is now used at NACO to simulate GSE also has options that the model developed in this thesis does not have. That is why it is also recommended to use the two options side by side. For example, the software that is already in use contains the option to simulate vehicle congestion. If the ideal locations for the vehicles have been determined based on this, energy consumption could, for example, be determined using the developed model.
- Self-built tools are currently being developed and used within NACO for various other applications. It is therefore recommended to put the input and output data of the model developed in this thesis in the same format as that of the other tools.

Recommendations for KLM:

- For KLM, it is recommended to incorporate the KLM-specific procedures into the model. Additionally, it is advisable to extract the equipment specifications from practical data for KLM's GSE fleet. This approach will lead to results that better align with reality. It enables KLM to use the model at a strategic, tactical, and operational level. Depending on this level, disruptions in the flight schedule can also be included as part of the rolling horizon.
- At KLM, the people and therefore the vehicles are currently assigned by hand by someone who has an overview of the open flights and the availability of staff. There are currently people employed for this per GSE type. In combination with the previous recommendation, it is advisable for KLM to see whether a tool can be developed at an operational level that supports the work of these people, based on the model developed in this research. This offers the possibility of a more efficient allocation of resources, because the model can better determine the influence of a decision. A live data feed can be used for this, so that changes in the operation can be taken into account.
- In the current model, every flight task associated with a certain type of aircraft has the same properties. However, if the data per flight is available, it is relatively easy to include it in generating the tasks. This allows a distinction to be made in the logistics demand, but also the numbers of equipment required. This level of detail makes it possible to obtain more realistic results at an operational level.
- It is recommended to keep the logistics locations and parking locations of the vehicles close to each other (as far as possible). The case study indicates that water trucks have high initial "operating costs" because they need to fetch water at the beginning of the day. With the introduction of electric vehicles, this "problem" becomes more significant. Therefore, it is also advisable to consider (fast) charging of vehicles at logistics locations when they need to wait there.

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A
Research paper

The impact of implementing electric Ground Support Equipment (eGSE) on the capacity and demand of GSE fleets at airports

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Abstract

Airports and airlines are examining and committing to the electrification of Ground Support Equipment (GSE). To be able to estimate the required quantity of eGSE, the charging requirements of eGSE, the change of airport electricity requirements, and the scheduling possibilities of eGSE charging for the existing turnaround procedures, a model was developed to simulate and optimize the GSE operations at airports. This was done by means of a Task Scheduling Problem (TSP), that is optimized using Mixed-Integer Linear Programming (MILP). A case study was performed on KLM's GSE fleet at Amsterdam Airport Schiphol. Based on this, it was concluded that there is no difference in the capacity that can be achieved for GSE types that can last an entire day on a single battery charge. However, another group of GSE types experiences battery depletion before the day concludes, requiring measures to maintain the capacity. The results indicate the model's suitability for strategic decision-making. Next to that, the model is effective on an operational level. The use of the model has the potential to make the use of resources in the operation more efficient.

Keywords: electric ground support equipment, airport operations, ground handling, multi-objective optimization, vehicle scheduling, fleet optimization

1. Introduction

In 2017, the aviation sector was the second most important source of Greenhouse Gas (GHG) emissions in the transport sector after road traffic (European Commission, 2021), and it seems that these environmental problems will continue, as the current traffic growth is outpacing fuel efficiency improvements and reductions of emissions from other sectors (European Union Aviation Safety Agency, 2022). To mitigate climate change and control temperature rise, the aviation sector needs to reduce GHG emissions, like CO_2, and the emission of air pollutants from fossil fuels. According to Kirca et al. (2020) aircraft operations are accountable for the majority of the aviation carbon emissions. Hence, there are a number of projects going on to achieve technological advancements to introduce low emission aircraft (Brelje and Martins, 2019). And while aircraft dominate the carbon emissions in the aviation sector, Ground Support Equipment (GSE) also has a share (Kirca et al., 2020). GSE supports the turnaround process of aircraft between the arrival and departure at an airport (National Academies of Sciences, Engineering, and Medicine, 2015). Besides their contribution to carbon emissions (National Academies of Sciences, Engineering, and Medicine, 2015), GSE is known to have a significant contribution to the NO_x pollution (Kirca et al., 2020). In 2012, GSE accounted for 13% of

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NO_x at all airports in the US (Benosa et al., 2018). According to Alruwaili and Cipcigan (2022) and Kirca et al. (2020), one path to cut airport related GHG emissions is to use low or zero-emission GSE and provide infrastructure provision for supporting decarbonization solutions since much of the GSE is at present powered by diesel or petrol fuel. Yim et al. (2013) estimated that electrification of GSE could avert 28% of the early deaths, caused by airport emissions in the UK. Hence, to reduce both carbon and air pollutant emissions from GSE at airports, airports and airlines are examining and committing to the electrification of GSE (Kirca et al., 2020; Francfort et al., 2007).

A number of challenges arise as a fully electrified fleet of GSE is realized. The two main challenges pertain the significantly longer charging time compared to refueling conventional fossil-fueled vehicles and the increased burden on the electric grid (Gulan et al., 2019). Electric versions already exist for a number of, especially smaller GSE types, but these are still being developed for other larger vehicles (Timmermans, 2023). For the early stage decision making of different stakeholders, such as 1.) airport operators, 2.) ground service providers, and 3.) airline companies, it is therefore important to be able to estimate the required quantity of electric GSE (eGSE) types, the charging requirements of eGSE, the change of airport electricity requirements, and the scheduling possibilities of eGSE charging for the existing turnaround procedures. Therefore, the primary focus of the research is the development of a model that can be used to gain insight into the operational requirements for the implementation of an eGSE fleet at airports.

This paper is organized as follows: Section 2 reviews the relevant literature. The conceptual framework is explained in Section 3. After that, the problem formulation is provided in Section 4. In Section 5 several measures to improve the solvability are discussed. The model is applied in a case study for KLM Royal Dutch Airlines at Amsterdam Airport Schiphol (AAS) in Section 6. The results are discussed in Section 7. Finally, conclusions and future research lines are provided in Section 8.

2. Literature review

This section presents a review of the existing literature on operations research that is considered relevant for this research. Section 2.1 discusses different works on the optimization of operations. Next, Section 2.2 reviews different works on energy management, including topics like charging (scheduling), and charging infrastructure as well. Most of the works being reviewed focus on GSE. However, some works focusing on (commercial) Electric Vehicles (EV) are included as well. After that, the scope is widened in Section 2.3, which looks into other related problems in the aviation industry. Finally, a comparison of the different works is provided in Section 2.4.

2.1. Optimization of operations

Scheduling GSE for airport operations is often treated as a VRPTW (Vehicle Routing Problem with Time Windows). Ip et al. (2013) address this problem with a hybrid assignment approach for multiple non-identical vehicles. A similar approach is taken by Padrón et al. (2016), who break down the VRPTW into distinct problems for each vehicle type, using Constraint Programming (CP) to minimize waiting time and total turnaround completion time. Padrón and Guimarans (2019) improved this work to reduce computational times. For baggage tugs, Wang et al. (2021) formulates the problem as a Mixed-Integer Linear Programming (MILP) model. When focusing on aircraft turnaround tasks and staff routing, Gök et al. (2022) treats the problem as a Resource-Constrained Project Scheduling Problem (RCPSP) and uses CP for team routing decisions. Another VRP formulation is presented by Bao et al. (2023), who establish a mixed operation model for aircraft towing tractors with time windows. Van Oosterom et al. (2023) also focus on the dispatching of a fleet of electric aircraft towing tractors. They propose a two-phased MILP program. The first phase takes care of the routing of the towing tractors. In the second phase, the towing tractors are scheduled for aircraft towing tasks or battery recharging. In the context of military aircraft handling, Zhang et al. (2022) suggest using an RCPSP instead of a VRP. They focus on resource allocation for job scheduling, emphasizing the maximization of resource utilization within time windows and constraints, rather than optimizing driving paths or times. Different scheduling algorithms are introduced by Kuhn and Loth (2009), including one MILP problem based on solving static vehicle scheduling problems within a moving time window. Lastly, in the work of Chen (2022), the main goal is to create an automated task allocation optimization mechanism. Here, an auction mechanism for task allocation is implemented.

VRPs are used in various contexts beyond GSE. Song et al. (2019) tackle a VRPTW problem to optimize vehicle routes for customer service. Arias-Melia et al. (2022) deal with a more complex Vehicle Sharing and Task Allocation Problem (VSTAP) problem, including vehicle sharing, using a heuristic approach for solving larger instances.

2.2. Energy management

Multiple studies address the energy management of GSE. Rensen (2013) develops a framework to assess airport design choices. His work analyzes GSE requirements, distance, operational time, and energy consumption. Gulan et al. (2019) presents an charging algorithm for fully electrified airports, using an scheduling algorithm based on variable pricing. Charging priority is assigned based on State of Charge (SOC) and availability of GSE. Kirca et al. (2020) develops a Multi-Input Multi-Output Airport Energy Management (MIMO-AEM) model for understanding eGSE charging requirements and scheduling. The model optimizes GSE usage, battery pack sizes, and gate scheduling.

For EVs, Clemente et al. (2014) tackles the integration of EVs with the power distribution problem, focusing on coordinated charging to prevent grid disruptions. Keskin et al. (2021) presents a Electric Vehicle Routing Problem with Stochastic Waiting Times (EVRPTW), addressing queuing and recharging times at charging stations using a two-stage MILP program with a simulation-based heuristic.

2.3. Related problems in the aviation industry

Francfort et al. (2007) compare eGSE with conventional GSE, demonstrating that eGSE yields lower operating costs at select U.S. airports. Hannah et al. (2012) create a decision support tool to assess carbon-neutral growth strategies at airports. van Baaren (2019) conduct a feasibility study for fully electric towing systems, finding that they are technically and operationally viable with substantial fuel and emissions savings, although cost and logistical challenges remain. Sznajderman et al. (2022) develop an integrated model for GSE and associated emissions, considering loading and unloading stages, and aircraft service types, accurately replicating GSE movements. Bosma (2022) created a capacity model study for sustainable aircraft refueling service vehicles. And lastly, van Amstel (2023) and Horstmeier (2023) contribute to the field of electric aviation, by optimizing infrastructure and charging scheduling while minimizing costs and addressing renewable energy integration and various aspects of electric aviation adoption, charger types, and spatial considerations. These works provide an interesting look at the electrification of airports in general from a different perspective.

2.4. Comparing the existing works

The previous sections have discussed different works that are considered relevant for this research. An overview of the works on GSE, with a comparison on different aspects, is provided in Table 1. Here, the focus of the studies is denoted by an icon, referring to "optimization of operations" ( ), "energy management" ( ), "operational costs" ( ), or "environmental impact" ( ). In addition, a distinction is made between works that consider GSE or not. It stands out that the vast majority of works that consider GSE only look at one or a few GSE types, and in the works that consider several GSE types, the different properties of these GSE types are not taken into account. In some works, several GSE types are divided into a number of categories with similar properties.

Table 1: A comparison of different studies that include the modeling of GSE operations.

	Kuhn and Loth (2009)	Ip et al. (2013)	Padrón et al. (2016)	Song et al. (2019)	Wang et al. (2021)	Gök et al. (2022)	Zhang et al. (2022)	Arias-Melia et al. (2022)	Chen (2022)	Van Oosterom et al. (2023)	Bao et al. (2023)	Rensen (2013)	Clemente et al. (2014)	Gulan et al. (2019)	Kirca et al. (2020)	Keskin et al. (2021)	Francfort et al. (2007)	Hannah et al. (2012)	Van Baaren (2019)	Sznajderman et al. (2022)	Bosma (2022)	This paper
Focuses on	[route]	[route]	[route]	[route]	[route]	[route]	[route]	[route]	[route]	[route]	[route]	[battery]	[battery]	[battery]	[battery]	[battery]	[coins]	[leaf]	[leaf]	[leaf]	[leaf]	[route]
Considers GSE	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓
Includes all common GSE types															✓			✓				✓
- Number of GSE types included	1	0	7	0	1	6	3	0	6	1	1	6	0	6	16	0	3	8	1	11	1	16
- Considers GSE types individually	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓					✓		✓	✓	✓	✓
GSE turnaround operations	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Task allocation	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓								✓		✓	✓
- Travel time between locations	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓			✓	✓	✓	✓
- Service time window	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓										✓
- Service time at aircraft stand	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Individual service times	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓				✓	✓	✓	✓
- Energy consumption of vehicles				✓						✓	✓	✓	✓		✓	✓			✓	✓	✓	✓
Considers eGSE										✓	✓	✓		✓	✓		✓	✓	✓		✓	✓
- Considers mixed fleets											✓			✓	✓			✓			✓	
- Charging (scheduling)										✓	✓		✓	✓	✓	✓			✓		✓	
Determines number of vehicles				✓		✓		✓		✓		✓			✓						✓	✓
Number of vehicles as an input	✓	✓	✓		✓		✓		✓		✓			✓				✓	✓	✓		

3. Conceptual framework

The airport forms an essential part of the air transport system, as it is the physical site at which a modal transfer is made from the air mode to the land modes or vice versa. It accommodates for the interaction of the two other major components of the air transport system, namely: the airline and the user. An airport is designed to enable an aircraft to, if required, unload and load passengers, cargo, and crew (Ashford et al., 2013). These events form the essential parts of the turnaround process of an aircraft. The turnaround process describes all operations for preparing an aircraft for the flight. Aircraft depend on GSE to perform the required processes, such as cleaning, maneuvering and refueling (National Academies of Sciences, Engineering, and Medicine, 2015). Airports that service many yearly passengers must have ground handling service provider(s) that can supply the handling of those passengers and the servicing, maintaining, and engineering of aircraft (Ashford et al., 2013).

The turnaround process is performed during the Ground Time (GT). It starts when an aircraft reaches its parking position at the Actual In Block Time (AIBT) and lasts until the aircraft is ready to depart at the Actual Out Block Time (AOBT) (Schmidt et al., 2016; More and Sharma, 2014; Horstmeier and de Haan, 2001). This is the case for flights that are made ready for take-off immediately after arrival. In general, the servicing time depends on the aircraft type, the number of passengers, the cargo to be (un)loaded as well as the business model of the aircraft operator (Schmidt et al., 2016). An efficient and reliable aircraft turnaround is an essential component of airline success, which allows them to maintain schedules (Schmidt, 2017; Vidosavljevic and Tosic, 2010). In 2019, 32.6% of all flight delays were caused by problems regarding the turnaround of aircraft at airports (Performance Review Commission, 2022). In 2021, this share, which also includes delays related to protective COVID-19 measures, has risen to 47.5%.

The turnaround time has hence become a very important key parameter in determining the profitability of an airline (More and Sharma, 2014).

Each type of GSE has specific properties, activities, and duty cycles. Largely based on the available ACRP reports (National Academies of Sciences, Engineering, and Medicine, 2012, 2015) about GSE, it is possible to classify the GSE types based on their use case: 1.) ground power/air conditioning, 2.) aircraft movement, 3.) aircraft servicing, 4.) passenger (un)loading, and 5.) baggage/cargo handling. The operation of GSE is a function of several parameters that can vary considerably from airport to airport. They influence the type, number and operation (service time) of GSE. A distinction can be made between 1.) operational characteristics, 2.) aircraft characteristics, and 3.) airport infrastructure (ICAO, 2020). Operational procedures determine the types and amounts of GSE services required. The aircraft characteristics influence the stand allocation and often the handling procedures involving GSE. And in terms of airport infrastructure, different aircraft stands exist. They can exhibit considerable differences in terms of location and technical equipment available, which influence the number and operations of GSE. They may also differ for reasons of dedicated usage (e.g. whether a stand is used for cargo aircraft or for passenger aircraft).

As part of noise abatement, night curfews on aircraft operations exist at many airports throughout the world (Ashford et al., 2013). Consequently, many airports only use (the majority of) GSE during the day, meaning they eGSE can and must be charged at night. The consumption of and the way in which the small GSE vehicles are used makes it possible to only have to recharge these vehicles at night, as they can be used for a complete day on one full battery charge. And if it turns out to be necessary, opportunity charging can be used during the day (Timmermans, 2023). Other, larger GSE vehicles, must be charged during the day. With these vehicles, the challenge still lies in battery capacity and the limited space and weight that can be spend on batteries. These vehicles therefore have a greater downtime than their diesel equivalents (Timmermans, 2023).

It has become apparent that there are many differences between the GSE types required for servicing aircraft at an airport. In order to use the proposed model as widely as possible, the model will therefore distinguish between a number of groups with GSE types that share the same properties. Based on literature research and interviews, a number of essential components that are important when modeling GSE operations at an airport can be defined. The literature research shows that there are only a few works that consider multiple GSE types and none of the works that do this do include all details that are assumed to be essential based on the literature research. The smaller GSE types currently do not pose a major challenge in the field of charging. This could possibly be the case in the future for the larger GSE types. Therefore, the model will mainly focus on simulating and optimizing the GSE operations and the associated energy consumption. A follow-up study could then focus on a possible charging strategy based on this energy consumption. In the same way, an addition could be made in the future that would allow mixed fleets to be considered. Including the above elements results in a contribution as shown in the last column of Table 1. Because the literature review also shows that the nature of the operations to be simulated often leads to a computationally complex problem, extensive attention will also be paid to improving the solvability of the model.

4. Problem formulation

4.1. Model setup

The problem at hand will be described as a Task Scheduling Problem (TSP). According to Bunte and Kliewer (2009), an optimal schedule is characterized by minimal fleet size and/or minimal operational costs. These elements are at the heart of the problem. In literature, MILP is widely used to solve TSPs and VRPTWs Bao et al. (2023); Keskin et al. (2021); Kuhn and Loth (2009); Clemente et al. (2014); Wang et al. (2021); Song et al. (2019). Its modeling capability and the availability of good solvers make that MILP is a powerful tool for planning and control problems Earl and D'Andrea (2005). Therefore, the problem at hand will also be solved using MILP.

Within the model there are 1.) parking tasks, 2.) flight tasks and 3.) logistics tasks. The properties of the task types are explained in the work of Timmermans (2023). Two parking tasks are defined for each parking location. The parking task from where a vehicle starts runs from the beginning of the day to the end of the day. This makes it possible for a vehicle to leave a parking location throughout the day. The parking task where a vehicle ends is defined at the end of the day. The flight tasks arise from the flight schedule and the turnaround tables of the aircraft types. The earliest time (ET_i) and latest time (LT_i) of a flight task i define the time window within which the task must be executed. The task time (TT_i) follows from the turnaround table as well. It always holds that $TT_i \leq LT_i - ET_i$. The demand (DEM_i) and energy consumption (EC) of a flight task depend on the aircraft type and the GSE type. One flight may result in multiple flight tasks, based on the required number of vehicles and how long the aircraft is on the ground. The location of a flight task is an aircraft stand. It is therefore possible that there are several flight tasks with the same location if 1.) in the flight schedule several flights are handled on one aircraft stand and/or 2.) several vehicles of one type are required to handle one flight. The logistics tasks may be used by a vehicle to refill or empty its storage compartment. They are therefore only necessary for GSE types with a so-called logistics function. In this paper, the logistics tasks are placed prior to a flight task in terms of time window. This makes it possible for a vehicle to go to a logistics task to refill before a flight, if necessary. The model in this paper can therefore only be used for vehicles that have a decrease in load when servicing a flight.

4.2. Rolling horizon approach

To reduce the computation time for the optimization problem at hand, a rolling horizon is implemented. Kuhn and Loth (2009) use a rolling horizon for the scheduling of GSE as well. Algorithm 1 explains how it is applied in the context of this research. Here CT is the current time and Π is the set of flight tasks that still need to be assigned. The set of all flight tasks is A. Each iteration set F is defined as the set of flights $i \in \Pi$ that have an earliest time (ET_i) that is within the next $t_{forward}$ minutes from the current time (CT). The optimization problem is then solved, which uses the data from the vehicles $k \in K$ and the flight tasks $i \in F$ to perform the assignment of tasks. The assigned flight tasks with a start time (s_i) that is within the current time and the time step at which the update takes place, t_{update}, are added to set Ω. Here, it holds that $t_{update} \leq t_{forward}$. The execution of the flight tasks in Ω is fixed and removed from set Π. The overall task list is updated and the current time is increased with t_{update}. After this, set F is defined again, based on the new CT. This process repeats until $\Pi = \emptyset$.

Algorithm 1: Rolling horizon approach

$CT \leftarrow 0$
$\Pi \leftarrow A$
while $\Pi \neq \emptyset$ **do**
    $F \leftarrow \{i \in \Pi : ET_i \leq CT + t_{forward}\}$
    Solve: optimization problem using data regarding all $k \in K$ and $i \in F$
    $\Omega \leftarrow \{i \in F : s_i \leq CT + t_{update}\}$
    Assign: all tasks in Ω
    $\Pi \leftarrow \Pi \setminus \Omega$
    Update: overall task list together with vehicles states and SOC
    $CT \leftarrow CT + t_{update}$

4.3. Mathematical model

The notations used in this paper are shown in Table 2. In the sets used in the model, a distinction is made between numerical sets and modeling sets. For the modeling sets, the model formulation sometimes uses one or more subscripts, which indicate a subset. Three subscripts can be distinguished: 1.) S (start), for the tasks that need to be used as start tasks, 2.) B (between), for the tasks that can be used in between, and 3.) E (end), for the tasks that need to be used as end tasks. For example, P_S is a subset of set P, i.e.

Table 2: Notations used in this paper.

Set	Description
$\mathbb{R}^+$	Set of all positive real numbers
$\mathbb{R}_0^+$	Set of all positive real numbers including 0
$\mathbb{N}_0^+$	Set of all positive integers including 0
P	Set of parking tasks
F	Set of flight tasks
L	Set of logistics tasks
T	Set of all tasks ($P \cup F \cup L$)
K	Set of all vehicles ($K_{unused} \cup K_{used}$)
K_{unused}	Set of vehicles that have not been used yet ($K_{unused} \subseteq K$)
K_{used}	Set of vehicles that have been used in a previous run ($K_{used} \subseteq K$)
$K_{depleted}$	Set of vehicles that are used and depleted ($K_{depleted} \subseteq K_{used}$)

Index	Description	
i	Index for current task	$i \in T$
j	Index for the next task	$j \in T$
k	Index for vehicle	$k \in K$

Parameter	Description	Domain
ET_i	Earliest time of performing task i	$\mathbb{R}_0^+$
LT_i	Latest time of performing task i	$\mathbb{R}^+$
TT_i	Required time for task i	$\mathbb{R}_0^+$
D_{ij}	Distance between task i and j	$\mathbb{R}_0^+$
V	Travel speed of vehicles	$\mathbb{R}^+$
RT_k	Time at which vehicle k becomes ready	$\mathbb{R}_0^+$
ST_k	Starting task of vehicle k	T
SL_k	Starting load of vehicle k	$\mathbb{R}_0^+$
EP_k	Ending parking task of vehicle k in previous run	P
LOC_i	Location number of task i	$\mathbb{N}_0^+$
TN_i	Task name of task i	-
DEM_i	Demand of task i	$\mathbb{R}_0^+$
C	Capacity of vehicles	$\mathbb{N}_0^+$
R	Logistics refilling time constant	$\mathbb{R}^+$
M	Big M for time constraints	$\mathbb{R}^+$
Q	Big M for capacity constraints	$\mathbb{R}^+$

Variable	Description	Domain
x_{ij}	Whether a vehicle travels from task i to j	$\{0,1\}$
y_i	Whether task i is visited	$\{0,1\}$
z_k	Whether vehicle k is used	$\{0,1\}$
s_i	Starting time of servicing task i	$\mathbb{R}_0^+$
w_i	Waiting time at task i	$\mathbb{R}_0^+$
q_i	Load quantity of a vehicle after visiting task i	$\mathbb{N}_0^+$

$P_S \subset P$, and it contains all task indices of parking tasks that need to be used as start tasks. If no subscript is indicated, the entire set is meant (e.g. $P_{SBE} = P$). After each optimization, the modeling sets P, F, L, K_{unused}, K_{used} and $K_{depleted}$ are updated as part of the rolling horizon. After each optimization during the rolling horizon, a number of parameters are updated based on the previous optimization. This concerns parameters RT_k, ST_k, SL_k, EP_k, and LOC_i.

The objective function consists of five parts: 1.) the total number of vehicles used, 2.) the total distance traveled by all vehicles (in km), 3.) the number of times vehicles went to a logistics task, 4.) the sum of the starting times at the flight tasks and 5.) the total waiting time of vehicles at a logistics task. Objective function components 1 and 2 are used to optimize actual scenarios and components 3, 4 and 5 are used to help the MILP's solver converge to a solution. Depending on the goal of the optimization, the weighting factors λ_1 to λ_5 can be used to determine the proportions of the five objective function components. However, the weighting factors λ_3 to λ_5 must be relatively small so that they do not influence the optimization of the first two objective function components.

$$\min \lambda_1 \underbrace{\left(\sum_{k \in K} z_k\right)}_{\text{obj1}} + \lambda_2 \underbrace{\left(\sum_{i \in T}\sum_{j \in T} \frac{D_{ij}}{1000} x_{ij}\right)}_{\text{obj2}} + \lambda_3 \underbrace{\left(\sum_{i \in F} s_i\right)}_{\text{obj3}}$$

$$+ \lambda_4 \underbrace{\left(\sum_{i \in T \setminus L}\sum_{j \in L} x_{ij}\right)}_{\text{obj4}} + \lambda_5 \underbrace{\left(\sum_{i \in L} w_i\right)}_{\text{obj5}}$$

Subject to

$$y_j = \sum_{i \in T} x_{ij} \qquad \forall j \in T_{BE} \tag{G1b}$$

$$y_i = \sum_{j \in T} x_{ij} \qquad \forall i \in T_S \tag{G1b}$$

$$z_k \geq y_i \qquad \forall k \in K, \;\; i = ST_k \tag{G2}$$

$$\sum_{i \in T} x_{ih} = \sum_{j \in T} x_{hj} \qquad \forall h \in T_B \tag{G3}$$

$$\sum_{i \in T} x_{ij} \leq 1 \qquad \forall j \in T \tag{G4a}$$

$$\sum_{j \in T} x_{ij} \leq 1 \qquad \forall i \in T \tag{G4b}$$

$$x_{ii} = 0 \qquad \forall i \in T \tag{G5}$$

$$x_{ij} = 0 \qquad \forall i \in T, \;\; j \in T_S \tag{G6a}$$

$$x_{ij} = 0 \qquad \forall i \in T_E, \;\; j \in T \tag{G6b}$$

$$x_{ij} = 0 \qquad \forall i \in T_S, \;\; j \in T_E \tag{G7}$$

Constraints G1b and G1b connect x_{ij} to y_i. Constraint G2 ensures that $z_k = 1$ if vehicle k is used for a task in F. Constraint G3 ensures the flow conservation for tasks in T_B. Constraints G4a and G4b ensure that task j can only be visited once and task i can only be left once, respectively. Constraint G5 ensures that vehicles do not drive from task i to task i. Constraints G6a and G6b ensure that a vehicle can not enter a start task and leave an end task, respectively. Constraint G7 ensures that a vehicle can not travel from a start to an end task.

$$s_i \geq ET_i \qquad \forall i \in T \tag{G8a}$$

$$s_i \leq LT_i \qquad \forall i \in T \tag{G8b}$$

$$s_j \geq s_i + TT_i + w_i + \frac{D_{ij}}{V} - M\left(1 - x_{ij}\right) \qquad \forall i, j \in T, \;\; i \neq j \tag{G9a}$$

$$s_j \leq s_i + TT_i + w_i + \frac{D_{ij}}{V} + M\left(1 - x_{ij}\right) \qquad \forall i, j \in T, \;\; i \neq j \tag{G9b}$$

$$s_j \geq \left(RT_k + \frac{D_{ij}}{V}\right) x_{ij} \qquad \forall j \in T, \;\; i = ST_k, \;\; k = LOC_i \tag{G10}$$

Constraints G8a and G8b ensure that visiting a task can not start before ET_i or after LT_i, respectively. Constraints G9a and G9b ensure that a vehicle can not start with task j before arriving at task j. Constraint G10 ensures that a vehicle does not start the servicing of task j before it arrives there (when traveling from starting task i).

$$z_k \leq z_l \qquad \forall k \in K_{unused}, \;\; l \in K_{used} \tag{G11}$$

$$y_i \leq y_h \qquad \forall k \in K, \;\; i = EP_k, \;\; h = ST_k \tag{G12}$$

$$z_k = 0 \qquad \forall k \in K_{depleted} \tag{G13}$$

Constraint G11 ensures that unused vehicles can only be used if all previously used vehicles are used again. Constraint G12 ensures that an end parking task can only be used if the vehicle that ended there in a previous run is used in the current run. Constraint G13 ensures that depleted vehicles are not used.

$$y_i = 1 \qquad \forall i \in F \tag{F1}$$

$$s_i \geq ET_i \qquad \forall i \in F \tag{F2a}$$

$$s_i \leq LT_i - TT_i \qquad \forall i \in F \tag{F2b}$$

Constraint F1 ensures that all flight tasks are performed. Constraints F2a and F2b ensure that performing task i can not start before ET_i or end after LT_i, respectively.

$$q_j \leq q_i - DEM_j + Q\left(1 - x_{ij}\right) \qquad \forall i \in T, \;\; j \in T \setminus L, \;\; i \neq j \tag{L1a}$$

$$q_j \geq q_i - DEM_j - Q\left(1 - x_{ij}\right) \qquad \forall i \in T, \;\; j \in T \setminus L, \;\; i \neq j \tag{L1b}$$

$$q_i \geq C - Q\left(1 - x_{ij}\right) \qquad \forall i \in L, \;\; j \in T \setminus L \tag{L2}$$

$$q_i \geq SL_k \qquad \forall i \in T_s, \;\; k = LOC_i \tag{L3a}$$

$$q_i \leq SL_k \qquad \forall i \in T_s, \;\; k = LOC_i \tag{L3b}$$

Constraints L1a and L1b ensure that the load of a vehicle at task j is equal to the load at task i minus the demand of task j. Constraint L2 ensures that a vehicle leaves the logistics task with a full load. Constraints L3a and L3b ensure that vehicle k leaves the starting task with a load of SL_k.

$$w_j \geq R\left(q_j - q_i\right) - M\left(1 - x_{ij}\right) \qquad \forall i \in T, \;\; j \in L \tag{L4}$$

$$s_i + w_i \leq LT_i \qquad \forall i \in L \tag{L5}$$

Constraint L4 ensures that the waiting time at a logistics task is R minutes per load unit that is added. Constraint L5 ensures that a vehicle leaves a logistics task before LT_i.

$$q_i \leq C \qquad \forall i \in T \tag{L6}$$
$$x_{ij} = 0 \qquad \forall i, j \in L \tag{L7}$$
$$x_{ij} = 0 \qquad \forall i \in L,\ j \in F,\ TN_i \neq TN_j \tag{L8}$$
$$x_{ij} = 0 \qquad \forall i \in L,\ j \in P \tag{L9}$$

Constraint L6 ensures that the load of a vehicle can not exceed the vehicle's capacity. Constraint L7 ensures that vehicles do not drive from one logistics task to another. Constraint L8 ensures that vehicles can only drive from a logistics task to its corresponding flight task. Constraint L9 ensures that vehicles can not drive from a logistics task to a parking task.

5. Model solving

Although mathematically correct, the model's solvability can be substantially improved by several measures. Powerful software packages can solve MILP-problems efficiently for problems in which the number of binary variables is of reasonable size (Earl and D'Andrea, 2005). A major disadvantage of MILP is its computational complexity. The NP-complete nature of many scheduling problems, and MILP-models in general, precludes their being solved within a reasonable time (Roslöf et al., 2002). According to Earl and D'Andrea (2005), the computational requirements can grow significantly as the number of binary variables needed to model the problem increases. Darvish et al. (2020) state that the effectiveness of solving optimization problems using a brand-and-bound/cut algorithm relies mainly on its mathematical formulation. Therefore, several improvements are implemented such as model tightening, increasing the model density, and breaking model symmetry.

5.1. Model tightness

The constraints below are mathematically redundant, but improve the solvability by enforcing variable upper bounds on each continuous variable to tighten the feasible region.

$$s_i \leq ET_i + M\,(1 - y_i) \qquad \forall i \in P_S \tag{T1}$$
$$s_i \leq ET_i + M\,(1 - y_i) \qquad \forall i \in P_E \tag{T2}$$

Constraint T1 forces a vehicle to start at ET at the start P task that is used. Constraint T2 forces a vehicle to arrive at its end P task at ET.

5.2. Model density

Although there is nothing wrong with the model formulation from a mathematical point of view, the model does contain a lot of binary variables that could never be part of a feasible solution due to the constraints in the model. This makes that the model is currently quite sparse.

In a similar way to the chain decomposition applied in the work of Hooker and Natraj (1995), by filtering the (i, j)-pairs based on the constraints of the model, it is already possible to omit a large number of (i, j)-pairs from the model in advance. This reduction does not affect the availability of potentially optimal solutions in the model, because only those decisions that are infeasible due to the constraints are omitted from the model. The reduction can go up to $> 85\%$. Let T be the set of tasks, and G_0 be the set of all pairs (i, j), i.e. $G_0 = \{\ (i, j)\ \mid i, j \in T\ \}$. Then, the steps to reduce the (i, j)-pairs are:

$$G_1 = G_0 \setminus \{\ (i,j)\ \mid i, j \in G_0, i = j\ \}$$
$$G_2 = G_1 \setminus \{\ (i,j) \mid i, j \in G_1, i \in L, j \in F, TN_i \neq TN_j \}$$
$$G_3 = G_2 \setminus \{\ (i,j)\ \mid i, j \in G_2, j \in T_S\ \}$$
$$G_4 = G_3 \setminus \{\ (i,j)\ \mid i, j \in G_3, i \in T_E\ \}$$
$$G_5 = G_4 \setminus \{\ (i,j)\ \mid i, j \in G_4, i, j \in L\ \}$$
$$G_6 = G_5 \setminus \{\ (i,j)\ \mid i, j \in G_5, i \in L, j \in P\ \}$$
$$G_7 = G_6 \setminus \{\ (i,j)\ \mid i, j \in G_6, i \in T_S, j \in T_E\ \}$$
$$G_8 = G_7 \left\backslash \left\{\ (i,j)\ \middle|\ i, j \in G_7, ET_i + TT_i + \frac{D_{ij}}{V} > LT_j - TT_j \right\}\right.$$

The set G_8 represents the filtered combinations after applying all the specified conditions.

To further reduce the number of variables in the model, logistics tasks are only created for vehicles with a logistics task. For vehicles without a logistics task it holds that $L = \emptyset$. The decision variable q_i and the "logistics task constraints" are also only added to the model if necessary. The above actions result in a lower computational load in two ways: 1.) when creating the model there are fewer constraints and variables that have to be included, and 2.) because the optimization problem is smaller, it can be solved faster.

5.3. Model symmetry

Degeneracy in MILP problems occurs when the optimal solution to the problem lies at a point where one or more of the binary variables can take on different values while still maintaining the same optimal objective value. In other words, there are multiple feasible solutions that all yield the same objective function value. These solutions are called symmetric. When degeneracy occurs, it means that the search space for finding the optimal integer solution is more complex and may require additional computational effort to explore all possible integer combinations. It has been a topic of interest since the invention of the simplex method (Gamrath et al., 2020). By augmenting the model with suitable symmetry-breaking constraints, the structure of the model can be considerably improved by reducing the extent of the feasible region that must be explored (Sherali and Smith, 2001).

In the developed model, degeneracy is resulting from the possible combinations to assign vehicles to a sequence of tasks. For a given vehicle set with $|K|$ vehicles, there are

$$C\left(|K|, N_u\right) = \binom{|K|}{N_u} = \frac{|K|!}{N_u!\left(|K| - N_u\right)!}$$

possible options to select N_u vehicles from the fleet. Second, among the selected vehicles, there are $N_u!$ options to allocate the sequences of tasks to the vehicles. Combining both types of symmetry results in

$$\binom{|K|}{N_u} N_u! = \frac{|K|!}{N_u!\left(|K| - N_u\right)!} N_u! = \frac{|K|!}{\left(|K| - N_u\right)!}$$

equivalent solutions.

To break the first type of symmetry, a constraint based on the work of Adulyasak et al. (2014) can be used: constraint S1 ensures that vehicle k can only be used if vehicle $k-1$ is used.

$$z_k \leq z_{k-1} \qquad \forall k \in K_{unused} \setminus \min\left(K_{unused}\right) \tag{S1}$$

To resolve the second symmetry issue, a hierarchical constraint inspired by Darvish et al. (2020) can be used: constraint S2 ensures that if task $j \in T_B$ is serviced by vehicle k, then at least one other task $j' \in T_B$, with $j' < j$, must be performed by vehicle $k-1$.

$$\begin{aligned} & x_{ij} \leq \sum_{j'=\min T_B}^{j-1} x_{i'j'} \\ & \forall j \in T_B,\ \ k \in K_{unused} \setminus \min\left(K_{unused}\right), \\ & k' \in K_{unused},\ \ k' = k-1,\ \ i = ST_k,\ \ i' = ST_{k'} \end{aligned} \tag{S2}$$

Both constraints are valid inequalities and strengthen the model formulation. These constraints can only be used if all vehicles in the fleet are homogeneous and start at the same location. If this is not the case, a more optimal solution could be prevented by one of the symmetry breaking constraints. The constraints are therefore only applied in the model if this is possible without excluding optimal solutions.

6. Model application

To validate the model, a sensitivity analysis and a case study were conducted based on the GSE fleet of KLM Royal Dutch Airlines that is operating at Amsterdam Airport Schiphol (AAS). To this extent, the MILP-problem was coded in Python and solved using Gurobi. This paper includes the validation for a GSE type without a logistics function (belt loader) and a summary of the results for a GSE type with a logistics function (water truck). We refer to Timmermans (2023) for the complete model validation.

6.1. Instances generation

The following datasets were used to generate the instances:

- Flight schedule: the used flight schedule was provided by KLM and based on the IATA Busy Day definition. Based on this definition, July 13 2023 was selected as the IATA Busy Day. Filtering the flight schedule on airlines that are handled by KLM resulted in a flight schedule with a total of 735 Air Traffic Movements (ATMs) by fourteen different aircraft types. The ATMs were matched with each other to create a flight schedule.

- Task information: The turnaround tables available at KLM for the various aircraft types were used to create the flight tasks. For aircraft types for which no turnaround table was available, a comparable aircraft type was used. A distinction was made between separate arrivals, separate departures and full turnarounds.

- Distances: the aircraft stands and parking locations are divided over 35 location groups. These location groups were based on a document used by KLM. It also includes the distances between the location groups and based on this the shortest distance between all combinations of location groups were calculated.

- Vehicle data: spec sheets by TLD (2023) and Charlatte (2017) were used for the belt loaders and spec sheets by Vestergaard (2023) and Orientitan Ground Support Equipment (2019) were used for the water trucks. The calculation proposed by Kirca et al. (2020) was used for the energy consumption of both vehicles. An average speed of 15 km/h was assumed for the driving speed.

For the sensitivity analysis, the objective function as discussed in Section 4 was first normalized. In this way, the sensitivity analysis is performed across the relevant range of the objective values. Only the first two sub-objectives were considered, which focus on minimizing the number of vehicles used and the distance driven.

6.2. Results for the belt loaders

Figure 1 shows the results of the sensitivity analysis for the belt loaders. A distinction is made between the total number of vehicles used in a day and the maximum number of vehicles required within a 30-minute time window. A number of interesting solutions are:

- Solution 6 with $(\lambda_1, \lambda_2) = (0.70, 0.30)$: This is the solution that requires the least number of vehicles, with the lowest total traveled distance (48.773 km) based on this number of vehicles. In this case, a total of 37 vehicles are used during the day. These vehicles are also all needed at the peak time.

- Solution 10 with $(\lambda_1, \lambda_2) = (0.50, 0.50)$: This solution shows that with 37 vehicles during the peak a lower total traveled distance of 40.733 km can also be achieved. A total of 41 vehicles is used during the day.

- Solution 18 with $(\lambda_1, \lambda_2) = (0.001, 1.00)$: This is the solution with the lowest total traveled distance (24.620 km). This requires a total of 52 vehicles. During the peak, 41 of these vehicles are used.

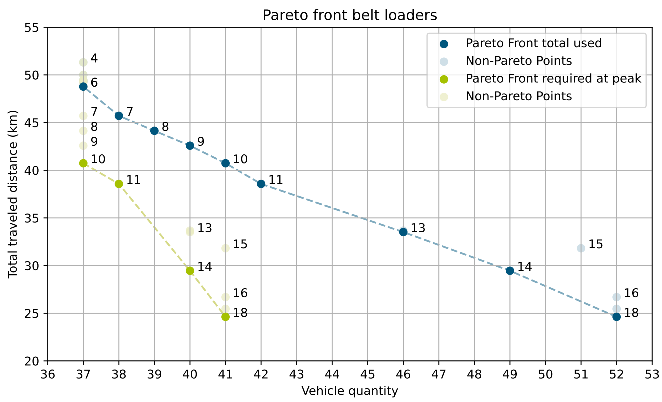

Figure 1: Two Pareto-fronts for the sensitivity analysis of the multi-objective optimization for the belt loader operations. The numbered labels next to the data points correspond to a combination of λ_1 and λ_2.

In general, there is a trend that shows that the use of more vehicles results in a lower total traveled distance. Because this type of GSE only operates at the aircraft stands, the vehicles can often remain idle nearby. The figure also includes solutions that are not in the Pareto front. Analysis of the results has shown that these solutions include inefficiencies that arise from the use of the rolling horizon approach. In these scenarios, a "choice" is made for certain vehicles in one optimization run that is optimal at that moment. However, this choice appears to be generally not optimal in the optimization runs in the remainder of the rolling horizon approach.

Solution 6 from Figure 1 is used for the model validation. Figure 2 shows how many vehicles are needed at each time of the day. The average utilization rate of the vehicles is approximately 21%. Here, the utilization rate is calculated as the total time that a vehicle is busy with (driving to) a task, divided by the time in one day (24 hours). This shows that there is room for charging in between. A total of 210 kWh was used to execute the task schedule. Of this, 182 kWh (86%) was used to perform the tasks on the aircraft stands, i.e. running the conveyor belt, and 29 kWh (14%) was used for driving a total distance of 48.773 km. This makes clear that most of the energy consumption for the belt loaders cannot be optimized, because the flight tasks have to be carried out anyway. If desired, the 29 kWh can be reduced by using more vehicles, as can be seen in Figure 1. None of the belt loaders had an depleted battery at the end of the day.

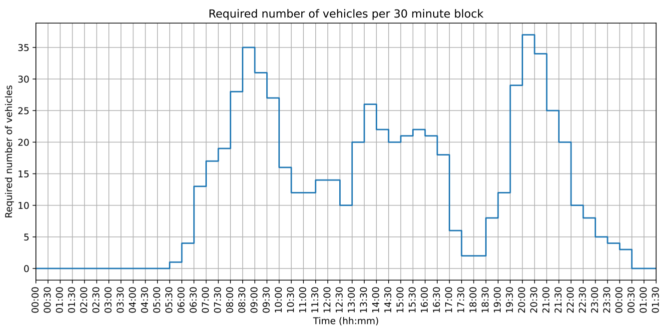

Figure 2: The required number of belt loaders per 30 minutes.

6.3. Validation for the belt loaders

The data available at KLM showed that the number of belt loaders as determined by the model is a bit too high, but in the right order of magnitude. This is mainly due to the fact that two belt loaders are used per flight in the model and in reality this is sometimes one because of 1.) the amount of baggage on a flight, and 2.) the availability of resources. The conversations with KLM also revealed that it is usually not necessary to charge the belt loaders during the day. This is confirmed by the solution of the model. The vehicles were originally purchased with a battery capacity that should last two shifts to operate a full day, but due to degeneration there are batteries that have an State of Health (SOH) that is lower than the 100% used in this model.

6.4. Results for the water trucks

Figure 3 shows the results of the sensitivity analysis for the water trucks. The vast majority of solutions are not part of the Pareto front. A trend that can be deduced from this is that a minimization of total traveled distance in this case also results in a minimization of the number of vehicles required. Because the water trucks first have to go to the logistics location to collect water, a relatively high initial "fixed" distance is required to put a new vehicle into use.

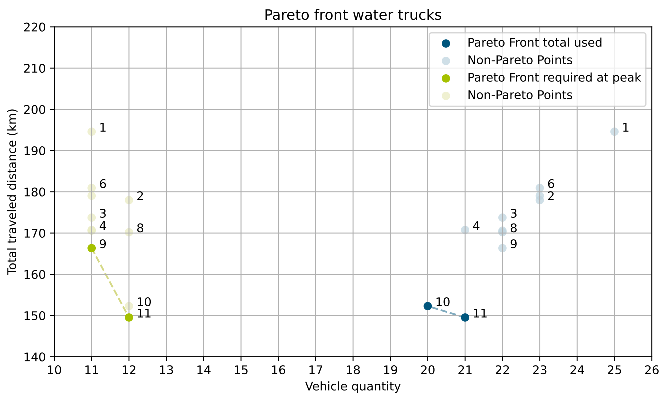

Figure 3: Two Pareto-fronts for the sensitivity analysis of the multi-objective optimization for the water truck operations. The numbered labels next to the data points correspond to a combination of λ_1 and λ_2.

The task schedule that follows from the model for solution 10 (in Figure 3) is shown in Figure 4. New vehicles are added gradually during the day, because other vehicles get depleted. For many vehicles, a time window can be identified in which it would be possible to use opportunity charging. This would result in fewer vehicles needed in total.

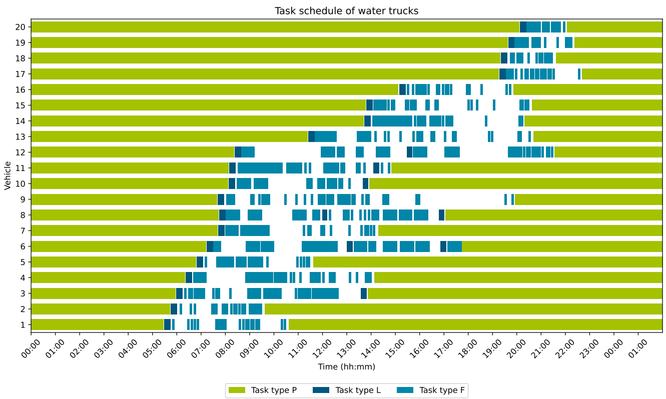

Figure 4: The task schedule for the water truck operations.

A total of 977 kWh was used to execute the task schedule in Figure 4. Of this, 30 kWh (3%) was used to perform the tasks on the aircraft stands, i.e. operating the pump, and 947 kWh (97%) was used for driving a total distance of 152.283 km. This makes clear that most of the energy can be optimized, by minimizing the total traveled distance. The batteries of 16 water trucks were eventually depleted ($SOC < 30\%$).

7. Discussion

Based on the literature review, it had already been established that there are many differences between the GSE types required for servicing aircraft at an airport. Based on this, the decision was made to differentiate certain groups of GSE types in the model that share similar characteristics, so that the model can be broadly applied. This decision was made because the literature review also revealed that there are few works that encompass all GSE types in the research. The results obtained from the model provide a good indication of the required number of vehicles, energy consumption, and the possibility of optimization. However, the validation of the model, in particular, shows that despite distinguishing between certain groups of GSE, there are still differences in the operation and performance of each individual GSE type that affect the results. This is where the desired application of the model becomes relevant. Making a distinction between a strategic and operational application of the model and the associated choices allows for an interpretation of the choices and assumptions that emerged in the review of the existing works and the contributions and limitations of this research.

The results of the model developed in this research show that the model can be used for making strategic decisions. The vehicle quantities generated by the model are in the right order of magnitude, and the total energy consumption provides sufficient insight for making decisions at a strategic level. By including all the components that were assumed to be essential for modeling GSE operations based on the literature review and interviews, the current model can already be used at an operational decision level more effectively than comparable works that have made more simplifications and assumptions at this level.

8. Conclusions and future work

From the results of the case study, it can be concluded that the impact of implementing eGSE on the capacity and demand of a GSE fleet depends on the type of GSE. For GSE types that can last an entire day on a single battery charge, there is no difference in the capacity that can be achieved. These vehicles can, therefore, be directly replaced one-to-one compared to their conventional counterparts. This primarily applies to smaller vehicles, and a condition for this is that the vehicles are not needed at night, which allows them to get charged again. This is the case at many airports due to nighttime curfews.

However, there is also a group of GSE types where the model results show that the vehicles become depleted before the end of the day. To maintain the capacity of these GSE types, it is necessary to either 1.) use more of these vehicles, 2.) charge the vehicles during the day, 3.) use batteries with a higher capacity, or 4.) use vehicles with a better efficiency. However, it should be noted that charging the vehicles during the day does not necessarily results in a maintained capacity, as this is depending on the possibility to charge. This is related to the distribution of the tasks over the day. Using the developed model, it is possible to determine how many additional vehicles are needed when there is no daytime charging. For interim charging, an estimate can be made based on the model results and the concept of opportunity charging, but optimality is not guaranteed in this case. Therefore, additional research is required for these vehicles, including the development of a charging strategy as part of the scope. The work of van Oosterom et al. (2023) provides a nice example of a method for routing the vehicles and scheduling them to either perform flight tasks or battery recharging.

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B

General flight cycle and A-CDM

The flight cycle of a commercial passenger aircraft can be broken down into four main phases (see Figure B.1) (Lubig et al., 2021):

Phase 1. **Outbound Roll Time (ORT):** This phase begins when the aircraft departs from the aircraft stand and ends when it takes off from the runway. Within this phase, a distinction can be made between the Taxi-Out Time (TOT) and the Departure Runway Occupancy Time (DROT).

Phase 2. **Air time (AT):** This is the phase where the aircraft is in the air, flying from its departure airport to the destination airport. The start and end of the phase is indicated by the Actual Time of Departure (ATD) and Actual Time of Arrival (ATA), respectively. The airline's schedule indicates the "scheduled" times: the STD and STA.

Phase 3. **Inbound Roll Time (IRT):** This phase begins when the aircraft touches down at the runway and ends when it arrives at the aircraft stand. Within this phase, a distinction can be made between the Arrival Runway Occupancy Time (AROT) and the Taxi-In Time (TIT).

Phase 4. **Ground time (GT):** This phase begins when the aircraft comes to a stop at the aircraft stand and ends when it is ready to depart from the aircraft stand. The start and end of the phase is indicated by the Actual In-Block Time (AIBT) and Actual Out-Block Time (AOBT), respectively. There is also an equivalent available for the scheduled times: the SIBT and SOBT. Here, the "block" is a reference to the chocks (large rubber or wooden wedges) that are placed SIBT and removed from SOBT around each wheel, to keep the aircraft from moving (Gök et al., 2022).

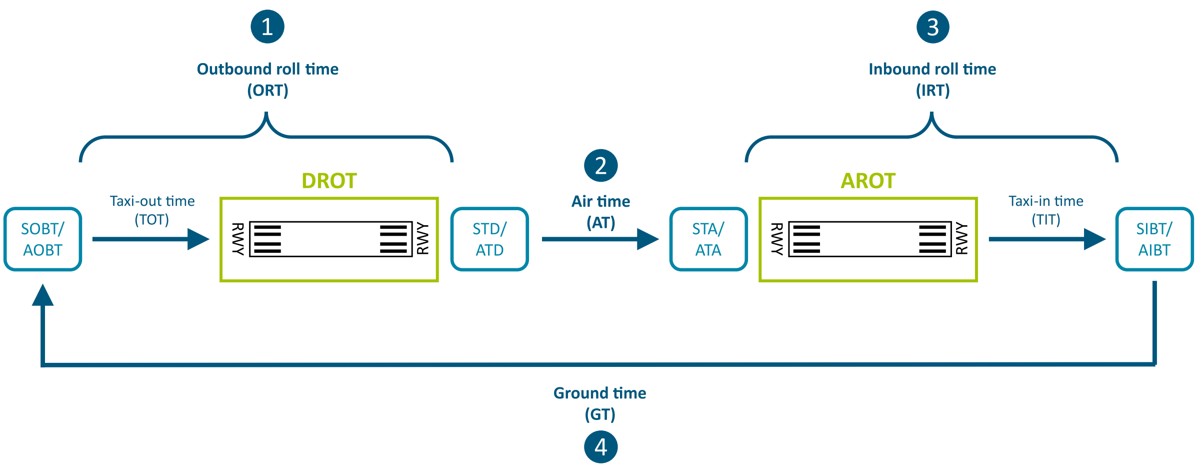


Figure B.1: *Principle of the general flight cycle (adapted from Lubig et al. (2021)).*

An approach to handle airport operations, including apron operations, has been put in place at some of the major European airports in the last two decades. This is called Airport Collaborative Decision Making (A-CDM), and it aims at enhanced information sharing between all airport stakeholders. Information to be shared includes the above mentioned timestamps around the status of all activities, and the establishment of certain milestones or key times for each turnaround, around which everything else is organized (Gök et al., 2022). In the case of AAS, EOBT and TOBT are also used (KLM Royal Dutch Airlines, n.d.-a). The "E" and "T" at the beginning of the acronyms hereby refer to "Expected" and "Target", respectively. Next to that, the Target Start-up Approval Time (TSAT), Calculated Take-Off Time (CTOT) and Target Take-Off Time (TTOT) are included.

C
Ground Support Equipment types

In this appendix the different GSE types at airports are described and specified. The classification and descriptions are largely based on the available ACRP reports (National Academies of Sciences, Engineering, and Medicine, 2012, 2015) about GSE. Not every type of GSE is used at every airport.

C.1. Ground power / Air conditioning

These GSE types are used to help start the engines, operate instruments and provide passenger comfort (e.g., lightning, air conditioning) while an aircraft is on the ground.

- **Ground Power Unit**
  A Ground Power Unit (GPU) is designed to provide electricity to an aircraft when it is parked on the ground and its main engines and on-board APU are off. Aircraft require power at 115 V and 400 Hz. Depending on the size of the aircraft, it may be necessary to connect multiple GPUs. They can also be used to start aircraft engines. There are three types of GPUs with respect to their location and mobility:

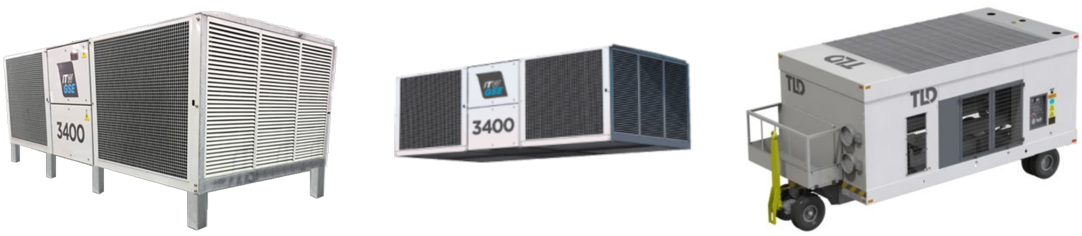
  1. Fixed GPU: Fixed GPUs are installed on an aircraft stand. They can only serve aircraft that arrive at the stand where they are installed. The type and quantity of these GPUs to be installed at each stand have to be decided in the airport planning phase.
  2. Bridge-mounted GPU: Bridge-mounted GPUs are installed under a Passenger Boarding Bridge (PBB). The mobility of this type of APU is therefore also restricted: as the PBB moves, so does the APU.
  3. Mobile GPU: Mobile GPUs are built upon a cart that is towed by a tug that transports them between the aircraft stands. Mobile GPUs can be fuel or battery powered.

(a) *An example of a fixed GPU (ITW, n.d.).* **(b)** *An example of a bridge-mounted GPU (ITW, n.d.).* **(c)** *An example of a mobile GPU (ITW, n.d.).*

Figure C.1: *Three different types of Ground Power Units.*

- **Air Climate Unit**
  Also referred to as air carts, these units provide Pre-Conditioned Air (PCA) (i.e., cooled and heated) to parked aircraft when their main engines and APU are off. As with the GPUs, the following three types of Air Climate Units (ACUs) can be distinguished:

  1. Fixed ACU: Fixed ACUs are installed on an aircraft stand and are generally electrically powered. They can only serve aircraft that arrive at the stand where they are installed.
  2. Bridge-mounted ACU: Bridge-mounted ACUs are installed under a Passenger Boarding Bridge (PBB) and are generally electrically powered. The mobility of this type of ACU is therefore also restricted: as the PBB moves, so does the ACU.
  3. Mobile ACU: Mobile ACUs are built upon a cart that is towed by a tug that transports them between the aircraft stands. Mobile ACUs can be fuel or battery powered.



(a) *An example of a fixed ACU (Aviation Ground Equipment Corp., n.d.).* **(b)** *An example of a bridge-mounted ACU (ITW, n.d.).* **(c)** *An example of a mobile ACU (TLD, n.d.)*

Figure C.2: *Three different types of Air Climate Units.*

- **Air Starter Unit**
  An Air Starter Unit (ASU) delivers compressed air for the initial rotation of the engine of an aircraft to help start the engines during instances when the on-board APU is not operational or there are no other means for starting the engines. A tug is often used to transport the ASU, but there are also “truck-mounted” ASUs. In addition to starting engines, an ASU can also be used for the supply of PCA. The ASU is then connected to an air conditioning “pack” on the aircraft.

Figure C.3: *An example of an ASU (TLD, n.d.).*

C.2. Aircraft movement

These GSE types assist with aircraft movements when an aircraft cannot operate its engines, or does not have sufficient maneuverability to move and turn under its own engine power. They are most frequently used to push an aircraft back from the gate/stand and onto the aircraft movement area (e.g., taxiway). It may also be used to move an aircraft to other locations on an airport (e.g., MRO facilities and parking bays).

- **Aircraft Tractor**
  Aircraft tractors are characterized by their large wheels (to increase its tires traction), powerful drivetrains, and heavy build. They exist in various designs and sizes, based on, among other things, the maximum weight of an aircraft, the slope of an apron and the surface conditions. At the time of writing, the vast majority of aircraft tractors are powered by an internal combustion engine. There are two main types of aircraft tractors:

  1. Conventional aircraft tractor: Conventional aircraft tractors use tow-bars that are connected to an aircraft's nose wheel. Different aircraft types have different designs of nose landing gear. Therefore, a tow bar cannot be used on all aircraft. A tow bar can be used only on a family of aircraft that have a similar design of nose landing gear.
  2. Towbarless aircraft tractors: Towbarless aircraft tractors scoop up the aircraft nose wheel and lift it off the ground before moving. Since an aircraft weight is distributed between its landing gears (nose gear and main gear), the aircraft tractor supports a major share of the aircraft's total weight on its own chassis. This weight fulfills the traction and friction requirements that were necessitating the use of ballasts on a conventional pushback tractor. Towbarless aircraft tractors are therefore lighter in weight. In addition, they can be used more widely than conventional aircraft tractors, because the maximum weight in particular plays a role and not the type of towbar.

(a) *An example of a conventional aircraft tractor (TLD, n.d.).* **(b)** *An example of a towbar (Aero Specialities, n.d.).* **(c)** *An example of a towbarless aircraft tractor (TLD, n.d.).*

Figure C.4: *Two different types of aircraft tractors and an example of a towbar.*

C.3. Aircraft servicing

These GSE types are used for aircraft service activities including replenishing supplies, aircraft refueling and maintenance.

- **Catering Truck**
  Catering trucks are used to deliver beverage and food trolleys but they are also used to remove trash and other used materials. Most catering trucks are equipped and registered to operate both on the airport site and on public roadways, as they are typically owned and operated by airlines or companies that are located near the airport and specialize in airline catering.

  Catering trucks use a scissor lift elevation system to raise their "container" to the level of an aircraft door. A bridge connection is created through an adjustable platform to allow the staff to replace trolleys. Next to that, they have built-in outriggers or stabilizers that to remove the load from the wheels of the truck and offer additional solid support and foundation on the ground to account for wind forces and other external forces that try to tip the truck over in elevated position. Different aircraft catering trucks have different service heights, container sizes and payload rating based on the largest aircraft they are designed to service.

Figure C.5: *An example of a catering truck (Hubei Dong Runze Special Vehicle Equipment Co., Ltd., n.d.).*

- **Lavatory Service**
  A vehicle that is designed for, and equipped with, a collection system and a storage tank for the recovery and transport of aircraft lavatory wastes. It is also used for rinsing the aircraft's waste tank and to replenish the disinfecting chemicals into the aircraft lavatory system. Fuel and electrically powered models are available.

Figure C.6: *An example of a lavatory service truck (TLD, n.d.).*

- **Water Truck**
  This vehicle is equipped with a transfer system (i.e., pipes/hoses, filters, pumps) and storage tank for the provision of (drinkable) water to an aircraft. Fuel and electrically powered models are available.

Figure C.7: *An example of a water truck (TLD, n.d.).*

- **Fuel bowser**
  A self-contained refueler with pumps, filters, hoses and valves can be used to dispense fuel directly to an aircraft's tank(s). The refueler needs to be refilled at an airport fuel storage facility. Some refuelers have an elevation platform to allow refueling staff to connect fuel hoses several feet above the ground. At the time of writing, most refuelers use an internal combustion engine. There are some electric models on the market (SEA Electric, 2022; Titan Aviation, n.d.-b).

Figure C.8: *An example of a fuel bowser (Refuel International, n.d.-a).*

- **Dispenser Truck**
  A dispenser truck can be used to refuel an aircraft when an airport has an underground fueling system and employs hydrant trucks as "connectors" between the underground refueling system and aircraft. Some dispenser trucks have an elevation platform to allow refueling staff to connect fuel hoses several feet above the ground. At the time of writing, most refuelers use an internal combustion engine. There are some electric models on the market (TFS Green, n.d.; Titan Aviation, n.d.-a).

Figure C.9: *An example of a hydrant dispenser truck (Refuel International, n.d.-b).*

C.4. Passenger loading / unloading

Depending on the airport, aircraft and available airport equipment/facilities, two methods are used to board passengers onto large aircraft: boarding stairs and Passenger Boarding Bridges (PBBs). These GSE types are used for the passenger loading / unloading:

- **Boarding Stairs**
  Boarding stairs allow the loading and unloading passengers at remote aircraft stands and in the absence of PBBs. They can be moved by towing, pushing, or they can be fixed to a truck / driving system. The height can be adjusted to align the stairs with the aircraft door. A disadvantage of the boarding stairs is that it is not possible to facilitate deplaning of passengers that need special care (especially passengers in a wheelchair).

Figure C.10: *An example of mobile boarding stairs (TLD, n.d.).*

- **Disabled Passenger Lift Truck**
  Disabled passenger lift trucks allow the loading and unloading disabled passengers (especially passengers in a wheelchair) at remote aircraft stands and in the absence of PBBs. Just like a catering truck, the vehicle uses a scissor lift elevation system to raise its “container” to the level of an aircraft door. At the rear of the vehicle is a loading ramp to get in and out of the “container” from the apron.

Figure C.11: *An example of disabled passenger lift truck (Orientitan Ground Support Equipment, n.d.-a).*

- **Bus**
  Buses may be used to transport passengers and crew from a remote stand to the terminal. The number of buses required depends on the number of passengers in an aircraft. Buses can also be used to transport passengers from the main terminal to remote "satellites" on the apron of a large airport.

Figure C.12: *An example of a bus (Ugurel Ground Support Equipment, n.d.).*

C.5. Baggage / Cargo handling

These GSE types are used for the handling of baggage / cargo between the aircraft and the gate / terminal:

- **Baggage / Cargo tug**
  Baggage/cargo tugs are used to transport baggage and cargo between an aircraft and the airport terminal and/or the processing/sorting facilities. Depending on the amount of baggage and cargo, several tugs are needed to handle an aircraft. Furthermore, depending on the weight to be towed, a distinction is made between baggage and cargo tugs. Baggage tugs can handle baggage and lightweight cargo, whereas cargo tugs can also be used for heavy cargo handling and sometimes even "light" aircraft pushback operations.

  The baggage tug is one type of GSE that is already electrically available. In this way, exhaust fumes in the "basement" of the airport terminal, where the baggage handling facility is often located, are avoided. For the cargo tug, many diesel models are still available.

(a) *An example of a baggage tug (TLD, n.d.).* **(b)** *An example of a cargo tug (TLD, n.d.).*

Figure C.13: *Examples of a baggage and cargo tug. The main difference is in the maximum weight that can be towed.*

The baggage/cargo tugs can pull several dollies connected together. A distinction is made between three types of dollies:

1. Baggage dolly: Baggage dollies can be used to transport free-loaded baggage. In addition, "special goods" such as animals and odd-size baggage can also be transported.

2. ULD dolly: An alternative to the use of baggage dollies is a ULD dolly with a Unit Load Device (ULD). A ULD is a standardized container for storing aircraft baggage or cargo. The advantage of using ULDs is the fact that the dimensions and characteristics are standardized, which allows for example automation of the transport process and ease multi-modal transport. Moreover, organizing baggage inside cargo compartments also becomes less laborious because manual sorting is not required. A ULD is designed to slide and fit inside cargo compartment with provisions to properly secure it to the surface and prevent movement or dislocation during flight. The ULDs are moved with special (powered) rollers.
3. Pallet dolly: Sometimes it is not possible to transport cargo in a ULD. In that case a pallet can be used. Pallet dollies are used to transport these pallets. Pallet dollies can often also be used for ULDs.

(a) *An example of a baggage dolly (TLD, n.d.).* **(b)** *An example of a ULD dolly (TLD, n.d.).* **(c)** *An example of a pallet dolly (TLD, n.d.).*

Figure C.14: *Three different types of dollies that can be towed by baggage/cargo tug.*

- **Cargo transporter**
  Cargo transporters can transport pallets and containers between warehouses, aircraft loading equipment, dollies and similar equipment.They use rollers to get the cargo from or onto the vehicle.

Figure C.15: *An example of a cargo transporter (TLD, n.d.).*

- **Belt loader**
  Belt loaders are used to load and unload baggage and cargo intro/from an aircraft. They have a conveyor belt installed on a boom whose inclination can be adjusted to match the height of the aircraft cargo compartment. There are fuel and electric powered models available.

  Belt loaders can be equipped with a power stow, which is an extension to facilitate the loading and offloading of passenger baggage and cargo in the aircraft cargo hold. The add-on enables airport ground handlers to load and unload bulk baggage and cargo faster and more efficiently, while also reducing the physical strain on the ground handling staff.

(a) *An example of a belt loader (TLD, n.d.).* **(b)** *An example of a belt loader equipped with a power stow (Power Stow, n.d.).*

Figure C.16: *A belt loader and an example of a "power stow".*

- **Deck loader**

  Deck loaders are used to load and unload the cargo that is within a ULD on an aircraft. A deck loader consists of a bridge platform and a loading platform. Both platforms use a scissor lift to adjust their height. The bridge platform acts as a bridge between the aircraft cargo compartment and the loading platform. The ULDs are moved between the ULD dollies and the loading platform. The loading platform is raised to the same height as the bridge platform, to enable the ULDs to be transferred on the level of the aircraft cargo compartment.

  The platforms of a deck loader are equipped with powered rollers to move the Unit Load Devices (ULDs). By using these rollers a ULD can move in two dimensions without human intervention. The cargo compartment of an aircraft is also equipped with rollers to take a ULD to the desired position inside the aircraft. A locking mechanism locks it in place to prevent it from sliding around and possibly getting damaged during aircraft takeoff, landing and other maneuvers in the air.

  A distinction is made between lower deck loaders and main deck loaders. The basic difference is that the main deck loader is more versatile. The main deck loader can load cargo into the main (top) deck and the lower deck of a NABO/WIBO aircraft. A lower deck loader is used to load cargo into both decks of a NABO aircraft and the lower deck of a WIBO aircraft. Main deck loaders usually have a larger weight capability then lower deck loaders.

(a) *An example of a lower deck loader (TLD, n.d.).* **(b)** *An example of a main deck loader (TLD, n.d.).*

Figure C.17: *Two different types of cargo loaders.*

C.6. Miscellaneous

These GSE types are not necessarily used for every aircraft handling. However, they are necessary to properly manage the operation of an airport (if there are irregular circumstances).

- **Supervisor vehicle**
  The various services that are active at an airport employ personnel who have a supervisory or management role. For example, airport authorities and team leaders of ground handling operators. They often use (modified) passenger vehicles to travel across the apron.

Figure C.18: *An example of a supervisor vehicle (PNG Wing, n.d.).*

- **Maintenance vehicle**
  Various types of maintenance vehicles are used to provide aircraft maintenance service. Some vehicles are used by airport and/or airline employees to travel to/from maintenance facilities and an aircraft in need of maintenance and repairs. Other vehicles are also used to perform quick maintenance tasks at an aircraft stand. These vehicles have, for example, a scissor lift and an oil reservoir.

Figure C.19: *An example of a maintenance vehicle (Franke Aerotec, n.d.).*

- **De-icer**
  Deicers are specially designed vehicles transport that heat, and spray de-icing fluid on an aircraft exterior to reduce and/or eliminate ice and snow prior to departure. They are equipped with a hydraulic boom and bucket system to allow the operator to reach different parts of an aircraft. The bucket can either be an open bucket or it can be in the form of a cabin which protects the operator from external weather conditions as well as the fumed of de-icing and anti-icing fluids as they are sprayed over the aircraft. The vehicles sometimes contain two engines: one to power the vehicle and one to heat the de-icing fluids.

Figure C.20: *An example of a de-icer vehicle (Turbosquid, n.d.).*

D
Additional information on batteries

In this appendix, additional information regarding batteries is provided. First, Appendix D.1 explains the commonly used battery types. After that, Appendix D.2 discusses additional battery characteristics, in addition to what has already been discussed in Section 2.2.2. Finally, Appendix D.3 elaborates on the charging standards that exist for EV batteries.

In this appendix the different GSE types at airports are described and specified. The classification and descriptions are largely based on the available ACRP reports (National Academies of Sciences, Engineering, and Medicine, 2012, 2015) about GSE. Not every type of GSE is used at every airport.

D.1. Commonly used battery types

Three main types of batteries which are currently suitable for road transportation are lead-acid batteries, nickel-based batteries, and lithium-based batteries (W. Chen et al., 2019; Dixon, 2010; Li et al., 2019). Each type of battery has its own characteristics and therefore advantages and disadvantages. This section discusses the characteristics of the most used battery types to get a better understanding of their differences and properties.

D.1.1. Lead-acid batteries

The initial battery technology used in transportation was the lead-acid (Pb-acid) battery (Yong et al., 2015). It is cheap and simple to us, but has reached its limits in specific energy (see Table D.2) and for that reason it will never be an option for long-range EVs (Dixon, 2010). In addition, it has a short cycle life (see Table D.2), which means that the battery pack has to be replaced every 2 to 3 years (Dixon, 2010; Li et al., 2019). Another drawback is that the battery causes environmental problems in the production and/or disposal process (Li et al., 2019; Yong et al., 2015).

D.1.2. Nickel-based batteries

The lead-acid battery was soon replaced by nickel-based batteries, such as nickel-iron, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and nickel-zinc (NiZn) batteries (Li et al., 2019; Yong et al., 2015). The nickel-based battery has a higher energy density compared to a lead-acid battery (see Table D.2). Most of the Electric Vehicles used NiMH batteries, especially for the propulsion (Yong et al., 2015). The NiMH battery is composed of non-toxic recyclable materials, it is environmentally friendly and maintenance free (Dixon, 2010). However, this type of battery has significant drawbacks, such as poor charge and discharge efficiency, high self-discharge rate, poor performance in cold weather (Yong et al., 2015), and its high cost (Dixon, 2010). As a whole, nickel-based batteries are generally superior to lead-acid batteries in terms of energy density, cycle life, and energy efficiency (see Table D.2) (Li et al., 2019).

D.1.3. Lithium-based batteries

The introduction of the lithium-based battery as EV battery has shifted the EV to a new era (Yong et al., 2015). Compared with lead-acid and nickel-based batteries, the lithium-based battery is featured by high energy and power density, long service life, environmental friendliness (W. Chen et al., 2019; Ding et al., 2019), reasonably fast-charge/discharge capability, as well as low self-discharge rate (see Table D.2) (Stan et al., 2014). At present, there are many different Li-ion chemistries available on the market, which employ various combinations of anode and cathode materials. Each of these chemistries has its own electrical and economical characteristics.

The most popular Li-ion chemistries that are suitable for EV applications are lithium-iron phosphate ($LiFePO_4$) (LFP), lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$) (NCA), and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$) (NMC) batteries (Ding et al., 2019; Stan et al., 2014).The key advantage of Li-ion batteries in the EV sector is their high specific energy. Two chemistries that excel in this aspect (see Table D.1), NCA and NMC, therefore dominate this application (Zubi et al., 2018). LFP batteries have a (slightly) lower specific energy than NCA and NMC batteries. Furthermore, as a result of their low volumetric energy density (220 Wh/L), they are more suitable for heavy-duty applications (e.g. buses and trucks) than for commercial EVs, since the specific energy is more critical for the latter (Ding et al., 2019). However, LFP batteries have a high power density (Li et al., 2019; Yong et al., 2015), are very safe, rely on abundant eco-friendly materials, have a high cycle life (Berckmans et al., 2017; Yong et al., 2015; Zubi et al., 2018), and are less stressed than other lithium-ion systems when kept at high voltage for a prolonged time, leading to a superior structural stability (Ding et al., 2019).

Table D.1: *Specific energy and cycle life of Li-ion batteries using various chemistries (based on Ding et al. (2019), Stan et al. (2014), and Zubi et al. (2018)).*

		LFP	NCA	NMC
Specific energy	Wh/kg	90 - 140	100 - 200	100 - 170
Cycle life	cycles	>3000	2000 - 3000	1000 - 3000

Li-ion batteries are widely used in EVs (W. Chen et al., 2019; Li et al., 2019; M.-K. Song et al., 2013; Stan et al., 2014; Yong et al., 2015; Young et al., 2012; Zakaria et al., 2019). It is currently the best choice for cost performance as it has a high specific energy, high specific power, low self-discharge, and a long lifetime with moderate cost (see Table D.2). However, the lifetime can be reduced abruptly due to the effects of high temperature and deep discharge (Li et al., 2019).

Table D.2: *Comparison of EV battery types (based on Berckmans et al. (2017), Dixon (2010), Li et al. (2019), and Yong et al. (2015)).*

		Lead-acid (Pb-acid)	Nickel-metal hydride (NiMH)	Lithium-ion (Li-ion)
Capital cost	$/kWh	60 - 200	100 - 300	300
Energy efficiency	%	63 - 90	<80	90 - 100
Specific energy	Wh/kg	25 - 50	70 - 95	60 - 250
Specific power	W/kg	150 - 180	200 - 300	500 - 2000
Cycle life	cycles	500 - 1500	1500 - 3000	2000 - >5000

D.2. Battery characteristics

Three of the most important battery performance characteristics for this research are the 1.) battery capacity, 2.) State of Charge, and 3.) State of Health. They are discussed in Section 2.2.2. Other battery characteristics are discussed below.

D.2.1. Energy/Power density

The energy density of a battery is determined as the amount of energy per unit weight (Wh/kg) or unit volume (Wh/L) of the battery. The power density is another feature that characterizes battery performance. It is determined as the amount of power per unit weight (W/kg) or unit volume (W/L) of the battery. Next to its chemical properties, the design and physical structure of a battery also determines its power output. There is therefore a trade-off between the power density and the energy density. For a battery with a high power density, the amount of materials that do not react electrochemically should increase. This, in turn, increases the volume and weight of the battery, resulting in a reduction in energy density (Aktaş & Kirçiçek, 2021).

D.2.2. Efficiency

The efficiency of a battery is calculated as the ratio of the total energy given by the battery to discharge to the total energy received by the battery. This ratio may decrease up to 0.6 due to energy losses in the battery resulting from internal resistance, charge cycles, and battery life (Aktaş & Kirçiçek, 2021).

D.2.3. Self-discharge

The self-discharge of a battery is the amount of battery discharge, as a result of certain chemical reactions that take place in the battery cells, when the battery is not used (Abdi et al., 2017). The self-discharge rate depends on the cell chemistry and operating temperature (Abdi et al., 2017; Aktaş & Kirçiçek, 2021).

D.2.4. Cycle life

As the number of battery charge-discharge cycles increases, the internal resistance of the battery increases due to structural defects and losses. As a result, the efficiency of the battery decreases. After a certain number of charge-discharge cycles the battery becomes unusable. The cycle life of the battery defines this number of charge-discharge cycles. The cycle life differs per battery type (Aktaş & Kirçiçek, 2021).

D.3. Charging standards

For EVs, there are numerous standards concerning the charging. A distinction can be made in 1.) EV charging standards, 2.) EV grid integration standards, 3.) safety standards for EV, and 4.) application of EV charging standards (H. Das et al., 2020). This section only discusses the "EV charging standards". SAE and IEEE are used by U.S.A. based manufacturers whereas IEC is mainly used in Europe. Japan has its own EV charging standards named CHAdeMO, and China uses the Guobiao (GB/T) standard (H. Das et al., 2020). The IEC and SAE standards will be further discussed, as these are widely used standards. Different charging modes are standardized in IEC 61851-1 and SAE J1772, according to the type of input current (AC or DC) and the power level (L. Wang et al., 2021). In IEC 61851-1, four charging modes are defined. Mode 1, 2, and 3 are AC charging modes and Mode 4 is a DC charging mode (see Figure D.1). Only Mode 3 and 4 support fast charging. SAE J1772 classifies the EV charging as levels, where AC Level 1 and 2 are the slow charging via AC on-board chargers, and DC Level 2 is the fast charge option via DC off-board chargers (see Figure D.1). There is a DC Level 1 as well, which has a charging power up to 36 kW (L. Wang et al., 2021; Yong et al., 2015).

In 2014, the emergence of the first and only open charging system, the Combined Charging System (CCS), promoted by the CharIn organization, tried to deal with the incompatibilities between vehicles, mostly associated with an initial lack of hardware standardization. It proposes a universal solution that covers single- and three-phase AC (IEC 61851-22 and SAE J1772) as well as DC high-power charging in the US (type 1) (SAE J1772) and Europe (type 2) (IEC 61851-23) (Rivera et al., 2021). Currently, the CCS supports a maximum power of 350 kW for mid-size EVs and covers a 1.5 kV and 3 kA range intended for heavy-duty EVs (Rivera et al., 2021; Suarez & Martinez, 2019; L. Wang et al., 2021). CharIn even launched a Megawatt Charging System (MCS) that allows charging at > 1 MW (Charin, 2022).

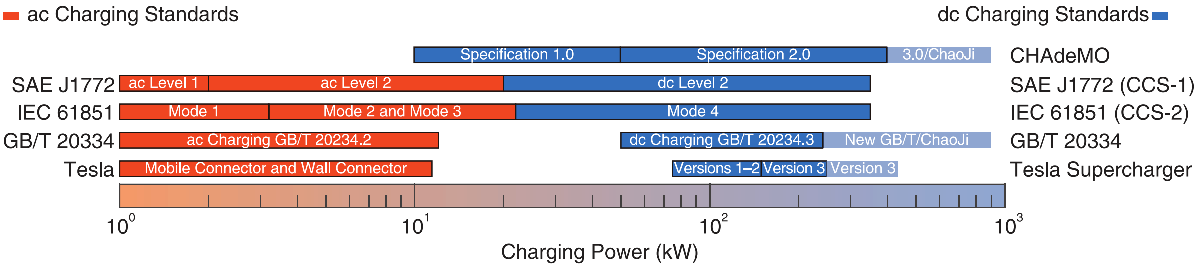


Figure D.1: *EV infrastructure charging classification. SAE J1772 and the CCS also define low-power dc levels (i.e., DC1, DC5, DC10, and DC20). They were omitted from the diagram for clarity purposes (adapted from Rivera et al. (2021)).*

E

Additional information on model development

E.1. Data processing

This appendix discusses the data processing that takes place in the model, based on Figure E.1. In this figure a distinction is made between input data, data that is generated and used in the model, and output data. The following explanation applies to the blocks shown in the figure:

Block 1. The air traffic movements are supplied as a list of arrival and departure movements. Each movement has a "flight date", "A/D indicator" (arrival/departure indicator), "airline", "trip Number", "A/C type" (aircraft type), "flight time" and a "stand". Table E.1 shows a sample of the air traffic movement data.

Table E.1: *A sample of the air traffic movements data.*

Flight Date	A/D Indicator	Airline	Trip Number	A/C Type	Flight Time	Stand
13/07/2023	A	KL	862	789	5:22	E17
⋮	⋮	⋮	⋮	⋮	⋮	⋮
13/07/2023	D	KL	1223	73H	6:39	C08

Block 2. To turn the air traffic movements data into a usable flight schedule, various steps are taken to filter and match the movements:

Step 1. The relevant airlines are filtered. These are the airlines handled by the GSE fleet of the ground handler.

Step 2. If necessary, filtering is also done on the day, if the air traffic movements data contains multiple days.

Step 3. It is checked which unique aircraft types remain in the list of air traffic movements. If it contains aircraft types that are not included in the aircraft data (Block 5), an error is raised so that these aircraft types can be added.

Step 4. The flight time is converted from hh:mm notation to minutes, where 00:00 at the beginning of the day is defined as minute 0.

Step 5. The air traffic movements are sorted by stand and then by flight time. This results in a list in which the air traffic movements are listed in alphabetical order of stands, with increasing flight time.

Step 6. For each stand, it is checked which flight movements belong together to form a full turnaround (FT) and which movements are separate arrivals (SA) or departures (SD). If there is only one movement on a position, then this is a SA or SD, depending on the A/D indicator. For multiple movements, the arrival and departure movements at one stand are matched based on the same aircraft types and airlines. If the difference between the arrival and departure time is longer than the standard turnaround time for the associated aircraft plus a threshold (of, for example, 30 minutes), the turnaround is also regarded as a separate arrival and departure.

Table E.2 shows a sample of the flight schedule. The A/D flight numbers are based on the flight numbers of the arrival and departure movements. In the case of an FT, this is a flight number in the form "arrival flight number_departure flight number".

Table E.2: *A sample of the flight schedule data.*

A/D Indicator	A/D Flight Number	Airline	A/C Type	Stand	SIBT	SOBT
SA	862_SA	KL	789	E17	5:22	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
FT	1736_1867	KL	E7W	C06	7:08	8:09
⋮	⋮	⋮	⋮	⋮	⋮	⋮
SD	SD_1227	KL	73W	D53		7:16

Block 3. The GSE vehicle data contains the properties of the GSE fleet. This includes, per GSE type, the number of available vehicles, the vehicle speed (in m/min), the logistic capacity (if applicable), the logistic time constant (if applicable), the battery capacity (in kWh), and the driving energy (in kWh/m).

Block 4. The stand data contains the properties of the aircraft stands. This includes, for example, whether an aircraft stand is equipped with a PBB or fuel pit, and whether a pushback is required.

Block 5. The aircraft data contains the data from the turnaround tables of the aircraft types and the energy consumption (EC) for one GSE type. Table E.3 shows a sample of the data for a belt loader. In this case, two belt loaders are required to handle an aircraft. That is why the data is shown for both belt loaders, separated by a semicolon. The task times can be based on A0 (calculated from the moment of arrival of the aircraft) or on D0 (calculated back from the time of departure). In this example, the task times are defined based on A0 as this is the data for a separate arrival. Table E.4 shows the data based on D0, for a separate departure.

Table E.3: *A sample of the aircraft data of a beltloader for a separate arrival.*

IATA Type Code	Norm Ground Time	A0 ET	A0 LT	A0 TT	A0 DEM	A0 EC
73H	50	1;1	23;18	22;17	0	0.21;0.16
⋮	⋮	⋮	⋮	⋮	⋮	⋮
321	50	1;1	21;22	20;21	0	0.18;0.20

Table E.4: *A sample of the aircraft data of a beltloader for a separate departure.*

IATA Type Code	Norm Ground Time	D0 ET	D0 LT	D0 TT	D0 DEM	D0 EC
73H	50	-30;-35	-2;-2	28;33	0	0.26;0.31
⋮	⋮	⋮	⋮	⋮	⋮	⋮
321	50	-28;-30	-2;-2	26;28	0	0.24;0.26

Block 6. To create the task list from the various sources of data, various steps are taken. A distinction is made between the generation of the parking, flight, and logistics tasks. Two parking tasks are generated for each parking location, according to the format in Table E.5. One task can be used as a starting task, and the other one as an ending task.

Table E.5: *The format for the generation of the starting and ending parking tasks.*

Task property	Value (starting task)	Value (ending task)
Task ID	[number]	[number]
Task type	P	P
SBE type	S	E
Task name	[parking location ID]	[parking location ID]
Location ID	[parking location ID]	[parking location ID]
Location number	[parking location number]	[parking location number]
AC type	N/A	N/A
Demand (DEM)	0	0
Energy consumption (EC)	0	0
Earliest time (ET)	0	1559
Latest time (LT)	1560	1560
Task time (TT)	0	0

A flight task is generated for each flight in the flight schedule, according to the format in Table E.6. If multiple vehicles of one GSE type are required for one flight, then multiple flight tasks are generated, based on the aircraft data (Block 5). These tasks can be distinguished based on the value of i at the end of the task name. In the case of a full turnaround (FT), the task may be defined on A0 or D0.

Table E.6: *The format for the generation of the flight tasks.*

Task property	Value (SA or FT)	Value (SD or FT)
Task ID	[number]	[number]
Task type	F	F
SBE type	B	B
Task name	[flight task name]_[i]	[flight task name]_[i]
Location ID	Aircraft stand	Aircraft stand
Location number	0	0
AC type	[AC type]	[AC type]
Demand (DEM)	A0 DEM	D0 DEM
Energy consumption (EC)	A0 PC	D0 PC
Earliest time (ET)	SIBT flight + A0 ET	SOBT flight + D0 ET
Latest time (LT)	SIBT flight + A0 LT	SOBT flight + D0 LT
Task time (TT)	A0 TT	D0 TT

For GSE types with a logistics function, a logistics task is generated for each flight in the flight schedule, according to the format in Table E.7. The earliest and latest time are based on the corresponding flight task. In addition, for the earliest time, the maximum time required for a vehicle in a logistics task and the maximum driving time are included so that a vehicle can always get from the logistics task to a flight task in time.

Table E.7: *The format for the generation of the logistics tasks.*

Task property	Value
Task ID	[number]
Task type	L
SBE type	B
Task name	[flight task name]_[i]
Location ID	L_[GSE type]_[number]
Location number	0
AC type	N/A
Demand (DEM)	0
Energy consumption (EC)	0
Earliest time (ET)	Flight task ET - Vehicle capacity · Logistics refilling time constant - (Max distance)/(Vehicle speed)
Latest time (LT)	Flight task LT - Flight task TT
Task time (TT)	0

Table E.8 shows a sample of the task list with the different task types. Additional examples can be found in Section 3.4.2.

Table E.8: *A sample of the task list.*

Task ID	Task type	SBE type	Task name	Location ID	Location nr.	Aircraft type	DEM	EC	ET	LT	TT
0	P	S	P_WAT_000	P_WAT_000	0	N/A	0	0	0	1560	0
1	P	E	P_WAT_000	P_WAT_000	0	N/A	0	0	1559	1560	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
24	L	B	SD_1223_0	L_WAT_000	0	N/A	0	0	305	384	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
365	F	B	SD_1223_0	C08	0	73H	65	0.04	350	389	5

Block 7. The GSE location group data defines for each piece of equipment in which location group the initial parking location is located. In the case of vehicles with a logistics function, the same has been done for the logistics location in this database. Table E.9 shows a sample of the GSE location group data.

Table E.9: *A sample of the GSE location group data.*

Location	GSE Type	Location group
0	BEL	A30
⋮	⋮	⋮
35	BEL	BPE

Block 8. As with the locations of the GSE types, the aircraft stands are also divided into location groups. Table E.10 shows a sample of the aircraft stand location group data.

Table E.10: *A sample of the aircraft stand location group data.*

Location	Location group
A31	A30
A32	A30
⋮	⋮
D41	DMN
D43	DMN

Block 9. The location group distances data contains the distances between all location groups. Table E.11 shows a sample of the location group distances data. The origin location group can be read in the first column and the destination location groups are at the top of the other columns. In this case the data is symmetrical, but this is not necessarily the case.

Table E.11: *A sample of the location group distances data.*

		Destination				
		A30	⋯	BPE	⋯	DMN
Origin	A30	68	⋯	960	⋯	1750
	⋮	⋮	⋱	⋮		⋮
	BPE	960	⋯	90	⋯	920
	⋮	⋮		⋮	⋱	⋮
	DMN	1750	⋯	920	⋯	60

Block 10. By combining the data of Block 7, 8 and 9, the distances between the individual locations can be generated.

Table E.12: *A sample of the location distances data.*

		Destination				
		A31	A32	⋯	D41	D43
Origin	A31	0	68	⋯	1750	1750
	A32	68	0	⋯	1750	1750
	⋮	⋮	⋮	⋱	⋮	⋮
	D41	1750	1750	⋯	0	60
	D43	1750	1750	⋯	60	0

Block 11. Based on the task list (Block 6) and the distances between the individual locations (Block 10), the distances between the tasks can be generated. The result is the source of the D_{ij} values in the mathematical model in Section 3.2.

Block 12. A lot of data flows come together in the rolling horizon algorithm. The steps performed in this block can be seen in Algorithm 1. To generate the optimization problem, the task list and the GSE vehicle data are used. Based on its solution, the post-processed task list is generated. This includes the SOC and the total traveled distance. After that, the algorithm uses this post-processed task list to determine which vehicles can be used in the next optimization run and which vehicles are depleted.

Block 13. The optimization problem includes the MILP problem as explained in Section 3.2. It is fed by the task distances (Block 11) and the sets provided as part of the rolling horizon algorithm (Block 12).

Block 14. The post processed task list is the task list, supplemented with information about the execution of the tasks. The tasks that have not been performed have been omitted here. Added here are the vehicles that performed the task, the start time, the end time, the load (if applicable), the energy consumption for the task, the distance driven to the task, the energy required for this and the SOC at the start and at the end of the task. Section 3.4.2 contains several examples of a post-processed task list.

Block 15. The MILP statistics contains information that can be used as a reference when analyzing the operation and efficiency of the model. It contains the number of variables per optimization run, the number of constraints, the objective bound and the MIP gap at the end, the runtime, the "work" spent on the optimization, the node count, the open node count, and the objective value. An advantage of the "work" is that it is deterministic, meaning that you will get exactly the same result every time provided you solve the same model on the same hardware with the same parameter and attribute settings. This is in contrast to the runtime, which is non-deterministic.

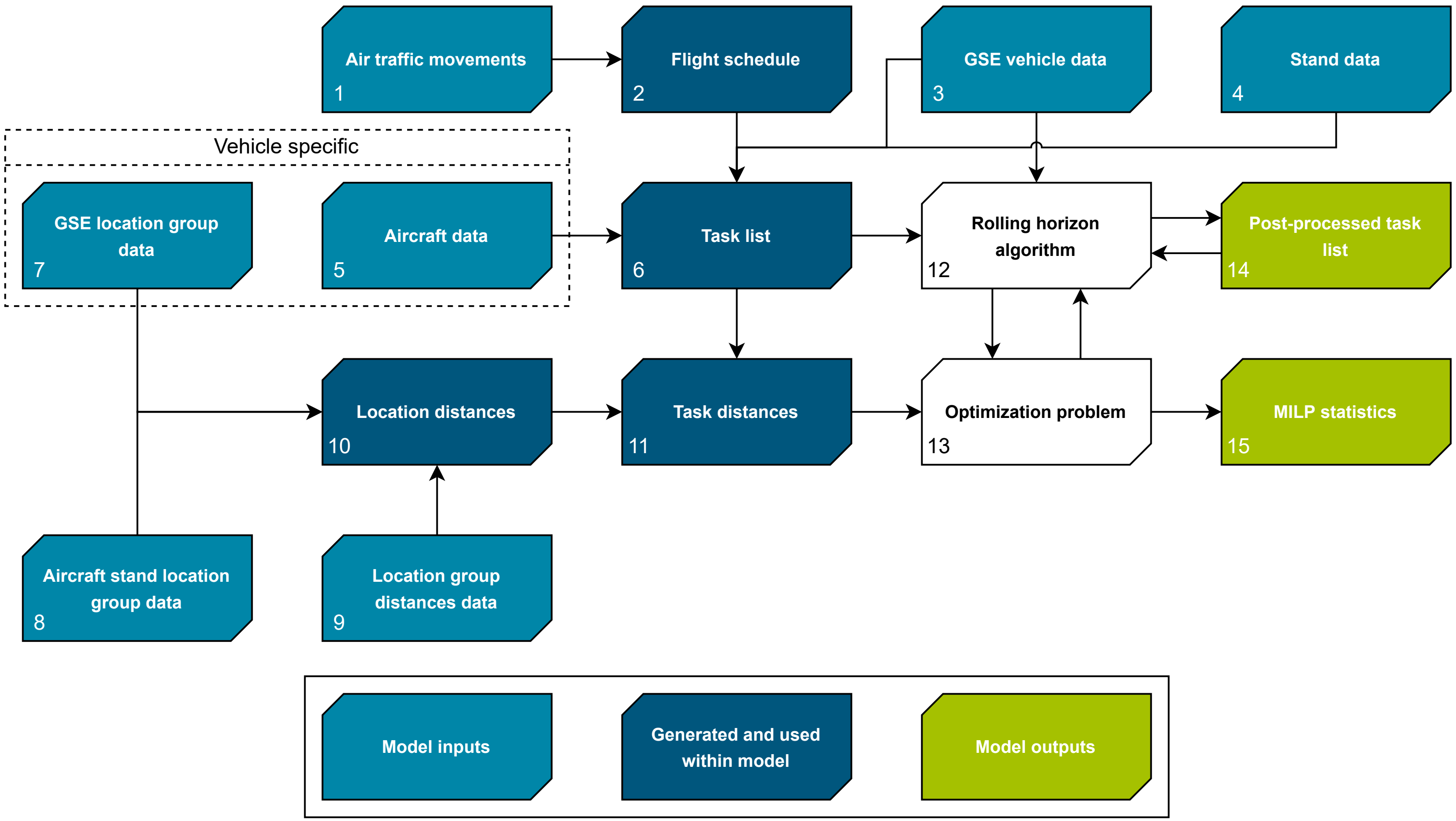


Figure E.1: *Schematic overview of data processing with a distinction in the model inputs, generated data, and model outputs.*

E.2. Variable reduction

As explained in Section 3.3.2, the number of binary variables needed to model the MILP problem is reduced by omitting all (i, j)-pairs that are considered infeasible as a result of the constraints that are in place. This reduction does not affect the availability of potentially optimal solutions in the model, because only those decisions that are infeasible are omitted from the model. Let T be the set of tasks, and G_0 be the set of all pairs (i, j), i.e. $G_0 = \{ (i, j) \mid i, j \in T \}$. The following filters are applied to reduce the number of (i, j)-pairs:

Filters

Filter 1: based on Constraint G5.

$$G_1 = G_0 \setminus \{ (i, j) \mid i, j \in G_0, i = j \}$$

Filter 2: based on Constraint L8.

$$G_2 = G_1 \setminus \{ (i, j) \mid i, j \in G_1, i \in L, j \in F, TN_i \neq TN_j \}$$

Filter 3: based on Constraint G6a.

$$G_3 = G_2 \setminus \{ (i, j) \mid i, j \in G_2, j \in T_S \}$$

Filter 4: based on Constraint G6b.

$$G_4 = G_3 \setminus \{ (i, j) \mid i, j \in G_3, i \in T_E \}$$

Filter 5: based on Constraint L7.

$$G_5 = G_4 \setminus \{ (i, j) \mid i, j \in G_4, i, j \in L \}$$

Filter 6: based on Constraint L9.

$$G_6 = G_5 \setminus \{ (i, j) \mid i, j \in G_5, i \in L, j \in P \}$$

Filter 7: based on Constraint G7.

$$G_7 = G_6 \setminus \{ (i, j) \mid i, j \in G_6, i \in T_S, j \in T_E \}$$

Filter 8: based on Constraint G9a and Constraint F2b.

$$G_8 = G_7 \setminus \left\{ (i, j) \;\middle|\; i, j \in G_7, ET_i + TT_i + \frac{D_{ij}}{V} > LT_j - TT_j \right\}$$

The set G_8 represents the filtered combinations after applying all the specified conditions.

F
Additional information on case study

F.1. Aircraft stand location groups

Table F.1: *Distribution of aircraft stands over the location groups at AAS.*

Location	Location group	Location	Location group	Location	Location group
A31	A30	C07	CPO	D94	DAS
A32	A30	C08	CPE	D95	DAS
A33	A30	C09	CPO	E02	ESE
A34	A30	C10	CPE	E03	ESO
A35	A30	C11	CPT	E04	ESE
A41	A40	C12	CPT	E05	ESO
A42	A40	C13	CPT	E06	ENE
A43	A40	C14	CPT	E07	ESO
A44	A40	C15	CPT	E08	ENE
A45	A40	C16	CPT	E09	ENO
A51	A50	C18	CPT	E17	ENO
A52	A50	D02	DWE	E18	ENE
A53	A50	D03	DWO	E19	ENO
A54	A50	D04	DWE	E20	ENE
A55	A50	D05	DWO	E22	ENE
A61	A60	D07	DWO	E24	ENE
A62	A60	D10	DMS	E72	DAN
A63	A60	D12	DMS	E75	DAN
A64	A60	D14	DMS	E77	DAN
A65	A60	D16	DSE	F03	FPO
A71	A70	D18	DSE	F04	FPE
A72	A70	D22	DSE	F05	FPO
A73	A70	D23	DSO	F06	FPT
A74	A70	D24	DSE	F07	FPT
A75	A70	D25	DSO	F08	FPT
A81	B90	D26	DSE	F09	FPT
A82	B90	D27	DSO	G02	GPE
A83	B90	D28	DSE	G03	GPO
A84	B90	D29	DSO	G04	GPE
B15	BPO	D31	DSO	G05	GPO
B16	BPE	D41	DMN	G06	GPE
B17	BPO	D43	DMN	G07	GPO
B20	BPE	D44	DNE	G08	GPE
B23	BPO	D47	DNO	G09	GPO
B24	BPE	D48	DNE	G71	GA
B27	BPO	D49	DNO	G73	GA
B28	BPE	D51	DNO	G76	GA
B31	BPO	D52	DNE	G79	GA
B32	BPE	D53	DNO	H01	HP
B35	BPO	D54	DNE	H02	HP
B36	BPE	D55	DNO	H03	HP
B92	B90	D56	DNE	H04	HP
B93	B90	D57	DNO	H05	HP
B94	B90	D88	DAS	H06	HP
B95	B90	D90	DAS	H07	HP
C05	CPO	D92	DAS		
C06	CPE	D93	DAS		

F.2. Location groups and distances at AAS

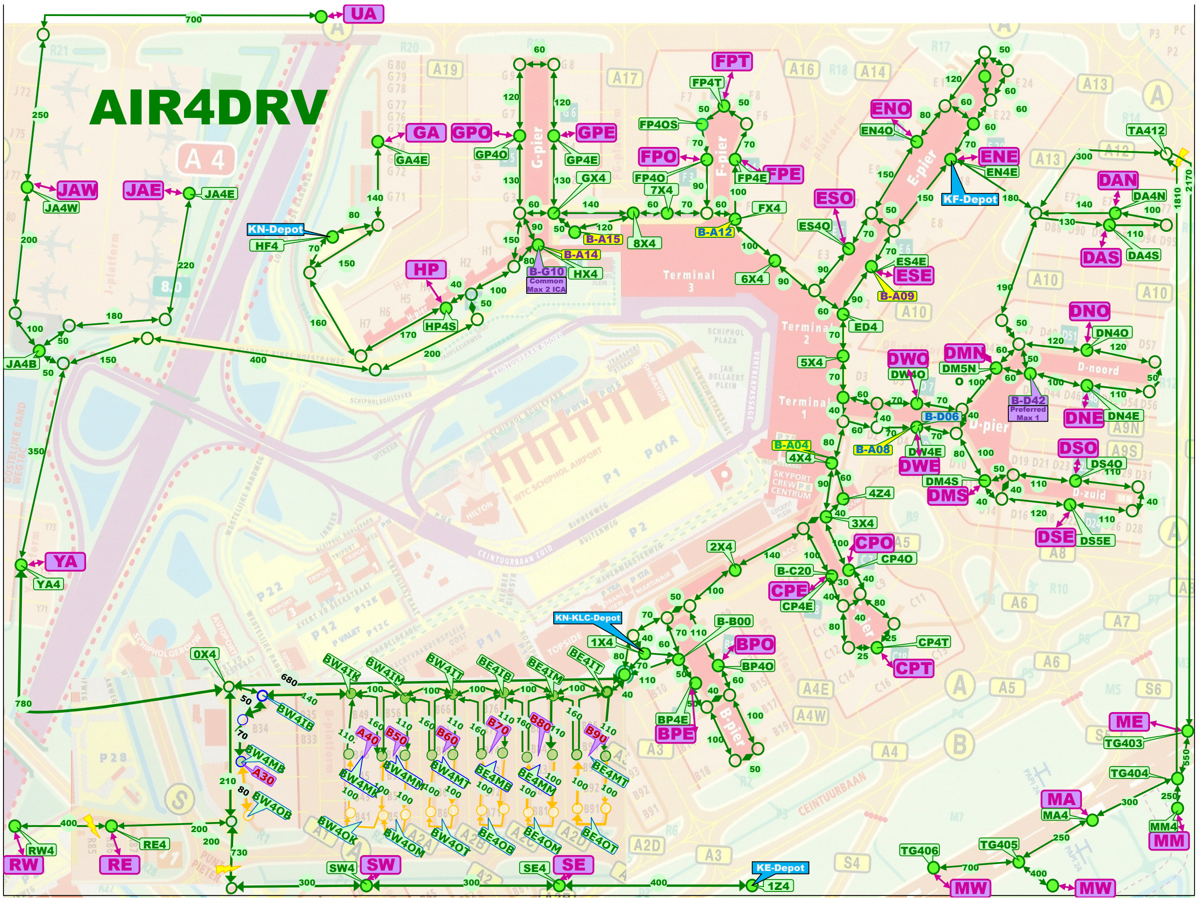


Figure F.1: *The locations and distances that are used for the models within KLM (Krijger, 2023).*

F.3. Sensitivity analysis solutions

Table F.2: *Overview of the solutions that are part of the sensitivity analysis for the belt loaders.*

Solution nr.	λ_1	λ_2	Total used nr. of vehicles	Nr. of vehicles used during peak	Total traveled distance
1	1.00	0.001	37	37	49.253
2	0.90	0.10	37	37	50.001
3	0.85	0.15	37	37	49.359
4	0.80	0.20	37	37	51.316
5	0.75	0.25	37	37	49.443
6	0.70	0.30	37	37	48.773
7	0.65	0.35	38	37	45.705
8	0.60	0.40	39	37	44.137
9	0.55	0.45	40	37	42.576
10	0.50	0.50	41	37	40.733
11	0.45	0.55	42	38	38.566
12	0.40	0.60	46	40	33.666
13	0.35	0.65	46	40	33.513
14	0.30	0.70	49	40	29.454
15	0.25	0.75	51	41	31.816
16	0.20	0.80	52	41	26.689
17	0.10	0.90	52	41	25.461
18	0.001	1.00	52	41	24.620

Table F.3: *Overview of the solutions that are part of the sensitivity analysis for the water trucks.*

Solution nr.	λ_1	λ_2	Total used nr. of vehicles	Nr. of vehicles used during peak	Total traveled distance
1	1.00	0.001	25	11	194.590
2	0.90	0.10	23	12	177.986
3	0.80	0.20	22	11	173.749
4	0.70	0.30	21	11	170.752
5	0.60	0.40	23	11	179.042
6	0.50	0.50	23	11	180.936
7	0.40	0.60	22	11	170.585
8	0.30	0.70	22	12	170.204
9	0.20	0.80	22	11	166.343
10	0.10	0.90	20	12	152.283
11	0.001	1.00	21	12	149.528

G
Interviews

G.1. Business Contract Manager GSE I

Function: Business Contract Manager GSE bij KLM
Experience: 30 jaar platformervaring, sinds 2019 de huidige functie
Date: 16-02-2023

1. **Zijn alle GSE types per turnaround nodig?**
   Ja, alle services moeten tijdens de turnaround langskomen.

2. **Hoe wordt bepaald welk voertuig aan welke vluchtafhandeling gekoppeld wordt?**
   De personen worden afgeroepen voor het afhandelen van een vlucht. De transporters, beltloaders, lowerdeckloaders en de CLT-8 mogen "vrij" door de hiervoor opgeleide personen gekozen worden. De overige GSE types (bagagetrekkers, waterwagens, pushback, tankwagen, etc.) zijn gekoppeld aan een persoon die via een systeem (staffcom) hun taken ontvangen.

3. **Welke GSE types moeten er klaarstaan bij een aircraft stand, zodra een vliegtuig daar aankomt?**
   De lowerdeckloaders, CLT's, transporters (indien van toepassing) en beltloaders zijn direct nodig om de bagage van boord te halen. De overige GSE types kunnen daarna langskomen. In sommige gevallen wordt een toestel afgesleept naar een bufferpositie waar dan de overige afhandeling plaatsvindt. Dit wordt gedaan om de gate vrij te maken voor het aankomstproces van andere vluchten.

4. **Zijn er GSE types afhankelijk van andere GSE types tijdens een turnaround?**
   In principe hebben alle GSE types hun eigen taak en kunnen deze parallel aan elkaar werken. Een uitzondering hierop zijn de water en lavatory service, omdat die vanwege regelgeving een bepaalde afstand tot elkaar moeten hebben. Op enkele vliegtuigtypes na heeft dit tot gevolg dat deze twee diensten nooit tegelijkertijd bij een vliegtuig actief kunnen zijn. Daarnaast kunnen de lower deck loaders niet zonder transporter werken (en andersom).

5. **Hoe zit het met de GPUs? Welke aircraft stands beschikken er over fixed GPUs?**
   Momenteel zijn de noordkant van de D-pier en de F-, G-, en E-pieren uitgerust met fixed GPUs. Op de overige pieren zijn mobiele GPUs nodig. Aan de binnenkant van de D-pier worden nu de eerste elektrische GPUs gebruikt. Dit heeft te maken met de wind en de fijnstof op deze locatie. De elektrische GPUs worden vooralsnog alleen voor NABOs gebruikt. Als de fixed GPU kapot is moet er alsnog gebruikgemaakt worden van een diesel GPU.

6. **Hoe zit het met de PCAs? Welke aircraft stands beschikken er over fixed PCAs?**
   De PCAs kunnen verplaatst worden, maar ze staan in principe vast op de aircraft stand. Op de E- en F-pier zijn alle PCAs elektrisch. Op de D-pier kunnen eventueel ook elektische PCAs gebruikt worden. Op het A-platform staan mobiele units die op verzoek van de captain bij de VOP geplaatst worden. Deze werken op diesel. Voor de WIBOs zijn nog drie diesel PCAs beschikbaar, die verplaatst kunnen worden.

7. **Hoe werkt de verplaatsing van de GPUs/PCAs?**
De PCAs kunnen verplaatst worden. Met name de diesel PCAs worden verplaatst. De GPUs die op diesel draaien worden op de aircraft stand getankt. Ze worden geplaatst en verplaatst door de "bovenrijders". De elektrische GPUs worden door KLM Equipment Services (KES) naar de laadpunten gebracht. KES heeft hiervoor eigen (diesel)trekkers in gebruik.

8. **Hoe werkt de verplaatsing van de stairs?**
Op de B-pier blijven alle stairs staan op de aircraft stand. Deze stairs zijn allemaal elektrisch en er is geen apart voertuig nodig om ze te verplaatsen. Op de buffers zijn er stairs gestationeerd die gedeeltjk op diesel rijden en gedeeltelijk elektrisch zijn. Deze blijven bij de buffer staan en de oplaadpunten voor de elektrische stairs zijn hier ook aanwezig. Bij de aircraft stands waar PBBs aanwezig zijn worden er soms ook stairs gebruikt die gesleept moeten worden. Dit slepen wordt gedaan door de "bovenrijder".

9. **Wordt er bij de afhandelingen die door de KLM gedaan worden nog GSE gebruikt die niet van KLM is?**
Nee, standaard wordt alles door KLM geleverd.

10. **Welke soorten wegen zijn er te onderscheiden en wat zijn hier de snelheidsrestricties?**
Er wordt onderscheid gemaakt tussen de randwegen en de aircraft stands. Op de randwegen geldt een maximumsnelheid van 30 km/h. Deze maximumsnelheid staat voor iedereen vast. Op de aircraft stands is de afspraak dat er stapvoets gereden wordt. Hoe snel hier dus gereden wordt verschilt, maar de KLM gebruikt hierbij 11 km/h voor de voertuigen die een snelheidslimitatie op de aircraft stand hebben. Elk voertuig heeft een groene lamp. Deze lamp brandt zolang het voertuig op de juiste snelheid rijdt. Zodra je te hard rijdt gaat deze lamp uit. Ieder voertuig op de aircraft stand heeft zo'n lamp om te kunnen controleren of de chauffeur zich aan de regels houdt.

11. **Rijden alle GSE types altijd over de randwegen of mag je ook over het platform van stand naar stand?**
Van aircraft stand naar aircraft stand moet je altijd via de randwegen rijden, tenzij je naar de naastgelegen aircraft stand moet. Er liggen wel wegen over het platform naar de buffer en deze mogen dan ook alleen gebruikt worden om van en naar de buffer te rijden.

12. **Wordt er onderscheid gemaakt tussen parkeer- en laadplekken?**
In het geval van de elektrische voertuigen zijn de parkeer- en laadplekken momenteel hetzelfde. De voertuigen die op diesel rijden mogen willekeurig in een vak geparkeerd worden. Deze hebben geen "eigen" parkeerplek. Een aantal GSE types is hiervan uitgezonderd en heeft een specifieke laad/tankpositie.

13. **Hoe wordt bepaald wanneer de voertuigen moeten opladen? Is dit vanaf een bepaald percentage?**
Elke nacht moeten de voertuigen sowieso opgeladen worden. In principe moeten de voertuigen het hiermee de hele dag redden, maar als in de loop van de dag blijkt dat de accu het niet gaat redden dan wordt er gewerkt met opportunity charging. De voertuigen worden dan opgeladen wanneer daar tijd voor is. De beltloader is het meest kritische voertuig hierbij. Op de lower deck loader zitten verschillende "thresholds" met lampjes ingebouwd. Bij een batterijpercentage van 20% of lager gaat er een oranje lampje brangen. De lower deck loader wordt dan langzamer, de taak moet afgemaakt worden en daarna moet deze opgeladen worden. Zodra het batterijpercentage onder de 10% komt kun je de lift alleen nog laten zakken en moet het voertuig opgeladen worden. Je hebt op dat moment nog wel voldoende energie over om naar de oplaadlocatie te rijden. Op dit moment is de 10% die hier aangehouden wordt voor de veiligheid eigenlijk 20%. Mogelijk worden er in de toekomst nog meer elektrische voertuigen van deze veiligheid voorzien.

G.2. Business Contract Manager GSE II

Function: Business Contract Manager GSE bij KLM
Experience: 26 jaar werkzaam bij meerdere divisies (waaronder cargo en bagage services) binnen KLM, 4 jaar ervaring in huidige functie
Date: 05-04-2023

1. **Waar tanken de verschillende GSE types?**
   Ter plaatse. KES (KLM Equipment Serivces) rijdt rond. Die heeft drie kleine tankwagens. Die tanken alle equipment af. Er zit een ring rond de tankdop met een sensor erin. Als er getankt wordt dan wordt dat geregistreerd. Zo kunnen we precies zien welke equipment (op diesel) er is getankt. Verder hebben we ter hoogte van de G-pier, voor de deur bij de sleepdienst, een klein tankeiland met vier pompen. Daar worden de pushback tugs, de catering trucks, de mulags en de water- en toiletservice getankt. De GPU's en transporteurs worden op de VOP getankt, net als drie diesel high loaders die we nog gebruiken als reserve. De tankwagens voor vliegtuigen worden bij hun eigen gebied getankt.

2. **Waar tanken de fuel bowsers?**
   Bij het KE-depot. Vroeger, meer dan 20 jaar geleden, zat de tankdienst op het Octaanplein. Dat is daar nu weg.

3. **Hoeveel bagagekelders zijn er?**
   De bagagedienst bestaat uit een aantal units. Er zijn afkortingen die gebruikt worden. SPL-KX is Zuid, dat is als je van de C-pier naar de D-pier rijdt. Daar heb je een glazen gebouw aan de zijkant. Daar zit het. Daar staan vijf robots voor de robotbelading. Dan heb je KT, dat is de Oosthal. Dat is de grootste hal. Dat is zo'n beetje 6m onder NAP en daar worden alle ICA vluchten afgehandeld. Dat zit onder de gehele E-pier. Dat is dus veel containerized. Af en toe eens een Europa-vlucht erbij. Dan heb je nog de D-pier. Die zit op de D-pier. Daar worden veel Europa-vluchten afgehandeld. Het bestaat dus uit drie hallen. Dan heb je de bagagerijderij. Dat zit helemaal achteraan de E-pier. Daar zit hal Centraal. Dat is de regie waar alle bagagerijders zitten. Die halen de bagage van een vlucht op en brengen het naar een bepaalde hal. De uitgaande vluchten worden ook door de bagagerijders gedaan. Inkomende en uitgaande bagage is gescheiden. De Oosthal is bijvoorbeeld alleen maar uitgaande bagage.

4. **Hoe werkt het met de bagagedienst? Altijd van VOP naar kelder? Of van VOP naar VOP?**
   Je hebt een proces dat noemen ze tail to tail. Dat zijn vluchten met een korte aansluiting. Stel er komt een vlucht uit Helsinki en die landt op Schiphol en daar zit een passagier op met een verbinding naar New York. Die overstaptijd is te kort om door het bagageproces heen te gaan. Dan wordt er voor gekozen, door een soort "tail to tail regisseur" die dat allemaal monitort, dat er een aparte rijder voor komt. Die koffer wordt dan al op het buitenstation apart geladen. Of als het meerdere koffers zijn soms zelfs een container. Dit proces valt wel buiten het reguliere proces. In het reguliere proces wordt er altijd gereden van een VOP naar een kelder of andersom.

5. **Hoeveel bagagetrekkers worden er (in ieder geval) gebruikt per afhandeling?**
   Dat verschilt per vlucht en het aanbod van bagage. Het gebeurt weleens dat je bij één vlucht zes bagagerijders ziet staan, omdat er dan bijvoorbeeld heel veel aansluitingen op zitten die één rijder tail-to-tail ook niet haalt. Daarnaast heb je er altijd één voor de Amsterdam bagage en één voor de gewone transferbagage. Er is vaak ook minimaal wel één tail-to-tail rijder. In de praktijk heb je maximaal zo'n 12 (tot soms 16) containers aan boord. De regie inkomend zet hier op in. Eén bagagetrekker mag met maximaal vijf containers rijden.

6. **Hoe verloopt het process in de bagagekelder?**
   De bagagetrekkers rijden de kelder in, koppelen daar de aanhangers los en gaan door naar de volgende opdracht. Heel af en toe is er nog wat oponthoud als het druk is, maar je bent veruit de meeste tijd op de VOP kwijt als bagagerijder.

7. **Hoe ziet de werkcyclus van een bagagetrekker eruit?**
   De bagagetrekker rijdt naar een VOP, door naar de kelder en daarna weer naar de volgende VOP. En hierbij wordt onderscheid gemaakt tussen het inkomende en uitgaande proces. Maar op basis van de bezetting kan het ook zo zijn dat een bagagerijder inkomende en uitgaande opdrachten krijgt.

8. **Op basis waarvan wordt bepaald welke bagage er naar welke kelder gaat?**
   De Oosthal wordt alleen gebruikt voor uitgaande bagage. Centraal is ook uitgaand en een minimaal deel wordt daar gelost. En de D-Hal en Hal Zuid wordt gebruikt voor zowel inkomende als uitgaande bagage. Welke kelder er gebruikt wordt, wordt beslist door de regisseur. Er is een inkomende bagage regisseur en een uitgaande bagage regisseur en die kijken, als de vlucht nog onderweg is, al naar de bagage flow van die vlucht. Dus ze kijken naar de aansluitingen die erop zitten en bepalen zo de verdeling tussen tail-to-tail, Amsterdam en transfer bagage. Als de transfer langer dan 70 minuten is gaat de bagage het reguliere proces in. Aan de hand van deze verdeling kijkt de regisseur op welke tijdstippen er in welke hallen ruimte is, want op bepaalde tijdstippen zijn bepaalde hallen heel druk. Hier worden een hoop strategische keuzes voor gemaakt, die puur gebaseerd zijn op omlooptijden en bezetting. Het is een heel gecompliceerd proces.

9. **Hoeveel verschillende types pushback tugs zijn er. Welke types worden voor welke aircraft types gebruikt?**
   This answer contains confidential information and is therefore not publicly available.

10. **Hebben alle VOPs een PBB, behalve A-platform, H-pier en de buffers?**
    Dat klopt.

11. **Welke VOPs zijn er uitgerust met fuel pits en welke niet?**
    Het A-platform, de A-pier met de Embraer vloot en de H-pier hebben geen fuel pits.

12. **Zijn alle VOPs op Schiphol push-out of zijn er ook power-out VOPs?**
    Op het A-platform hebben we twee stroken met Power-in Power-out stands.

G.3. Contract Manager GSE

Function: Contractmanager GSE bij KLM
Experience: 33 jaar ervaring in GSE en afhandeling vliegtuigen bij diverse afdelingen van KLM Ground Serices, committee member SAE AGE-3 Aircraft Ground Support Equipment Committee en Member IATA GAD GSE and working groups.
Date: 21-03-2023

This interview contains confidential information and is therefore not publicly available.

G.4. Airport Planner

Function: Airport Planner bij NACO
Experience: Since 2017 active in the aviation industry (including internships) and since 3 years employed at Royal HaskoningDHV of which over 2 years as Airport Planner at NACO.
Date: 14-03-2023

1. **Welke stappen zijn er volgens jou te onderscheiden in de Master Planning van Airports?**
   De klassieke stappen zijn 1.) huidige situatie, 2.) lange termijn forecast en dan terugwerkend 3.) landuse plan, 4.) masterplan, 5.) fasering en 6.) quick wins.

2. **In welke van deze stappen wordt er gekeken naar GSE?**
   GSE begint eigenlijk pas in het kopje masterplan. In het landuse plan zit het niet echt, dat is zo hoog over, dus in het masterplan komt het eigenlijk aan bod. En dan is vooral het belangrijkste waar kun je het parkeren en eventueel waar ga je het onderhouden? Om dat te weten moet je weten hoeveel voertuigen er gaan rondrijden en aan de hand daarvan kun je dan bepalen hoeveel ruimte je dan nodig hebt. Momenteel gebruiken we bij NACO nog niet echt een manier om het gedetailleerd te bepalen, maar volgens mij zijn er drie dingen die bepalen hoeveel GSE je op je luchthaven rond hebt rijden. Het bepalen van de hoeveelheid GSE is altijd de eerste stap. Dit hangt vooral af van het aantal piekuurbewegingen, want in je piek moet je alles kunnen afhandelen. Dus het hangt af van de hoogte van je piek. Het hangt ook af van het aantal Wide-Bodies en Narrow-Bodies in die piek. En je zou in feite zelfs nog kunnen hebben dat je peak in movements alleen maar Narrow-Bodies zijn en er een soort tweede of derde piek is met alleen maar Wide-Bodies en dat die in GSE dus eigenlijk veel maatgevender is. Dat blijft altijd een beetje oppassen. En wat ook een rol speelt, als je naar de hele luchthaven kijkt. Hoeveel ground handlers zijn er? Je gaat daar altijd inefficiëntie in krijgen. Dus ergens moet dat ook nog een rol in spelen. En van daaruit kun je dan wel zeggen, met behulp van een aantal parameters, we hebben ongeveer zoveel vierkante meters nodig per gemotoriseerd stuk GSE en ongeveer zoveel vierkante meter onderhoud nodig. En voor het parkeren speelt dan nog mee dat een bepaald deel kan parkeren op de stand. Die blijven op de stand, zoals een beltloader. Dat is ook equipment en dat is vaak ook gemotoriseerd, maar blijft in principe op de stand. Maar de andere dingen moet je ook ergens kunnen parkeren. De layout van je luchthaven wordt bij het bepalen van je GSE aantallen niet meegenomen, maar het zit er in die zin in dat je bepaalde equipment op een contact stand niet nodig hebt die je op een remote stand wel nodig hebt.

3. **Hoe heeft het aantal ground handlers invloed op je GSE fleet? Hoe neem je dit mee?**
   Dat is heel lastig. Daar is niet één getal aan te hangen. Het ligt er aan welke equipment zou je eventueel kunnen delen en welke niet? En ook dan weer, als je naar het dagpatroon gaat kijken, kunnen de pieken natuurlijk anders liggen per ground handler, afhankelijk van de maatschappijen. De combined piek kan daardoor anders liggen dan de pieken per handler. Dus als je gaat sharen, wil dat ook niet per se zeggen dat één en één is twee is. Wat je vaak wel ziet is dat de handler vaak ook wel aan een basecarrier gelinkt is en vaak al zijn vluchten wil afhandelen in een bepaald gebied van een terminal areaal, dus je wil dan eigenlijk het liefst alle equipment ook in dat gebied ergens kwijt kunnen, dus je probeert daar wel een beetje rekening mee te houden. Je weet niet altijd van tevoren hoeveel ground handlers er op een luchthaven gaan komen, dus ergens moet je er wel een beetje flexibiliteit inbouwen.

4. **Waar houd je rekening mee in de Master Planning als het gaat om GSE? En in welke stappen gebeurt dit dan?**
   Wat we voor Manilla gedaan hebben is eerst gezegd oké we hebben een X aantal equipment die we totaal inschatten. Dat hebben we opgesplitst in gemotoriseerd en non-gemotoriseerd en gezegd voor gemotoriseerd heb je een X aantal vierkante meters nodig om het kwijt te kunnen en voor non-gemotoriseerd heb je zoveel vierkante meters nodig om het kwijt te kunnen. Dan heb je dus een totaal aantal vierkante meters nodig om het ergens kwijt te kunnen. We hebben ook gezegd we hebben per stand zoveel vierkante meter en we hebben zoveel stands, dus dat deel van de equipment kunnen we daar kwijt. En voor de rest moet je dus ergens nog gebieden gaan toewijzen puur om te kunnen parkeren. Aan de hand van de stand layout is er voor de belangrijkste dingen altijd wel een plek. En ook de parkeergebieden hebben we wel echt rond de pieren gemaakt zodat je het wel altijd dicht bij de operatie houd. Het aantal vierkante meters per voertuig is een beetje een inschatting. En er wordt dus rekening gehouden met GSE maintenance. Ook dat moet je ergens op je luchthaven hebben. Eerst wordt er gekeken hoeveel gebouwen heb je nodig? Uiteindelijk is het ook maar gewoon een soort autogarage, dus een beetje common sense ook maar gebruiken, want er is niet echt ergens beschreven hoe het werkt. Dus als je zoveel voertuigen hebt, hoeveel van die baaien heb je dan nodig en hoe groot is zo'n baai ongeveer? Hoeveel van die garageboxen heb je nodig. Er moet wat kantoor bij en dan heb je een vloeroppervlakte en dat keer een bepaalde factor en dan heb je een plot te pakken. Verder houd je er rekening mee dat er ergens een plek moet zijn om te kunnen tanken, maar dat zijn niet de vierkante meters. De bagagekelder wordt vooral gedicteerd aan de capaciteit die nodig is aan de bagagekant, niet aan de equipmentkant. En catering ligt er heel erg aan hoe en waar dit gedaan wordt. Is dit op airside, of heel ergens anders? Het is niet gezegd dat dat altijd per se dicht bij de luchthaven is.

5. **Zit hier nog verschil in qua greenfield en brownfield airports?**
   Ja tuurlijk. Als je nu naar Schiphol kijkt dan heb je er daar 5 / 6? Dat is extreem veel. De kleintjes hebben er meestal één. Grotere twee of drie. Schiphol is dus echt een buitenbeentje wat dat betreft. Stel je begint aan een brownfield en die hebben er nu twee, dan zou je kunnen zeggen houd er rekening mee dat er ooit een derde bij komt, maar dat is ook niet per se een gegeven.

6. **Wat zijn volgens jou de verschillen om rekening mee te houden tussen GSE en eGSE?**
   De grootste vraag die er nu ligt is hoe en waar moet je ze opladen? Vooral waar. Hoe vaak? En dan is misschien nog wel de meest interessante vraag, heb je dan dadelijk meer equipment nodig of niet? Er wordt een beetje gekeken naar de bestaande mixen van equipment. De bagagedingen zijn bijvoorbeeld al jaren elektrisch, want die rijden in een afgesloten ruimte. Het grootste deel waar je rekening mee houd is je oplaadfaciliteit die je nodig hebt. Hier wordt nog niet echt rekening gehouden met laadtijden en het aantal vierkante meters per voertuig.

7. **Wordt er nu al rekening gehouden met de locatie van je oplaadpunten in je master planning?**
   In pricipe wil je dat op dezelfde manier als je parkeerplekken wel ergens in het gebied waar je ze ook gebruikt, om de pushbacktug laadlocatie situatie van Schiphol te vermijden. Het liefst houd je er nu al rekening mee dat het elektrisch gaat worden in je master planning. Zeker met het aanleggen van de stroomvoorziening. Dat is misschien uiteindelijk nog wel kritischer dan het ruimtevraagstuk. Op een masterplanniveau, op de tekening, zie je dat niet, maar die zie je juist wel weer in de vraag welke stroomvoorziening leg je aan?

8. **Wat zijn volgens jou de grootste uitdagingen van de implementatie van eGSE?**
   In ieder geval het stroomvraagstuk. Verder zitten er uitdagingen in de operatie, maar dat is meer aan de handlers. Daar hebben we weinig invloed op en weinig direct mee te maken. Dat is dan met name met betrekking tot het opladen ervan.

9. **Wat zijn volgens jou de belangrijkste variabelen van een GSE fleet?**
   Vooral hoeveel, hoe groot is je totale vloot? Het aantal voertuigen wil je zo laag mogelijk houden, dat zorgt er automatisch voor dat het aantal oplaadpunten en je maintenance zo klein mogelijk is. Maar dat is natuurlijk ook weer gerelateerd aan het hele stroomvraagstuk met je oplaadpunten. Het stroomverbruik is dus ook interessant om te bekijken, maar daar zit natuurlijk ook al een afweging in met wat voor charger je gebruikt. Er zitten verschillende scenario's in. En qua GSE aantallen misschien ook wel een split naar types.

10. **Wat zijn volgens jou interessante scenario's (op basis van variabelen) om mee te nemen in mijn onderzoek?**
    Ik denk niet dat er vast te stellen scenario's zijn, dat is zo airport specifiek. Je moet het meer zien als een soort sensitivity analysis binnen het model. De verhouding fast chargers versus normale chargers en de invloed daarvan op het aantal voertuigen en op de stroomvraag op het net. Als de locaties van de opladers grote invloed hebben op de stroomvraag van het voertuig zijn die ook interessant om te bekijken, want dan heeft dat dus ook invloed op al die andere dingen. In ieder geval dus het stroomverbruik op het net en het aantal voertuigen afzetten tegen de eigenschappen van je vloot en je airport.

11. **Komt NACO in een master planning ook met het aantal voertuigen en het stroomverbruik?**
    Ja, alleen is dat nu dus op heel veel aannames gebaseerd. In de masterplanning zitten nu ook geen scenario's voor de oplaadlocaties, omdat de informatie hiervoor er gewoon niet is.

G.5. Aviation Sustainability Consultant

Function: Aviation Sustainability Consultant at NACO
Experience: Since 2018 active in the aviation industry and since 1.5 years employed as an Aviation Sustainability Consultant at NACO.
Date: 21-03-2023

1. **What do you take into account in the Master Planning when it comes to GSE, and what steps are followed for this?**
From what I have done so far it is the road networks taken. So, do I have enough lanes. Maybe, outside of a baggage hall you want maybe 4 lanes, instead of 2, because you get a lot of congestion. On the power demand side of things you need to take into account electric GSE quite a bit. Hydrogen GSE has seen a lot of interest recently. I have gone to industry conferences myself and there is a lot of interest in hydrogen GSE, but there is a lot of, kind of uncertainty when it comes to the infrastructural element. So the power demands can be quite large, so that is something that you need to measure. Would you put your charging stations close to the aircraft stands or do you put them far away? Usually you find a little bit of an in-between. So the ones close to, you would have your baggage tractors, you would have your eGPUs, things that charge very quickly. Sometimes you have on-stand chargers, which would be used mainly for the ITWs, eGPUs for example. And then the further away ones you would have for the larger vehicles, like the apron buses, catering trucks, and the like, but catering trucks are seldom electrified so far I think. I haven't seen any actually. And what else, spatial planning as well. The maintenance areas and such. For me, what I have been aware of is the large vehicles versus small vehicles. The turning radius for example for an apron bus for example is far larger than say a baggage tug. So you need to take that into account if you are putting stands close together. If you are advising a client on a type of apron bus, say "this is the height they are going to be". I am most on the sustainability side, so the emissions reductions are quite huge. For the sustainability side of things, turnaround emissions can be around 40+% from just the diesel GPUs. So if you replace those, then you reduce quite a lot. So that is something that we do like to put forward as a good option if you do want to reduce your emissions. And then taking into account the code A, B, C, all the ICAO codes as well, but in the end at the sustainability front where I am coming from we are mostly concerned about APU usage, emissions on the stands, and particulate emissions that like workers are breathing in.

2. **What do you think are the differences to be taken into account between GSE and eGSE?**
First, the downtime of electric vehicles will be a lot more. It is changing recently, but you have to account for what exists now, so if you're planning an airport for 25-30 years from now you take what you have now. You know, something that is going to charge in three hours now, maybe in 20 years will charge in 20 minutes. But, we have to take the three hours. You take the large scenario in essence. The main differences, I go back to the emissions, is a big issue. I worked in Dublin airport and I talked to some people there. The whole reason for electrifying vehicles wasn't environmental, it was operational, because the BHS systems were underground, and they didn't want to use HVAC (heating, ventilation and air conditioning) systems to exhaust the fumes, so they just mandated electric vehicles then. So that is how the electrification started. It started as an operational thing. So the difference is that it is quite hard for these companies to bring it in. A lot of them find it difficult to have experience with it, I noticed. There is a lot of operational difficulties with electric vehicles, with electric GSE, that we seldom see on a master planning level, but when I talk to people on an operational level there is a fair amount of difficulties in terms of maintenance and charging times that we may not necessarily see, so then they end up using the diesel vehicles instead. So yes, mainly emissions and operational issues to me.

3. **What do you think are the biggest challenges of implementing eGSE?**
I would say the largest one is power demand, because if you need a lot of fast chargers, it's gonna have huge power demand implications, especially at like peak times. And it's kind of hard to smooth that out, because can start impacting the flight schedule negatively, and you don't really want to do that. So, then about the charging times. A lot of vehicles don't use lithium-ion batteries, but they use lead-acid batteries, which means that for maintenance reasons, they go down and they need to be overhauled every year and sometimes more often. So that leads to extra costs, which they wouldn't experience on a diesel, because they have a lot more experience working on them. So I would say, charging times, which ties into operational, and the maintenance level as well. And also the charging infrastructure is quite a large investment as well, which is what airports are quite interested in looking into. But there is kind of a cost-benefit thing in there as well.

4. **For which (e)GSE types do you expect this to have the greatest influence?**
The GPU first, quite a lot. Because they sit on the stand, they are operating the entire time. Next would be the baggage / cargo tugs. Baggage tugs are electrified already and the cargo tugs are kind of getting there, because of torque issues with electric vehicles. The batteries drain to quick. It would basically be the vehicles that operate for the longest period of time on stand. So, apron buses, you would initially think “those are bad”, but they drive over and then they turn off, they drive back to the bus gate and they turn off and open the doors. So I would go, GPU, baggage tug, cargo loaders as well, so lower deck and main deck, and I would think catering as well. So the vehicles that operate there for the longest. You see that from the terminal planning manuals, but those terminal planning manuals for like Airbus and Boeing take quite a lot of generalizations.

5. **What do you think are the most important variables of a GSE fleet that I can have a look at?**
The charging time and how long the battery lasts. It dictates how many vehicles you are gonna have operational in a day. So if you have 20% of your fleet sitting there just charging, that's 20% of your fleet that is not working around and making money. So you want to have as much vehicles out there as possible. So first things to me would say charging times tied to the battery capacities. Those would be the main things to me. And also the market demands, because the market for GSE is quite slow-moving and they don't really adapt very quick, so there is only a few companies electrifying everything, but that is kind of varying a bit. So in terms of doing models, markets don't matter as much, but it does matter quite a bit once in the operational sense, once they start purchasing vehicles and say “we want to electrify everything, but they don't exist”, or they're too expensive. But going back to the original, it's primarily charging times tied to battery capacities, and then the vehicle market availability.

6. **How are these variables taken into account within NACO?**
We try to take into account the types of fast chargers for example. But these chargers generally are smart chargers. So you kind of have to take a bit of an average in between them. So it is kind of hard to pin down exactly what that might be, but to a master plan level there is a point where you cut off and just say we take 80, that is the average and we will take it. So the electric vehicles traditionally haven't been taken into account. I only started doing it last year. And what I found is that longer charging times has quite drastic implications on the charging area, like spatial demands. And to the few space constrained airports, such as the Schiphols or the Rotterdam The Hagues, this could be a big issue. So either you invest really heavily in fast chargers and peak your power demands, or you just have less of those chargers and then use bio-diesel or something for the other vehicles, which is what Schiphol has recently done. So I think the smart chargers are something difficult to take into account. The spatial constraint is directly linked to how long the vehicles can stay operational and that is something that is kind of hard to pin down, especially at a high level, at a master plan level.

7. **What do you think are interesting scenarios (based on variables) to include in my research?** Charging times, power demands, battery capacity, and how that interrelates with space constraints. At a master plan level at least, we would be very interested. They are not gonna be parked all at the same time. You can slow charge them over nighttime, but maybe they won't last for the whole next day, so you might have to charge them intermittently during the day, so then it goes into a charging strategy then. So what happened, I was talking to my old employer. They were managing ramp equipment. The old employer is a ground handler company in Dublin airport and I was asking "how do electric vehicles work?". And on the practical level, they just charge them whenever they don't use them. Because they don't want to risk the vehicle not being available at any time. So, the manufacturer recommends do not charge it over 25%, otherwise you will kill the battery. And it is lead-acid batteries, so this has big implications on maintenance. But on the ramp this is how operations are: you just want the vehicle now. So people just go over to the vehicle and charge and then take it off again, so then that brings the need in for close-by chargers really, like close to the aircraft stands. So that's something that has been very important, and something that was quite eye-opening to me and doesn't have a solid answer I guess. It is inevitable that people aren't gonna follow manuals when they have a flight that needs to leave in ten minutes, so you need to work around them.