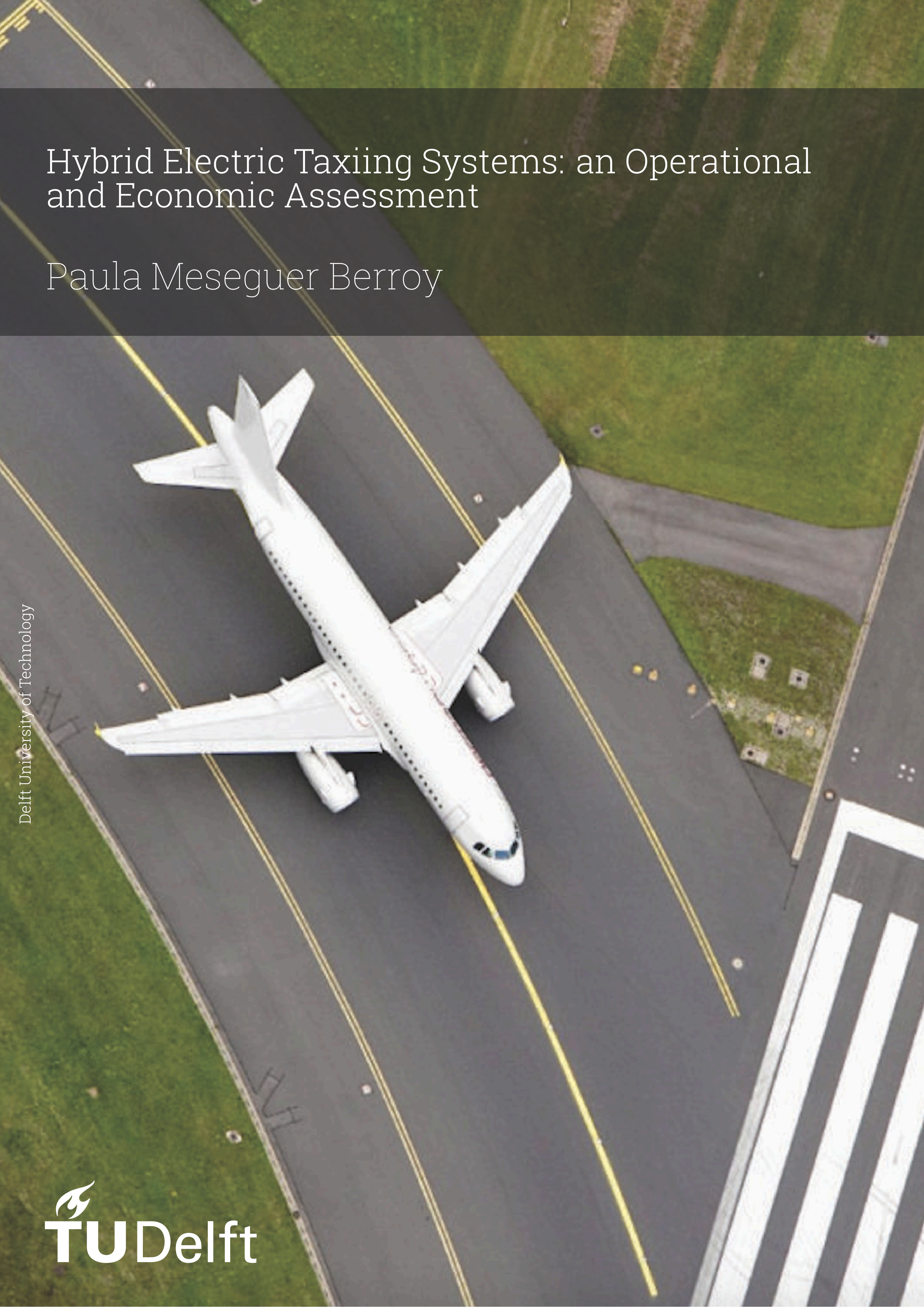

Hybrid Electric Taxiing Systems: an Operational and Economic Assessment

Paula Meseguer Berroy

Delft University of Technology

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Hybrid Electric Taxiing Systems: An Operational and Economic Assessment

by

Paula Meseguer Berroy

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on July 10th, 2023.

Student number:	4530934	
Project duration:	September 2021 – July 2023	
Thesis committee:	Dr.ir. B.F. Lopes Dos Santos	TU Delft, Chair
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Acknowledgements

This thesis presents the final step in my Master's Degree in Aerospace Engineering at TU Delft. After seven years of hard work, my educational path comes to an end and it is now time to look into what the future holds. However, I would first of all like to express my gratitude to some of the people that have been by my side along the way, especially during the last year.

I would have never been here without the unconditional support of my family. I will forever be grateful for the sacrifices you have made and for always sticking by my side, no matter how far we were from each other. I would also like to thank the person that has seen me struggle the most for the last months, Simon. Thank you for always keeping the brightest smile and for believing in me no matter what. Even after proofreading my thesis for a thousand times you would still say it was an interesting read and, let me tell you, there is no better definition for unconditional support.

I would also like to thank my friends for not making these years only about studying but also about travelling around the world, dancing the stress out and enjoying the little moments. PACKS, Salchis, CamCam, Delft and Brussels friends: I am so thankful to have you in my life and I am sure that the friendships we have made will last for a very long time.

Lastly, I would also like to thank the supervisors that I have had during the two internships that I did during my Masters Degree: Frederik, Yolanda and Peter. From my own experience, I know how valuable it is to have a good supervisor by your side and they have always pushed me to produce ambitious results, while providing the necessary tools and support.

This thesis is dedicated to the two brightest stars in the sky, Vicente and Enrique.

Paula Meseguer Berroy
Delft, June 2023

Contents

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List of Abbreviations

Acronyms

ACID	Aircraft Identification Code
AEA	All-Electric Aircraft
APU	Auxiliary Power Unit
ASU	Air Start Unit
BEV	Battery Electric Vehicle
B2C	Business to Consumer
CEMF	Counter-Electromotive Force
DLR	German Aerospace Centre
EGTS	Electric Green Taxiing System
EIS	Entry Into Service
EP	Electric Pushback
ETS	Electric Taxiing System
EU ETS	European Union Emission Trading System
FCEV	Fuel Cell Electric Vehicle
FOD	Foreign Object Damage
GPU	Ground Power Unit
GSE	Ground Support Equipment
HETS	Hybrid Electric Taxiing System
ICAO	International Civil Aviation Organisation

ID	Identification Code
IDG	Integrated Drive Generator
MEA	More-Electric Aircraft
MILP	Mixed Integer Linear Program
MLG	Main Landing Gear
NB	Narrow Body
NLG	Nose Landing Gear
PCA	Pre-Conditioned Air Unit
RAMS	Reliability, Availability, Maintainability and Safety
ROI	Return on Investment
TAT	Turnaround Time
TM	Traction Motor
TOT	Time of Taxiing
TR	Ton of Refrigeration
TRL	Technology Readiness Level
WB	Wide Body

Airport ICAO Codes

EHAM	Amsterdam Airport Schiphol
LEMD	Adolfo Suárez Madrid-Barajas Airport
LFPG	Charles de Gaulle Airport
LIRF	Fiumicino International Airport ("Leonardo da Vinci")
LROP	Bucharest Henri Coanda International Airport

Chemical Formulae

CO	Carbon Monoxide
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxide

List of Symbols

ρ	Air density	$[\frac{kg}{m^3}]$
ρ_H	Density of compressed hydrogen	$[\frac{kg}{m^3}]$
C_D	Aerodynamic drag coefficient	[-]
$C_{D,g}$	Ground drag coefficient	[-]
D	Diameter	[m]
D_{ac}	Aircraft's drag force	[N]
$D_{g,ac}$	Aircraft's ground drag force	[N]
$D_{g,et}$	External truck's ground drag force	[N]
dP	Varied amount of parameter's reference value	[-]
E_{tot}	Energy required	[J]
g	Gravitational acceleration	$[\frac{m}{s^2}]$
$m_{ac,ramp}$	Ramp mass of the aircraft	[kg]
m_{ASU}	Mass of the Air Start Unit	[kg]
m_{et}	Empty mass of the external truck	[kg]
m_{fuel}	Mass of external truck's fuel	[kg]
m_{GPU}	Mass of the Ground Power Unit	[kg]
m_{PCA}	Mass of the Pre-Conditioned Air Unit	[kg]
P	Parameter's reference value	[-]
P_{ASU}	Power required by Air Start Unit	[W]
P_{GPU}	Power required by Ground Power Unit	[W]

P_{PCA}	Power required by Pre-Conditioned Air Unit	[W]
P_{tot}	Power required	[W]
P_{tr}	Power required from terminal to runway	[W]
P_{rt}	Power required from runway to terminal	[W]
S	Wing surface area	[m^2]
S	Sensitivity of the parameter's reference value	[-]
S^+	Sensitivity above of the parameter's reference value	[-]
S^-	Sensitivity below of the parameter's reference value	[-]
t_{SR}	Time taken to go from the runway to the terminal through the service roads	[s]
t_{taxi}	Time taken to taxi from stand to runway	[s]
V_{SR}	Service road speed	[$\frac{m}{s}$]
V_T	Taxi speed	[$\frac{m}{s}$]
X	Mean of the model's output	[-]
X^+	Mean above of the model's output	[-]
X^-	Mean below of the model's output	[-]

Introduction

Background

The use of air transport keeps increasing every year and is expected to double every 15 years [19]. In 2019, 4.5 billion passengers were carried by the worlds airlines [3], meaning that in 2034 a total of 9 billion passengers would be travelling around the globe on a yearly basis. This increase in the use of air transport will evidently have a positive impact on the economic growth of airports, airlines and the cities nearby. Moreover, as air traffic increases, so will the job opportunities in the aviation sector, which in 2019 already generated 65.5 million jobs globally [1]. On the social side, air transport improves the quality of life by expanding the range that people can reach, enriching their culture. It also promotes social inclusion, by bringing tourism to countries that are affected by poverty [2].

However, if the number of flight movements doubles in the next decades, so will the emissions and fuel consumption associated to aviation. Currently, the global aviation industry already produces 2% of all human-induced carbon dioxide (CO_2) emissions and aviation is responsible for 12% of CO_2 emissions from all transport sources [3]. These numbers are expected to increase if no sustainable solutions are implemented to reduce pollution. Moreover, the noise levels at airports and neighbouring areas will also rise, possibly attaining levels that are harmful for the population. On the operational side, congestion at airports will be difficult to deal with, as some of the biggest airports are already reaching maximum capacity and expansion of some of these airports will not be possible. Currently, research to decrease the negative impact of aviation is mostly focused on the airborne phase, where the benefits of More-Electric Aircraft (MEA) and All-Electric Aircraft (AEA), amongst others, are being studied. Experts believe that the implementation of such aircraft would result in a 10% decrease in aircraft weight and 9% decrease in fuel consumption [19]. However, in order to ensure sustainable growth, techniques that reduce noise, emissions and fuel consumption on ground also need to be executed.

Alternative taxiing solutions are being researched by many institutions and companies worldwide, with most focusing on either on-board or external taxiing systems. However, a downside that both options share is that such systems cannot be used in all types of airports. For example, when the taxiing time is lower than 5 minutes, it is not beneficial to use these systems, as the time it would take to heat the engine can double the taxiing time, increasing congestion at the airport [19]. Developing a system that could combine characteristics of both on-board and external systems, would be an interesting area of research. Hybrid Electric Taxiing Systems (HETS) have not been widely researched yet, making it an interesting and innovative research topic to explore.

Research Aim

A research gap that has not been fulfilled yet would be the use of a hybrid electric taxiing system to mitigate pollution and reduce fuel consumption at airports and their surroundings. In order to assess the feasibility of such system in the aviation market and ensure the success of this concept against its competitors, it is necessary to assess the economical and operational capabilities of the designed HETS. The research objective can be summarised as follows:

To assess the operational and economic feasibility of hybrid electric taxiing systems by designing a mixed on-board and external electric system and comparing its characteristics with other existing electric taxiing solutions.

With the research objective being identified, the research questions and subquestions that follow and that will be carefully addressed throughout this research project are stated below:

RQ-1 What is the working principle of the HETS?
  RQ-1.1 How is the system be powered?
  RQ-1.2 What are the changes needed in the aircraft systems architecture?
  RQ-1.3 How should airport infrastructure change to accommodate HETS?

RQ-2 What are the benefits and downsides of such system?
  RQ-2.1 What is the environmental footprint of the system?
  RQ-2.2 Will congestion issues arise due to the implementation of the HETS?
  RQ-2.3 Are research and development costs justified?
  RQ-2.4 Is the performance of the system better than its competitors?

RQ-3 What are the feasibility margins of the HETS?
  RQ-3.1 Is the system able to penetrate in low-cost carriers' markets or solely in network carriers?
  RQ-3.2 In which airports can the product be implemented: international hub-, international- or regional airports?

Report Structure

The reports is structured as follows. Part I contains the scientific paper, where the main information with regards to the thesis work can be found. In this part, the main results and conclusions are presented. Then, a literature study that compiles all research work performed prior to the thesis is presented in Part II. Lastly, Part III includes all supporting work that has been done by the author. Here, detailed results that complement the conclusions can be found.

I

Scientific Paper

Hybrid Electric Taxiing Systems: an Operational and Economic Assessment

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Abstract

Fuel consumption during the taxi phase of flight can be reduced by using electric wheel propulsion instead of aircraft engines. Currently, this can be either done by having external trucks towing the aircraft from the gate to the runway, or by incorporating electric motors on the aircraft wheels to power the aircraft without using the engines. The purpose of this research is to investigate whether a Hybrid Electric Taxiing System (HETS) that combines both technologies is feasible and yields better results in terms of sustainability, congestion and operation. First, a preliminary design phase of the HETS is carried out yielding the main characteristics of the system. An assessment model to study the feasibility of such system is then created by following a series of decision criteria, such as aircraft utilisation and taxi times at destination airports. Two scenarios are considered to examine the effect of the size of the network and fleet on the feasibility of HETS. The first case study includes flight data from the perspective of a single airline, while the second comprises data from five different airlines within an alliance. In conclusion, although many aircraft are eligible for the placement of electric motors, not many airports are eligible for the implementation of external vehicles. Moreover, although the introduction of HETS would lead to improvements on sustainability, it would increase airport congestion and require investments on the airport infrastructure that cannot be justified at the proposed scale.

Keywords: Hybrid Electric Taxiing System, Electric Towing, Engineless Taxiing, Assessment Model, Operational Feasibility

1 Introduction

The operational and environmental issues created by the continuous growth in air transportation are becoming a challenge in society. Currently, the global aviation industry produces 2% of all human-induced carbon dioxide (CO_2) emissions and aviation is responsible for 12% of CO_2 emissions from all transport sources [Air Transport Action Group, 2020]. This shows that congestion, carbon emissions, air pollutants and noise faced at airports due to aviation must be tackled in order to achieve sustainable growth in this industry. Most current research to make aviation more sustainable focuses on the airborne phase, although taxiing is the main contributor to airport congestion, emissions and noise. When it comes to the latter, the aviation sector is mainly researching on on-board or external electric taxiing systems. However, the idea of a hybrid system that combines both on-board and external technologies has not been widely researched yet. The advantage of combining both taxiing alternatives would be having a movable power source provided by an external truck, which would avoid the use of the aircraft engines or Auxiliary Power Unit (APU). The truck would be attached to electric motors placed on the aircraft wheels and it would provide power to them in order to drive the aircraft through the taxiways in an engineless manner. This would help avoid traction issues, created by pulling forces on the nose wheels, that are common when solely using external trucks to tow the aircraft through the airport surfaces.

The purpose of this research is to assess the operational and economic feasibility of Hybrid Electric Taxiing Systems (HETS) by designing a mixed on-board and external electric system and comparing its characteristics with other existing electric taxiing solutions. This will be done by first deciding on the preliminary technical specifications of the HETS and followed by an assessment model, which will simulate and assess the benefits and downsides that an HETS would bring to the industry. In order to make the research as broad as possible within the required timeline, both Narrow-Body (NB) and Wide-Body (WB) aircraft are considered. Moreover, an analysis of the results will be performed at two scales in order to assess the effect of the network size on the feasibility of the HETS. First, data from only one airline, KLM, will be taken. Then, a comparison will be made with a bigger network comprised of five airlines that will be assumed to form an alliance: KLM, Air France, Air Europa, ITA Airways and Tarom. Lastly, it must be noted that in order to limit the scope of the research project, only commercial flights will be taken into account and seasonal flights will be disregarded.

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This paper is structured in the following way. First, a short summary is given on the state of play of alternative taxiing procedures in section 2. Then, the preliminary design of the HETS is carried out in section 3. The methodology followed by the assessment model is presented in section 4, accompanied by the introduction to the case studies in section 5. Lastly, the results obtained and comments on the feasibility of HETS can be found in section 6.

2 Literature Review

Taxiing is described as the phase of flight in which an aircraft moves under its own power on the surface of an aerodrome, excluding take-off and landing [Lukic et al., 2018]. This phase of the flight cycle is highly inefficient, as the propulsive and thermodynamic efficiencies of aircraft engines are low at respectively low speeds and low thrust settings. As a result, taxiing is one of the main sources of pollution and noise at airports [Lukic et al., 2018]. The pushback phase is an important factor in slowing down the total ground procedure [Lukic et al., 2019], leading to significant delays in departure and arrival times of aircraft, higher fuel consumption and greenhouse gas emissions. European flights spend up to 30% of the time and consume 5-10% of all mission fuel for ground operations and taxiing [Re, 2012], representing 25% of airline costs [European Union Aviation Safety Agency et al., 2019]. Some airports and airlines are beginning to implement alternative ground propulsion systems in order to mitigate noise and emissions, and to reduce fuel consumption. There are two types of solutions: operational solutions, which involve the improvement of airport operations at an airport level and still require engines to taxi, and technological solutions, which focus on the employment of engineless-based approaches that allow for smarter and greener taxiing [Lukic et al., 2019].

2.1 Operational Taxiing Solutions

On the operational side, single-engine taxiing could be implemented as a new form of taxiing, meaning that only one engine is used for taxiing twin-engine aircraft or two engines for four-engine aircraft [Guo et al., 2014]. It has the potential to reduce fuel consumption and carbon dioxide (CO_2) emissions by 20-40%, and nitrogen oxide (NO_x) emissions by 10-30% [Pillirone, 2020]. The advantage of using this technique is that its implementation would not require major changes in airport infrastructure or aircraft design, allowing for a faster adoption. However, the manoeuvrability and balance of the aircraft would be affected if the thrust power came from one side only. Furthermore, depending on the weather conditions and the shape of the taxiway, it is sometimes impossible to shut down half of the engines. These technical and safety constraints render single-engine taxiing prohibited in some airports and not recommended by aircraft manufacturers [Pillirone, 2020].

2.2 Technological Taxiing Solutions

Technological taxiing solutions can be categorised into external and on-board solutions. Both are based on the same principle: engineless-based taxiing. However, the main difference is that external systems consist of towing tractors that move the aircraft from the gate to the runway, whereas on-board systems involve the installation of electric motors on the wheels of the aircraft to electrically power the aircraft from the gate to the runway.

2.2.1 External Systems

The least complex and costly external system to apply, but also the least sustainable, is dispatch towing. It consists of using standard towing tractors that are already used for pushback to carry the aircraft along the entire taxiing path. These tractors consume diesel, gasoline or natural gas and they emit less on average than conventional aircraft engine-based taxiing [Deonandan and Balakrishnan, 2010]. A method similar to dispatch towing but slightly more sustainable is semi-robotic dispatch towing, which employs fully- or hybrid-electric trucks that are more efficient and environmentally friendly [Lukic et al., 2019]. An example of this is TaxiBot, a semi-autonomous hybrid electric tractor developed by Israeli Aerospace Industries [Lukic et al., 2018], which is one of the few certified and commercially operational alternative taxiing solutions to date. The third alternative to external systems is the use of Electric Pushback (EP) systems. These are designed to replace conventional fuel towing tugs with electrical ones. An example of an EP system is Mototok, which requires no driver and therefore has lower operating costs. In addition, Mototok produces no emissions and relatively low noise during pushback procedures. The towing trucks are smaller than conventional tractors, making storage and manoeuvring in airport hangars more accessible and flexible. The main drawback is that EP systems can only reach very low speeds, making them acceptable for pushback operations only [Lukic et al., 2019].

The main advantages of external systems are that they do not add any mass on-board, modifications done to the aircraft are minor and Foreign Object Damage (FOD) risk is reduced by 50% due to the engines not running [TaxiBot, 2013]. When compared to the other taxiing solutions, external systems lead to the highest fuel savings.

Furthermore, the certification process is considerably easier than for other Electric Taxiing System (ETS) solutions [Lukic et al., 2018]. However, the implementation of these systems presents a range of disadvantages. Congestion at airports would increase as the aircraft would have to stop and wait several minutes to be attached and detached from the tractor after landing and before take-off, respectively. Moreover, the airport infrastructure would have to undergo major modification, as secondary roads for the movement of the tractors would have to be built. Furthermore, each vehicle should be equipped with a human driver or an automated guidance system, resulting in additional operational costs [Lukic et al., 2018]. From an economic point of view, it would be a considerable investment for airports and airlines to use external systems. For example, the price of a single TaxiBot is $1.5M for Narrow-Body (NB) aircraft and $3M for Wide-Body (WB) aircraft [Airside International, 2018].

2.2.2 On-Board Systems

On-board systems are located inside the aircraft and typically include an electric drive concept with an electric motor, a power converter and an electrical power source. These systems lead to the maximum carbon monoxide (CO) reductions compared to other existing taxiing alternatives. In addition, implementing such systems minimises airport surface movements by towing tractors and significantly reduces pushback times [Lukic et al., 2018]. Another important benefit is that on-board systems can be used by the same aircraft on all airports, so if an airline decides to make an investment, the use of the system will not depend on the flight's departure or destination airport but only on the aircraft chosen for that route. The drawbacks of integrating the electrical motors into the aircraft are the increase in the total weight of the aircraft, as well as modifications in the aircraft's architecture [Lukic et al., 2018]. Moreover, cooling for the additional systems (e.g. generator, electric motors) might be needed [Re, 2012]. In order to offset the weight penalty caused by on-board systems, a reduction of two or more passengers and/or stricter baggage allowance restrictions could be imposed [Lukic et al., 2019].

The first company to develop an on-board ETS was WheelTug [Lukic et al., 2018]. Its system consists of two induction machines located on the Nose Landing Gear (NLG) and powered with the help of the Auxiliary Power Unit (APU) [Lukic et al., 2018]. The additional mass in the aircraft, including all modifications, is 130 kg [Svragulja, 2015] and the aircraft can reach a maximum speed of 9 kt (16.7 km/h) [Lukic et al., 2019], which is relatively low compared to the 30 kt (55.6 km/h) normally reached in conventional taxiing. The main issue of this system is the limited traction due to the limited weight supported by the nose wheel. The German Aerospace Centre (DLR) and Lufthansa Technik also worked on a joint project to design an on-board system located on the NLG, which is powered by fuel cells. The achieved speed was higher than that of WheelTug, with a maximum of 13.5 kt (25 km/h) [Lukic et al., 2018]. However, it is difficult to predict when this system might be introduced, as the Technology Readiness Level (TRL) of fuel cells is still low. The most promising concept was the Electric Green Taxiing System (EGTS) developed by Safran and Honeywell Aerospace. It was located at the Main Landing Gear (MLG) and powered through the APU. It was a relatively light system with a total weight of 36 kg, including the cooling fan [Lukic et al., 2019] and it could reach speeds of up to 20 kt (37 km/h) [Lukic et al., 2018]. However, this project was terminated in 2016 for undisclosed reasons. Nevertheless, Safran has kept working on other projects such as e-taxiing with Airbus, which intends to offer a market-ready APU powered product for the future versions of the A320neo [Lukic et al., 2019], and a joint project with the University of Nottingham on the design of an optimum energy storage system for electric taxiing [Lukic et al., 2018].

From the research performed in this review, a research gap is identified: the use of a Hybrid Electric Taxiing System (HETS) to mitigate pollution and reduce fuel consumption at airports and their surroundings. This would allow for a system in which the external truck would act as a movable power source, decreasing Turnaround Time (TAT) and allowing for fully engineless taxiing. Additionally, the use of electric motors would mitigate traction issues created by pulling forces on the nose wheels due to towing by an external truck.

3 Design of the Hybrid Electric Taxiing System

In the previous section, the technologies that are currently being developed have been presented, with technological taxiing solutions yielding the most promising results. Developing a system that could combine characteristics of both on-board and external systems would be an interesting area of research. Hybrid Electric Taxiing Systems (HETS) would allow for the combination of electric motors and external vechicles or the single use of one of the technologies, depending on the needs. This chapter aims to develop the preliminary design of a HETS.

The purpose of this research is to present a system that is able to assist aircraft of all sizes that travel on any route. For this, two different external trucks will have to be designed: one for Narrow-Body (NB) aircraft and another for Wide-Body (WB) aircraft. NB aircraft are defined as those aircraft that have a single aisle of seats [Alternative Airlines, 2023a] and WB aircraft have more than one aisle [Alternative Airlines, 2023b]. The Airbus A320 and Airbus A330-200 have been chosen as the reference NB and WB aircraft, respectively, as they are some of the most common aircraft types being used worldwide. The dimensions of these reference aircraft must be taken into account in order to determine what the maximum dimensions of the external truck should be. The initial dimensions and configuration of the trucks are based on the dimensions of the reference aircraft and can be seen in Figure 1 and Table 1. It must be noted that, while deciding on the truck dimensions, a height margin has been left between the aircraft belly and the top of the external truck to avoid any collisions and to allow for faster attachment and detachment of the external system.

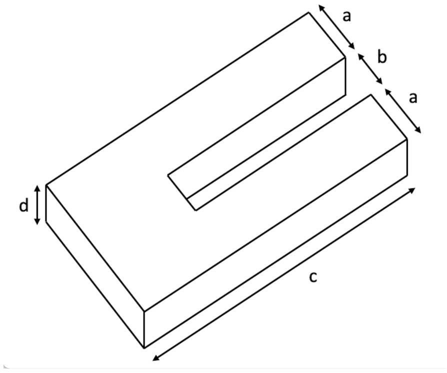

Figure 1: Preliminary design of external trucks.

Table 1: Initial dimensions of the Narrow-Body (NB) and Wide-Body (WB) external trucks.

	a [m]	**b [m]**	**c [m]**	**d [m]**
NB external truck	1.6	0.5	6	1.5
WB external truck	2.1	1.5	7.5	2

3.1 Integrating Ground Support Equipment

Although the main goal of the external truck would be to provide energy to the electric motors in order to transport the aircraft during the push-back and taxi phases, it could also be used to further reduce noise, emissions, fuel consumption and turnaround time. There are three systems that substitute the functionalities of the Auxiliary Power Unit (APU) while the aircraft is at the stand. Once the aircraft starts the push-back operation, the APU takes on the functionalities of these systems until the aircraft's engines are running. However, if these systems could be placed inside the external truck, the APU would not have to be powered on at least until the end of the taxi phase, thereby reducing noise and emissions while the aircraft is on the ground. These three systems will now be discussed in more detail.

3.1.1 Pre-Conditioned Air Unit

Pre-Conditioned Air Units (PCAs) are systems that ensure a comfortable environment in the cabin depending on outside weather conditions. They supply fresh air into the cabin after the air has been cooled or heated to the desired temperature [Aviation Learnings, 2020b]. It is currently only used while the engines are off during (dis)embarkation of the passengers and aircraft servicing. However, if a PCA was to be integrated into the external truck, it could be used to provide air conditioning during the entire taxi phase. Electric PCAs receive electrical power from external power supplies and they are more efficient and provide less operating noise than engine-driven PCAs [Aviation Learnings, 2020b]. One PCA is required for Narrow-Body (NB) aircraft with a capacity ranging from 40 to 60 Tons of Refrigeration (TRs), depending on the climate at the airport. For this reason, NB aircraft only have one PCA receptacle for ground connection. This is not the case for Wide-Body (WB) aircraft, which have two PCA receptacles, except for the Airbus A380 that has four receptacles [Aviation Learnings, 2020b].

3.1.2 Ground Power Unit

Ground Power Units (GPUs) are in charge of providing power to the aircraft when the engines are turned off. The required number of GPUs follows from the same reasoning as for PCA units: one unit for NB aircraft and two units for WB aircraft [Aviation Learnings, 2020a]. Battery powered GPUs are the most environmentally friendly and least noisy of all GPU types. It is believed that they can bring down carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions by 90% and 95%, respectively [ITW GSE, 2019]. However, these units have a downside, which is their limited time in which they can offer their services due to the limited energy source and long charging times.

3.1.3 Air Start Unit

Air Start Units (ASUs) are used for starting the jet engine before push-back, especially when the APU is inoperative. However, if engineless-based taxiing is performed, the engines will need to be turned on at a later stage when the aircraft is not at the gate anymore. Thus, the ASU needs to be carried on-board of the external vehicle as well.

3.1.4 Preliminary Sizing of the Ground Support Equipment

The dimensions and weight of all Ground Support Equipment (GSE) units are estimated from reference ground equipment [Nordic Heater AB, 2019, ITW GSE, 2019, Guinault, 2018] and are presented in Table 2. The estimated power consumption by the APU unit and ASU is based on the research carried by E.V.M. van Baaren on their MSc thesis project [van Baaren, 2019]. Here, the author gives an approximation on the power that would be consumed during operation by both GSE units combined. The values for the power consumption of the GPU have been taken from the requirements stated in [Aviation Learnings, 2020a] of 90 kVA for NB aircraft and 180 kVA for WB aircraft. Assuming a power efficiency of 0.8 for both reference aircraft [ITW GSE, 2023], the values for the power consumed by the GPU are computed and presented below.

Table 2: Technical specifications of Ground Support Equipment (GSE) to be carried on the external truck.

	Length [m]	**Width [m]**	**Height [m]**	**Weight [kg]**	**Power Consumption NB Truck [kW]**	**Power Consumption WB Truck [kW]**
PCA unit	1.50	1.40	1.20	650	436	783
ASU	1.71	1.40	1.32	2,000		
GPU	1.61	1.23	0.91	1,500	72	144

As shown in Figure 2 and Figure 3, the wheels of the external truck will be placed outside in order to save some height and avoid any potential collision between the external truck's roof and the aircraft's belly.

In order to avoid imbalances on the NB external truck's configuration, it is preferred to place the PCA and GPU on one side and the ASU on the other side. This will minimise the weight difference between both sides to approximately 150 kg. The PCA is located towards the end of the truck as it is connected to the aircraft near its Main Landing Gear (MLG). Moreover, as the receptacle for the GPU is close to the aircraft's nose, the configuration depicted in Figure 2 is optimal. The rest of the space in the external truck can then be used for energy storage. In order to compensate the weight difference between both sides of the truck, it is assumed that the power system's weight will take this role by ensuring an overall even weight distribution.

When it comes to the configuration of the WB external truck, it is necessary to have two PCAs and GPUs, one on each side. Having the PCA to the back of the truck and the GPU more to the front is justified following the same reasoning as for the NB external truck. The positioning of the ASU is however arbitrary this time. A similar approach as in the NB external truck will be taken when dealing with imbalances. The configuration of the WB external truck can be seen in Figure 3.

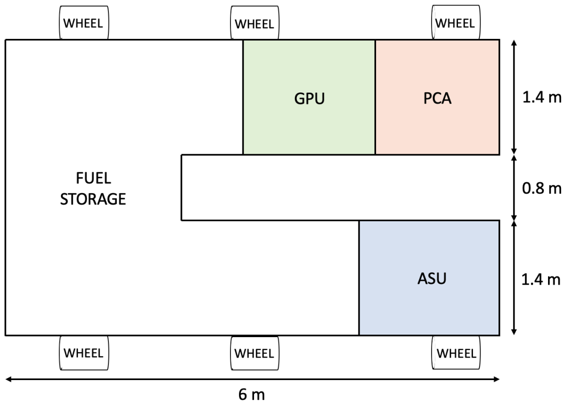

Figure 2: Top view of Narrow-Body (NB) external truck configuration.

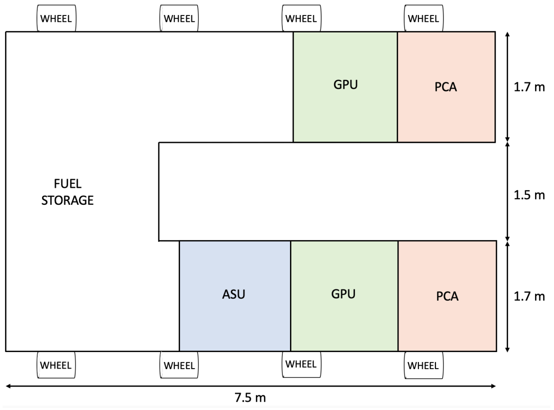

Figure 3: Top view of Wide-Body (WB) external truck configuration.

3.2 Power and Energy Required by the System

In order to determine how many operations can be performed after each refuelling procedure, it is first necessary to estimate how much power one operation requires. In this research, an operation is seen as: aircraft servicing after disembarkation - aircraft push-back - aircraft taxi until runway - external truck returns back to the terminal.

The total amount of power required during operation, P_{tot}, can be calculated by adding all the forces acting on the aircraft and truck and multiplying them by the speed at which the aircraft and truck drive. Also, it is necessary to take into account the power required by the Ground Support Equipment (GSE).

$$P_{tot} = D_{ac} \cdot V_T + D_{g,ac} \cdot V_T + D_{g,et} \cdot V_T + D_{g,et} \cdot V_{SR} + P_{PCA} + P_{GPU} + P_{ASU} \tag{1}$$

where D_{ac} represents the drag force acting on the aircraft, and $D_{g,ac}$ and $D_{g,et}$ account for the ground friction force acting both on the aircraft and the external truck, respectively. The maximum allowed speed in service roads, V_{SR}, is equal to approximately 25 km/h (6.71 m/s) [Salina Airport Authority, 2017]. V_T represents the average taxi speed and has a value of 30-35 km/h [MIT Lincoln Laboratory, 2010]. In order to not underestimate the power required, 35 km/h (9.72 m/s) has been taken as the value for V_T. The values for P_{PCA}, P_{GPU} and P_{ASU} represent the power required by the GSE and they are presented in Table 2. By expanding and rearranging the terms, Equation 1 can be written in the following way:

$$\begin{aligned} P_{tot} = &\left[C_D \cdot \frac{1}{2} \cdot \rho \cdot V_T^2 \cdot S + C_{D,g} \cdot g \cdot \Big(m_{ac,ramp} + m_{et} + m_{energy} + m_{PCA} + m_{GPU} + m_{ASU}\Big)\right] \cdot V_T + \\ &+ C_{D,g} \cdot g \cdot \Big(m_{et} + m_{energy} + m_{PCA} + m_{GPU} + +m_{ASU}\Big) \cdot V_{SR} + P_{PCA} + P_{GPU} + P_{ASU} \end{aligned} \tag{2}$$

The coefficient for ground drag is assumed to be the same for the aircraft and the external truck. An estimation of $C_{D,g} = 0.02$ is made. Then, the mass of the empty external trucks, m_{et}, is estimated based on the mass of the Narrow-Body (NB) and Wide-Body (WB) TaxiBot vehicles. For the smaller version, the mass is approximately 26000 kg, while the bigger version is nearly double the mass with 50000 kg[1]. When computing the energy mass of the external trucks, m_{energy}, the values depend on the energy source (hydrogen or batteries), which will be estimated in subsection 3.3. Finally, the gravitational acceleration, g, and the air density, ρ, are equal to 9.81 m/s^2 and 1.225 kg/m^3, respectively, assuming that all airports are at sea level.

The values for m_{PCA}, m_{GPU}, m_{ASU} represent the mass of the GSE and they are presented in Table 2. The values for C_D, $m_{ac,ramp}$ and S can be found in Table 3.

Table 3: Design parameters based on NB and WB reference aircraft [Airbus, 2023a, Airbus, 2023b].

Parameter	**Description**	**Value NB**	**Value WB**	**Unit**
C_D	Aerodynamic drag coefficient	0.055	0.049	[-]
$m_{ac,ramp}$	Aircraft's ramp mass	78,400	242,900	[kg]
S	Wing surface area	122.6	361.6	[m^2]

The resultant values for the power consumed in one operation are 0.76 MW and 1.58 MW for the NB and WB aircraft, respectively. Once this is calculated, the amount of energy needed in one operation, E_{tot}, can be estimated by applying the relationship between power and energy (E = P · t), which can be translated into Equation 3. P_{tr} represents the power used to go from the terminal to the runway by the aircraft and the external truck and P_{rt} the power used to go from runway to the terminal by the external truck.

$$E_{tot} = P_{tr} \cdot t_{taxi} + P_{rt} \cdot t_{SR} \tag{3}$$

The taxi time, t_{taxi} is calculated by taking the average of the unimpeded taxi times in different American airports [Simaiakis and Balakrishnan, 2010]. Unimpeded taxi times are defined as the taxi times under optimal operation conditions, i.e. any delay factors can be disregarded as they are not significant. After conducting a mathematical model that predicts unimpeded taxi out time based on the number of flights per year in each airport, the average is estimated to be 8.66 minutes. As the speed allowed in service roads is slightly lower than the one in taxiways, it is predicted that the time that it will take the external truck to reach the terminal, t_{SR}, is equal to 12.54 minutes. Therefore, the total amount of energy needed for the NB case is 405 MJ, whereas it is 840 MJ for the WB case.

3.3 External Truck Power System

The values and methods to calculate the number of towing operations before refuelling differ depending on the power system, which will be presented in this section.

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[1] Values taken from LinkedIn conversation with Nicolas Girard (TaxiBot project manager at Smart Airport Systems) on March 4th 2022.

3.3.1 Compressed Hydrogen External Truck

When it comes to the process of compressing hydrogen, there are a series of steps that take place which reduce the efficiency, such as electrolysis, compression, transportation and filling. The total efficiency of the process is estimated to be between 25% and 35% and an average value of 30% will be taken for this research [Volkswagen, 2020]. The efficiency of the electric motors must be also taken into account, which is estimated to be 90% [Renault, 2021]. The two most common compression pressures are 35 MPa and 70 MPa. When storing hydrogen, usually a level of 70 MPa is selected. However, when the tanks of a vehicle are filled, a pressure of 35 MPa is preferred [Office of Energy Efficiency & Renewable Energy, 2023]. The density of compressed hydrogen at 35 MPa is $\rho_H = 23$ kg/m^3.

Pressure vessels with elliptical heads that are as long as possible are placed in the vehicle. The diameter of these vessels is an important design choice, as it is directly proportional to the stresses acting on the vessel, and it is chosen to be $D = 1$ m and for the Wide-Body (WB) this value increases to $D = 1.5$ m. With this in mind, the total available volume for compressed hydrogen will be 5.08 m^3 and 9.72 m^3 for the NB and WB external vehicles, respectively. The total mass of the tanks is 355 kg for the NB external truck and 888 kg for the WB external truck. The resultant available space in the external trucks will be used for the placement of the fuel cell and any other cabling or systems required. With all the gathered information it is computed that the NB and WB external trucks will be able to operate 9 cycles before refuelling is needed.

3.3.2 Battery-Powered External Truck

This system of converting energy into usable power for vehicles comprises of less steps than that for compressed hydrogen. For this reason, the overall efficiency is also higher with an average of 80% [Volkswagen, 2020], including the 90% electric motor efficiency.

In this preliminary research, the Rivian R1T truck battery pack has been used as reference [EV Charge+, 2023]. Each battery pack has a battery capacity of 180 kWh and a weight of 918.37 kg (assuming the energy density of Li-Ion batteries is 196 Wh/kg [Panasonic, 2010, Panasonic, 2007]). The number of possible operations before charging will depend on the number of battery packs placed in the external truck. In order to make a valid comparison with the compressed hydrogen case, it has been computed that in order to operate 9 cycles before refuelling, 9 battery packs would be necessary for NB external trucks, whereas 17 would be needed for WB external trucks. The total weight of this would be 8.3 tonnes and 15.6 tonnes for the NB and WB cases, respectively. This weight is too high to be carried by the external trucks. Thus, it is concluded that the battery-powered external truck would not be able to operate as many cycles per charge as the compressed hydrogen external truck per charging.

3.3.3 Selection of Power System

Now that both methods have been introduced, a selection must be made for the power system of the Hybrid Electric Taxiing System (HETS). In order to assess which of the two power systems will better satisfy the needs of the HETS, four main criteria have been selected for the comparison.

Cost is an important parameter to take into account as the HETS should be as cost-efficient as possible in order to be purchased by stakeholders. The main differences with regards to cost between both power systems are the overall design and production costs, as well as the purchasing costs of the energy (hydrogen or electricity) and tanks (pressure vessels or battery packs). In terms of design and manufacturing, the Battery-Electric Vehicle (BEV) will be cheaper, as this technology is already widely used in the automotive sector. On the contrary, Fuel Cell Electric Vehicles (FCEVs) are still state-of-the-art with few concepts operational worldwide. Moreover, the price of electric charging is currently much lower than hydrogen fuelling [International Council of Clean Transportation, 2019].

Sustainability is one of the main focus points of this research, as the aim of the HETS is to reduce the emissions of the taxi phase to zero. Both BEVs and FCEVs produce zero harmful emissions on the road and they are equally silent techniques. However, the energy source is not always necessarily emission-free. As mentioned previously, the hydrogen compression process goes through several steps before it is available as an energy source. These steps could contribute to the emission of greenhouse gasses (e.g. fuel cell and power generation). On the contrary, the electricity used to power BEVs is nearly directly taken from its source, with the exception of the transportation process, making BEVs the most sustainable option in the present.

Reliability, Availability, Maintainability and Safety (RAMS) are key criteria during the design process as they define the functional requirements that the project must meet. Due to the current broader development of BEVs, it is predicted that the battery-electric external vehicle will perform better in all RAMS criteria. Also, due to the mechanics having more experience with BEVs, maintenance will be carried out with higher quality, thus attaining higher maintainability, reliability and safety standards for the battery-powered external truck. Moreover, due to the use of similar tooling, materials and processes as for BEVs, the battery-powered external truck will also reach higher levels of availability, if charging is neglected.

Finally, the charging characteristics will be compared. As explained earlier, the compressed hydrogen external truck would be able to operate more cycles per fuelling operations than the battery-powered external truck. This would thus allow for higher availability of the trucks and, potentially, less trucks needed per airport. Moreover, the charge rate for FCEVs is comparable to that of diesel vehicles, whilst for BEVs the charging time is significantly higher.

After evaluating all main criteria, the battery-powered external truck is chosen as part of the design of the HETS due to its significant advantages over its competitor, even though compressed hydrogen offers better charging characteristics than battery packs. The Entry Into Service (EIS) of this system is key, as it would be used for conventional aircraft. Thus, if hydrogen technologies take decades to get certified within airport infrastructures, it could lead to a late adoption of this system when newer and more sustainable aircraft technologies are available, leading to a lower demand of HETS. As concluded previously, the battery-powered external vehicle would not be able to operate as many cycles per charge as the compressed hydrogen external vehicle. The battery-powered case would allow for three battery packs to be placed on board due to imbalance issues that could arise if additional packs - and thus, weight - would be carried. This leads to the conclusion that a total of 3 cycles can be carried out before charging is needed for the NB case. However, for the WB case, recharging will be needed at the end of each cycle. The charging time is given by dividing the battery size over the charge power [RAC, 2021]. The battery size is 180 kWh and the charger power is assumed to be equal to one of a Tesla supercharger with 145 kW, leading to a charging time of 1.24 hours.

3.4 Preliminary Configuration of the Hybrid Electric Taxiing System (HETS)

The Hybrid Electric Taxiing System (HETS) will consist of two main systems: the electric motors and the external truck. The philosophy behind this system is to allow for different modes of moving the aircraft, by either only using the onboard electric motors, only the external truck or by combining both systems into the HETS. The advantages would be to have a movable power source provided by the external truck, which would avoid the use of the aircraft engines or Auxiliary Power Unit (APU). The truck would be attached to electric motors placed on the aircraft wheels and it would provide power to them in order to drive the aircraft through the taxiways in an engineless manner. This would avoid traction issues created by pulling forces on the nose wheels that are common when solely using external trucks to tow the aircraft through the airport surfaces.

The electric motors are usually located either on the Nose Landing Gear (NLG) or Main Landing Gear (MLG) of the aircraft. It has been determined that in order to ensure better stability, reliability and redundancy, the electric motors of the HETS will be placed on the MLG. This will also mitigate the risk of having too little friction between the tire and the ground in all surface conditions. The electric motors will be either powered by the Auxiliary Power Unit (APU) or, preferably, by the battery pack located in the external truck. The choice of this will be analysed in a later design phase and will depend on factors such as the airport congestion or flight schedule of that specific aircraft.

The preliminary configuration of the external trucks can be seen in Figure 2 and Figure 3. The energy source will also be used to power part of the Ground Support Equipment (GSE), thus decreasing Turnaround Time (TAT). The movement of trucks along airports can be done in several ways, such as using taxiways, service roads or additional tracks. It is considered that the best option would be to have the trucks go on the service roads. These roads are able to withstand the weight of fire trucks, which can be as high as 30 tons [Fire Apparatus Manufacturers' Association, 2017]. According to the calculations performed, this would not be a problem for the Narrow-Body (NB) external truck. However, it could lead to the need of having reinforcement material to be placed on the service roads for the Wide-Body (WB) external trucks due to the high weight of these. In order to have an accurate model, it is assumed during this preliminary design phase that NB trucks will move along service roads while WB trucks will do so along taxiways.

3.5 Sensitivity Analysis of Preliminary Design Results

In order to ensure the validity of the results obtained during the design phase of the Hybrid Electric Taxiing System (HETS), a local sensitivity analysis is carried out. This consists of changing the parameters used as model inputs one at a time to then examine how the model outputs change. The model in this case is the series of calculations performed to estimate the power required per operation. Following the procedure explained in [TU Delft, 2021], each parameter is changed by dP = +/- 5% of the reference value P. Then, the values for sensitivity are calculated with the following equations:

$$S^{+} = \frac{X^{+} - X}{(dP/P)} \qquad S^{-} = \frac{X - X^{-}}{(dP/P)}$$

where X, X^{+} and X^{-} represent the mean values of the model output in the P, 1.05P and 0.95P case, respectively; P is the reference value and dP the change in reference value. The results obtained can be classified in low sensitivity ($S < 0.1$), medium sensitivity ($0.1 \leq S < 1$) and high sensitivity ($S \geq 1$). The higher the sensitivity value, the higher the chance that small changes in the parameter's value will lead to a change in the model's output. After conducting the sensitivity analysis, a series of parameters have led to high sensitivity values. In order to ensure that the values are acceptable for this preliminary design phase, further analysis has been carried out.

Some of the values, such as the aircraft ramp mass ($m_{ac,ramp}$), the ground drag coefficient ($C_{D,g}$), the power consumed by the PCA and the ASU ($P_{PCA} + P_{ASU}$), the electric motor efficiency (η_{EM}) and the capacity of the R1T battery pack (c_{bat}) have been retrieved from reliable data sources. These sources are either manufacturer's specifications or published scientific papers that have validated their results. In some cases, if such verified sources were not available, a minimum of three reliable sources have been checked to ensure that the selected value was the same in all cases. When slightly changing the value for unimpeded taxi times (t_{taxi}), the number of possible operations before refuelling changes. Thus, in order to validate the computed value, a second method for calculating t_{taxi} has to be implemented. This time, instead of using the flow in American airports, European airports have been used. The average unimpeded taxi time obtained is very similar (within a 1% margin), meaning that the initial value can thus be validated. Average taxi speed (V_T) is taken at its maximum value when computing the model's outputs. As the factor that makes the number of operations change is X^{+} and it is known that the value will not go past the current one, the parameter can be deemed valid. The total volume of pressure vessels (V_{pv}) was first estimated with the use of an online tool[2]. In order to ensure that the values obtained were correct, hand calculations have been performed, which have led to the same results as the online tool. The efficiencies of the fuel cell and Li-Ion battery processes (η_{FC} and η_{bat}) are estimated by researching the efficiencies of each separate step to then compute the overall efficiency of the process. Similar values to the initial ones are obtained, with none of them altering the output. After performing this sensitivity analysis, it can be assumed that the values of all parameters can be validated for the preliminary design phase of the HETS. However, in further design phases, these parameters should be computed again with the use of more accurate methods and analyses. A graphical representation of the median, quartiles and minimum and maximum values can be found in Figure 4 and Figure 5.

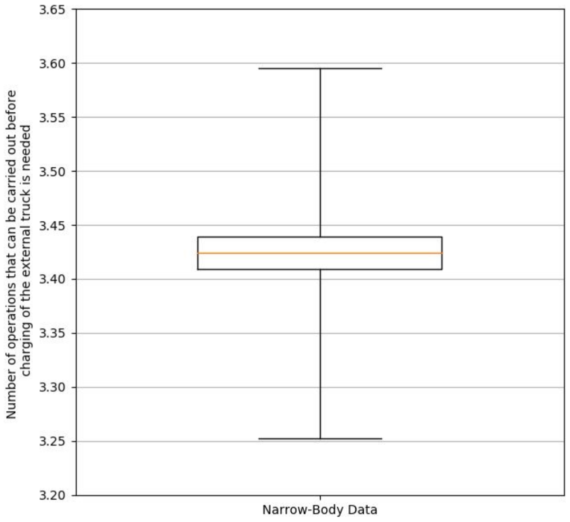

Figure 4: Box plot on number of operations possible per charging cycle of the Narrow-Body (NB) external vehicle.

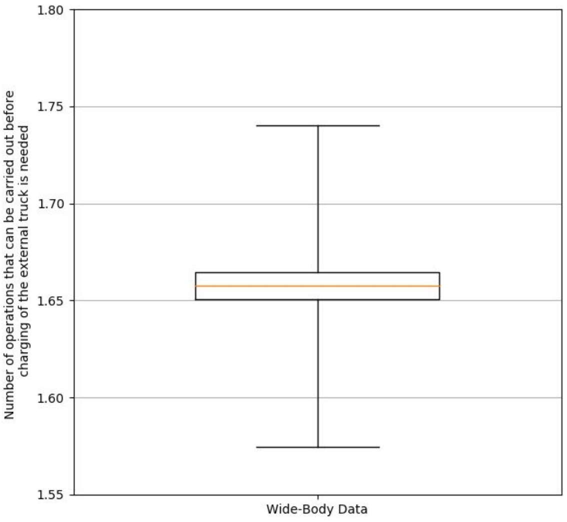

Figure 5: Box plot on number of operations possible per charging cycle of the Wide-Body (WB) external vehicle.

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[2] Online tool used to calculate volume of pressure vessels: https://checalc.com/calc/vessel.html

4 Methodology

Modelling the decision procedure for the assessment of Hybrid Electric Taxiing Systems (HETS) can be done at different levels of detail. For time constraint options, the following assumptions have been put in place. It must be noted that the model will still yield very detailed results that can be used to assess the feasibility of HETS.

Table 4: List of assumptions.

Code	**Assumption**
Assumption 01	All flights of the airline during one week are gathered and assumed to have a constant flow throughout the year.
Assumption 02	Disturbances in the flight schedule network are disregarded (e.g. delays, cancellations and aircraft repairs are assumed to not exist).
Assumption 03	Seasonal flights are not considered in the flight schedule.
Assumption 04	Only passenger commercial flights are included in this analysis.
Assumption 05	When taking turnaround values, transit turnaround is always taken as an input. This assumes that more complete aircraft servicing is done at night or while the aircraft is not flying for a long period of time.
Assumption 06	Only hub and spoke airlines are considered in order to simplify the retrieval of data.
Assumption 07	When computing profit, only operational savings are considered.
Assumption 08	The cost of electric motors shall be covered by the airline, whilst the cost of external vehicles shall be shared by the alliance.

In order to assess the feasibility of the HETS, two major steps are carried out. First, feasible flight schedules are created that are then used as inputs of air traffic in all destination airports of the network. For this analysis, a heuristic was chosen over a Mixed Integer Linear Program (MILP). The reasons for this are the shorter running time of the heuristic simulations compared to the MILP, the freedom of constraints that could be chosen and the fact that optimisation is not the goal of this project. At the end of the simulation, it was seen that all flights were still assigned to the aircraft and continuity of flow was ensured with no empty flights being operated, as will be explained later in section 4.1. Moreover, in order to assess the feasibility of HETS, a similar approach to the flight schedule heuristic was taken, where decisions were made on a first-come first-served criterion.

The following sections will explain in detail how the flight schedule and assessment model heuristics were created and which decision criteria were taken into account. They will be accompanied by flow charts that will give a better picture to the reader on the flow of decisions taken by each heuristic.

4.1 Flight Schedule

The first step in the model is to create a feasible flight schedule that will look for maximum aircraft utilisation. Utilisation is defined as the percentage of time the aircraft is being in operation throughout the week, as described in Equation 4. All phases of flight are considered as operational time, including turnaround. As per Assumption 01, the utilisation calculated for one week is assumed to remain constant for the time being.

$$\text{Utilisation [\%]} = \frac{\sum_{i=1}^{n}\left(t^{ID}_{flight_i} + t^{ID}_{taxiout_{D,i}} + t^{ID}_{taxiin_{A,i}} + TAT^{ID}_{k,i}\right)}{t_{week}} \cdot 100 \tag{4}$$

In the equation above, i represents each of the flights flown by aircraft ID, with n being the total number flights operated by the aircraft. The terms t_{flight}, $t_{taxiout}$, t_{taxiin} and TAT represent the different times in the flight cycle, more specifically the flight time, taxi out time at departure airport D, taxi in time at arrival airport A and turnaround time associated to aircraft type k. The time in one week is equal to 10080 minutes and it is represented by t_{week}.

In order to provide some structure to the flight schedule, two main conditions are imposed. First of all, conservation of flow is enforced. This means that if an aircraft lands at airport A, the next flight assigned to this aircraft can only depart from airport A. Secondly, flight savings per route are prioritised and the aim is to allocate the most profitable routes belonging to the same aircraft type into the same Aircraft Identification (ACID) code. However, this is not a hard constraint, as maximising aircraft utilisation and avoiding empty routes are prioritised. Most profitable routes are found by computing the savings of each route using the following equation:

$$S_{fuel} = \dot{m}_{taxi_k} \cdot (t_{taxiin_A} + t_{taxiout_D} - 2 \cdot t_{eng}) - W_{EM} \cdot \left(1 - e^{\frac{-R}{c}}\right) \tag{5}$$

where S_{fuel} represents fuel savings and $\dot{m}_{taxi_k}$ symbolises fuel consumption during the taxi phase of aircraft type k in kg/s. Then, taxi in time of arrival airport A, taxi out time of departure airport D and the time in which the aircraft's engines are on while taxiing are represented by t_{taxiin_A}, $t_{taxiout_D}$ and t_{eng}, respectively. The weight of the electric motors is described by W_{EM}. Lastly, R depicts the range of the route and c is the specific fuel consumption. Most values are dependent on the aircraft route and are extracted from the database. However, the weight of the motors and specific fuel consumption depend on if the aircraft body is narrow or wide. The values for these parameters can be found in Table 5.

Table 5: Values for W_{EM} and c.

Parameter	**Narrow Body Aircraft**	**Wide Body Aircraft**
Weight of electric motors (W_{EM})	500 kg	750 kg
Specific fuel consumption (c)	20,000	30,000

Once a feasible flight schedule is obtained, utilisation values for each ACID are computed. These values will play a crucial role in the decision procedure for the implementation of Hybrid Electric Taxiing Systems (HETS). A flow chart describing the working principle of this heuristic is presented in Figure 6.

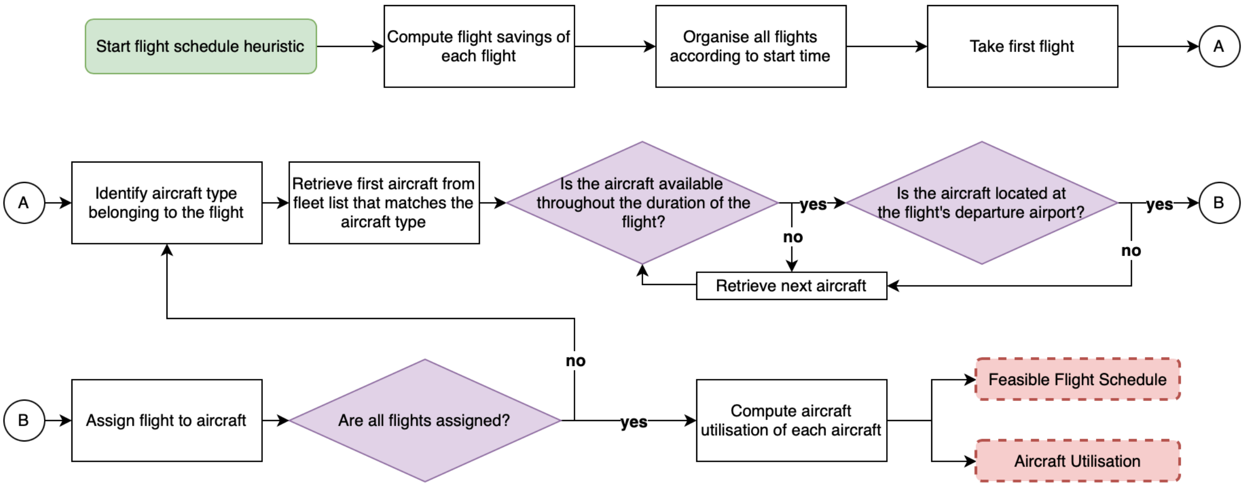

Figure 6: Flow chart for flight schedule heuristic.

4.2 Assessment Model

This research considers three alternatives for conventional taxiing: either placing electric motors on the aircraft wheels to power the aircraft through the taxiways while having its engines turned off; attaching external electric vehicles to the aircraft to tow them from the gate to the runway; or mixing both options into a Hybrid Electric Taxiing System (HETS).

4.2.1 Conditions for Placement of Electric Motors

The decision for the placement of electric motors is based solely on the characteristics of the specific aircraft and the flights operated by it. An aircraft has to meet certain criteria before it can be eligible for the placement of electric motors. An important factor is the utilisation of that aircraft, which needs to be at least 50% before electric motors are placed on its wheels and its value is given by Equation 4. Moreover, the operational savings need to be sufficient in order to justify the purchasing and installation costs of the electric motors, which are estimated to be around \$1M per Narrow-Body (NB) aircraft and \$2M per Wide-Body (WB) aircraft. An aircraft's average lifespan is 22.8 years. In order to determine the profitability of the placement of electric motors, the difference between the total savings, S_{tot}, over one fourth of the average lifespan and the cost of the system is computed. The design choice of determining profitability after 5.7 years is an assumption in order to ensure that all aircraft will be able to make a profit before their End of Life (EOL), as not all aircraft in a fleet are brand new. If the difference yields a positive number, then that aircraft is eligible for the placement of electric motors.

$$S_{tot} = S_{fuel} + S_{taxi} + S_{maint} + S_{env} \tag{6}$$

Fuel savings, S_{fuel}, are described by Equation 5. Savings related to operations mainly performed during the taxi phase are grouped into S_{taxi}. Following the reasoning of [Hospodka, 2014], during pushback, 25 EUR will be saved by taking into account the cost of fuel saved, as well as maintenance and depreciation per pushback operation. Moreover, it is estimated that 1 EUR during each taxi cycle accounts for brake wear-out savings, and 11 EUR for Foreign Object Damage (FOD) savings. Thus, taxi savings equal 37 EUR for each flight cycle. Engine life and maintenance savings, S_{maint} are described by Equation 7, where TOT represents time of taxiing, C_{maint} the engine maintenance cost, which is estimated to be 150 EUR per working hour, and n_{eng} the number of engines on the aircraft [Hospodka, 2014]. Lastly, savings related to lower emissions, S_{env}, also follow from [Hospodka, 2014] and are depicted in Equation 8. C_k is the cost of kerosene, which has been set to 0.68 EUR/kg [IATA, 2023], and the cost of the European Union Emission Trading System (EU ETS) allowance, C_{EUETS} is estimated to be 5 EUR/ton.

$$S_{maint} = TOT \cdot C_{maint} \cdot n_{eng} \tag{7}$$

$$S_{env} = \frac{S_{fuel}}{C_k} \cdot 0.15 \cdot C_{\text{EU ETS}} \cdot 3.15 \tag{8}$$

4.2.2 Conditions for Towing by an External Vehicle

Contrary to the previous case, the decision for the adoption of an external vehicle is based on the characteristics of hub and destination airports in which the airline or alliance operates. External vehicles need to be attached to the aircraft before towing and detached after the aircraft is on the runways, adding up to 2 minutes to the taxi operation. Moreover, the aircraft needs 5 minutes to warm up the engines before take-off and cool them down after landing. In order to avoid unnecessary congestion, airports in which the average taxi in and taxi out times are lower than 7 minutes are disregarded from having external vehicles put into place. This is because in addition to the 2 minutes needed for attachment and detachment, the engines would be operating during the first or last 5 minutes of the taxi phase, depending on if it is a landing or a take-off. Furthermore, out of the remaining airports, only the arriving and departing flights that cover routes above the average savings, are eligible for external vehicles.

The flow chart describing the heuristic implemented for this assessment model is depicted in Figure 7. Outputs O.1 and O.2 will be used as inputs for the assessment model of HETS that follows in the next section.

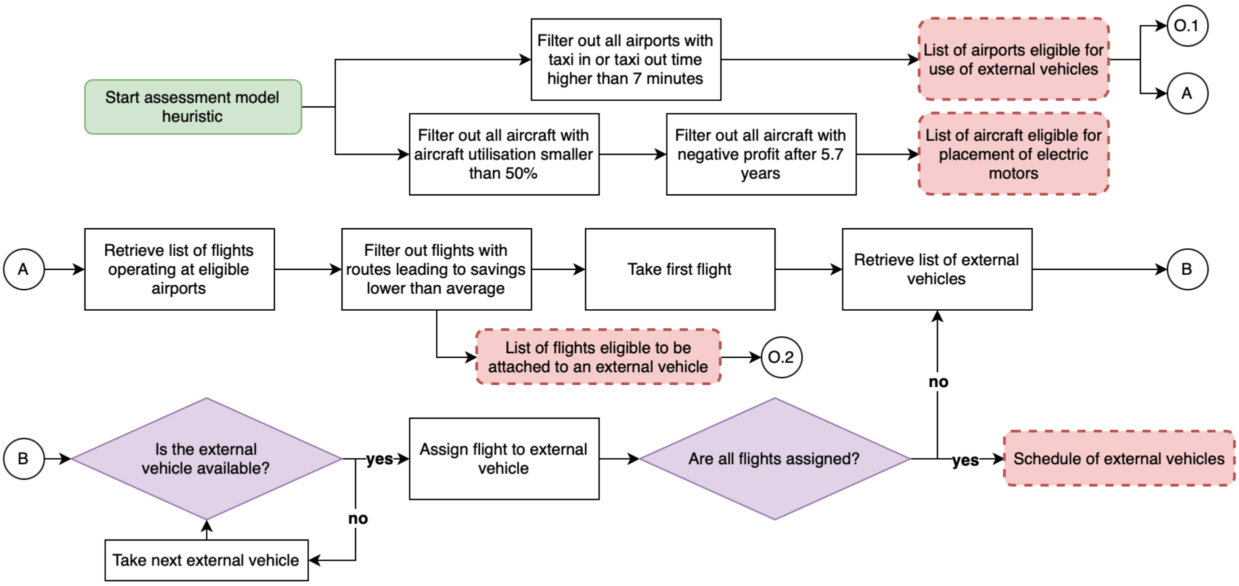

Figure 7: Flow chart for assessment model heuristic per airport (not considering HETS).

4.2.3 Conditions for a Hybrid Electric Taxiing System

The use of a HETS takes place when the aircraft is carrying electric motors, the airport where the aircraft is operating, is eligible for external vehicles and the flight leads to savings above average. The selection procedure to assess if the combination of a flight and airport is eligible for a HETS, is presented in Figure 8.

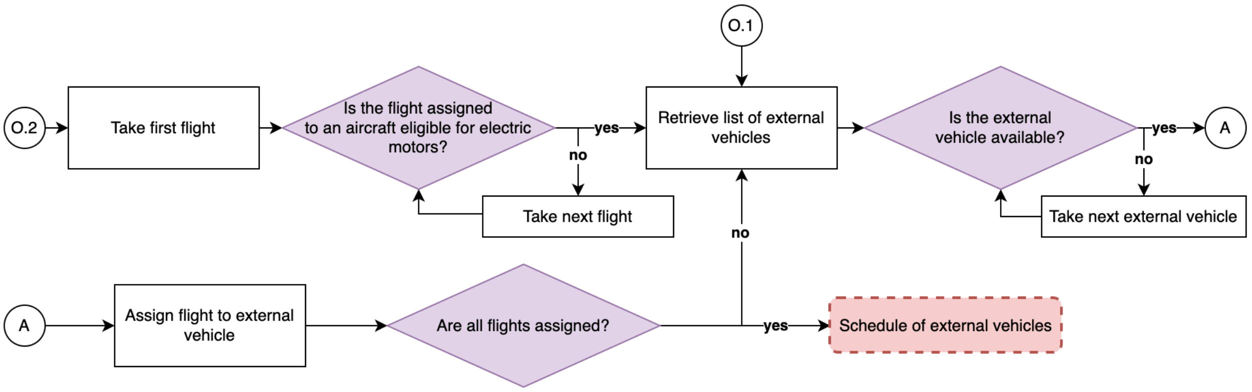

Figure 8: Flow chart for assessment model heuristic per airport (considering HETS).

5 Description of the Case Studies

The assessment model uses data from airlines as inputs at a flight schedule-, destination airports- and fleet-level. The necessary data from the airlines participating in the case studies must be retrieved and gathered in a structured manner. First of all, the relevant information about the flight schedule of the airline is grouped into a database. The required inputs, with an example of how data is introduced in the system, can be found in Appendix A. It must be noted that all data retrieved has been taken from [Flightradar24, 2023].

Secondly, the hub and destination airports database is created. Here, all airports which are either hub or destination of the airline are gathered and relevant information for the model is collected, as shown in Appendix B. Taxi times have been retrieved from EUROCONTROL time statistics [EUROCONTROL, 2022] and the time difference is calculated by taking the time difference between the hub airport and the corresponding arrival or destination airport of that flight.

Lastly, the fleet of the airline must be taken into account when developing the first model that creates a feasible flight schedule. By knowing the quantity and types of aircraft available, it is possible to use this for the creation of a feasible flight schedule. Additionally, the aircraft's turnaround time is key in order to later assess what the operational impact of the Hybrid Electric Taxiing System (HETS) would be on each aircraft type and flight network. An example of the data used can be found in Appendix C.

5.1 Scenario 1: Assessment of HETS at Airline Level

The impact that the HETS could have at an airline level is the first case study that will be studied. Here, only the flight schedule of the corresponding airline (KLM) will be computed, together with the economic and operational benefits compared to conventional operations. In this scenario, it is assumed that the costs for both the electric motors as well as the external vehicles are covered by the airline, as mentioned in Assumption 08.

5.2 Scenario 2: Assessment of HETS at Alliance Level

Airline alliances are partnerships between or among airlines allowing for collaboration, such as share of resources or pick up and extension of partner routes [Altexsoft, 2023]. In order to prove if the cooperation between airlines would lead to better results in the assessment of the HETS, five different airlines have been combined into one alliance (KLM, Air France, Tarom, Air Europa and ITA Airways). All airlines have their hub airports located in Europe and most of their flights are operated within the same region. This has been chosen in order to better see the difference between low- and high-frequency of flights in destination airports. In this scenario, as mentioned in Assumption 08, it is assumed that the costs involved with the electric motors are covered by the airline operating that aircraft, whereas the external vehicle costs are shared among all airlines that are part of the alliance and that have aircraft flying to that destination airport.

6 Results

Once the assessment model is carried out, it is possible to determine the feasibility margins of Hybrid Electric Taxiing Systems (HETS) by analysing the model's outputs. The feasibility study will be performed from an operational and economic perspective considering the three possible configurations (electric motors only, external vehicle only or HETS) and the two scenarios (airline and alliance). The results will then be subject to a local sensitivity analysis that will serve as a verification of the model outputs.

6.1 Operational and Economic Assessment of the Implementation of HETS

The operational and economic feasibility of HETS has been determined by implementing the steps presented in the methodology. A summary of the main results can be found below.

6.1.1 Electric Motors

In order to place electric motors in the aircraft wheels, the investment costs need to be justified. Figure 9 depicts all aircraft that yield a positive profit over 5.7 years of operation in addition to a utilisation equal or higher than 50%. Thus, all aircraft in the figure will have electric motors incorporated in their wheels to make the taxi phase more sustainable and profitable.

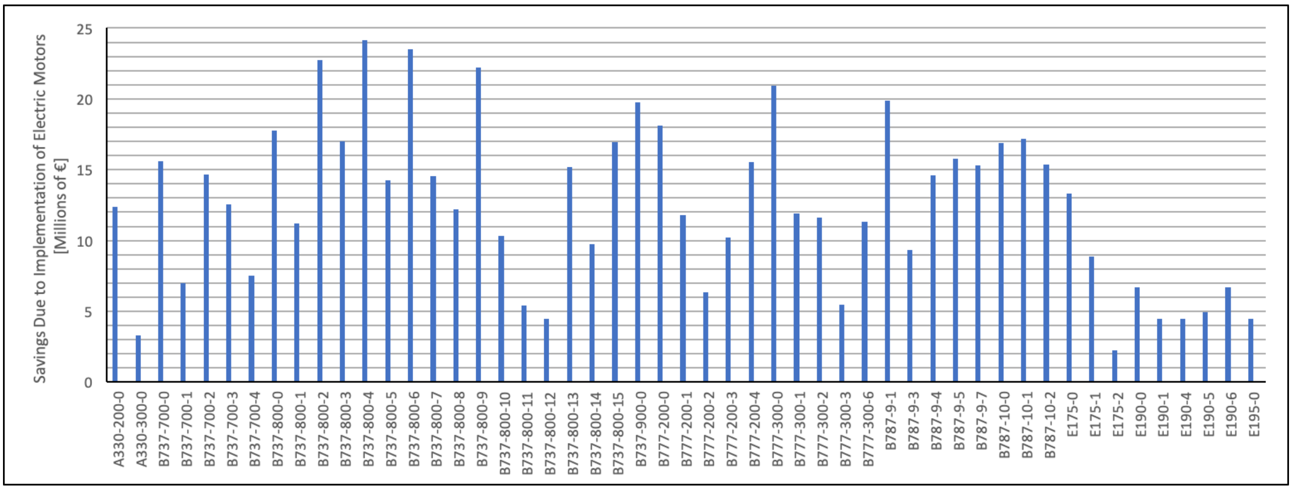

Figure 9: Savings due to the placement of electric motors after 5.7 years.

Out of all aircraft in KLM's fleet, 31.5% are eligible for the placement of electric motors. This shows that if the flight schedules were to be designed to achieve maximum aircraft utilisation, less aircraft would be needed to operate all routes by the airline. Moreover, when it comes to eligibility for the placement of electric motors, there is no trend that shows preference over one of the aircraft types. In other words, Narrow-Body (NB) aircraft represent 63% of KLM's fleet, which can be comparable to the ratio of aircraft eligible for electric motors: 61% are NB and 39% are Wide-Body (WB) aircraft. Although the savings per flight are related to the distance flown, NB aircraft can also achieve high savings due to the fact that they operate several routes per day, thus performing more environmentally-friendly taxi operations and compensating for the weight added by the electric motors' systems. For this reason, it can be seen in Figure 9 that no correlation can be made between the aircraft type and the savings over a period of 5.7 years but, instead, several factors play a role on the output for the profit.

6.1.2 External Vehicles

Every airport that has taxi in and taxi out times higher than 7 minutes, is eligible for the placement of external vehicles. The naming of each external vehicle is defined in the following fashion: 'EV' + airport International Civil Aviation Organisation (ICAO) code + external vehicle identification (ID) number. The external vehicle ID number is composed by a letter and a number. The letter can be either 'W' or 'N', which represents if it is an external vehicle designed for wide- or narrow-body aircraft, respectively. The numbers start from 0 and go as far as how many vehicles are needed at the airport.

After combining the eligible airports with the flights that operate routes with savings higher than average, the external truck utilisation can be computed. Table 9 in Appendix D shows the results with highest utilisation at an airline level by using KLM's flight schedule. It can be seen that the external vehicles with the highest utilisation are the ones in Amsterdam Airport (EHAM), which is the hub for KLM. Out of all external vehicles, only the ones with utilisation higher than 50% will actually be operational at their corresponding airport. However, none of the external vehicles reach a utilisation higher than 50%, and they thus not qualify for a placement of an external vehicle in any of the airports operated by the airline.

If all airlines from the alliance are considered, utilisation of external trucks increases, as shown in Figure 10 and in Table 11 (Appendix D) in a more detailed way. Most of the external vehicles that are considered are for Wide-Body (WB) aircraft. This can be explained by the fact that only flights with savings higher than average are eligible for the use of external vehicles. Short-haul flights, operated by Narrow-Body (NB) aircraft, lead to the lowest savings due to the shorter distances flown and thus, the less they can counteract for the added weight of the electric motors or cost of kerosene. A consideration for future research would be to remove the requirement of minimum flight savings to be eligible for an external vehicle to better see the effect of HETS in intra-European networks.

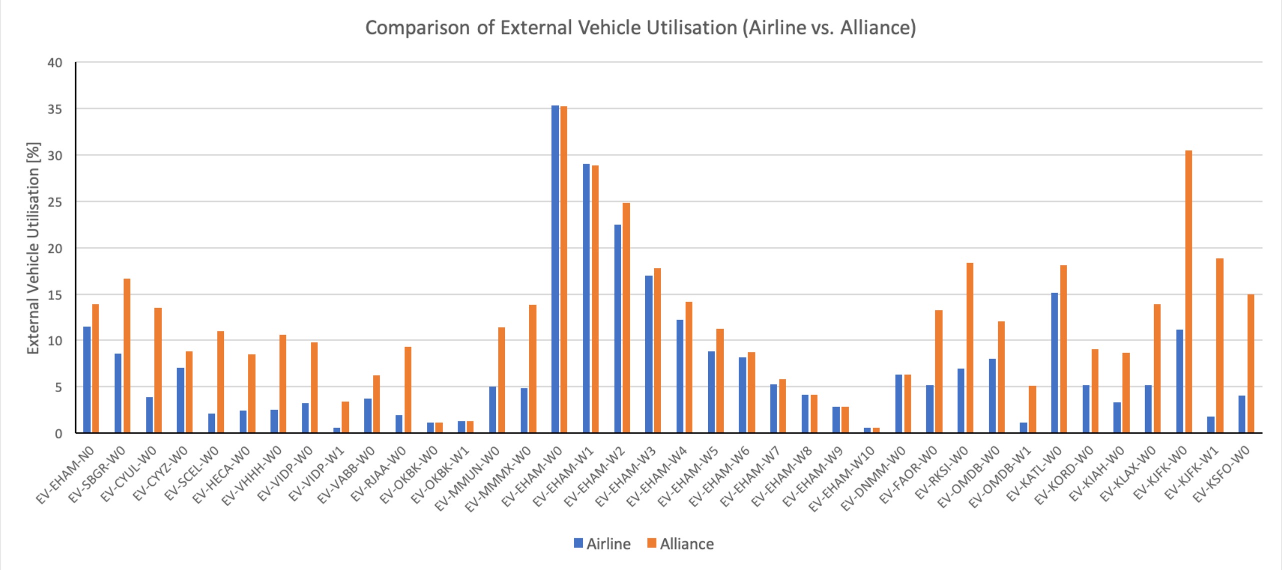

Figure 10: Visual showing that utilisation of external vehicles increases when more than one airline is taken into account.

Amsterdam Airport (EHAM), Paris Charles de Gaulle (LFPG) and Adolfo Suárez Madrid Barajas Airport (LEMD) experience peak utilisation in the alliance scenario. This comes to no surprise as these airports represent the hub airports for three of the alliance airlines: KLM, Air France and Air Europa. Leonardo da Vinci Fiumicino Airport (LIRF) and Henri Coanda Bucharest Airport (LROP) are the two other hubs for the alliance. As their taxi times are lower than 7 minutes, they are not eligible for external vehicles. However, these airlines can benefit from external vehicles placed in other destination airports that do exceed the minimum required taxi times. Moreover, destination airports where all or most alliance airlines fly to, also attain high levels of utilisation. The schedules of feasible external vehicles (with utilisation over 50%), EV-LFPG-W0 and EV-LFPG-W1, are presented in Figure 11 and Figure 12. Out of all airlines in this research, Air France is the one with the largest list of destination airports, making it reasonable to have LFPG as the airport with the highest traffic and, therefore, highest external vehicle utilisation.

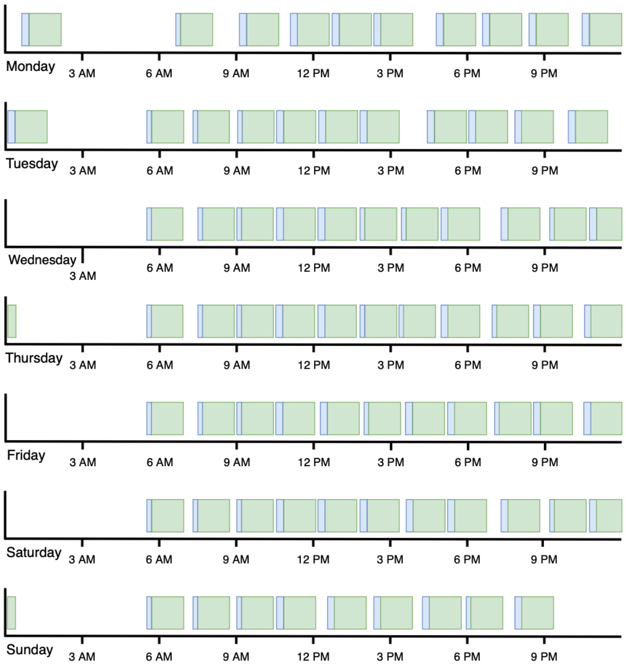

Figure 11: Schedule of EV-LFPG-0 for alliance scenario under *external vehicle only* case. Green boxes represent charging times and blue boxes operational times of the external vehicles.

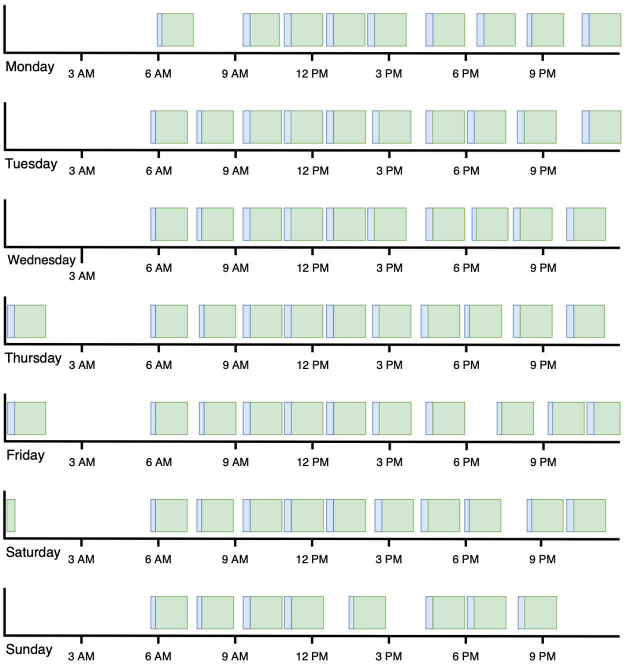

Figure 12: Schedule of EV-LFPG-1 for alliance scenario under *external vehicle only* case. Green boxes represent charging times and blue boxes operational times of the external vehicles.

6.1.3 Hybrid Electric Taxiing Systems

The combination of aircraft with electric motors and their routes that yield more than the average route savings, leads to the following utilisation rates of external vehicles per airport. Firstly, the results for the airline scenario are presented in Table 10 of Appendix D. As expected, the airport with peak utilisation is EHAM, although no external vehicles will be placed there as utilisation levels do not exceed 50%. Secondly, the alliance scenario results in having one external vehicle placed at LFPG, EV-LFPG-W0, as presented in Table 12 and depicted in Figure 13.

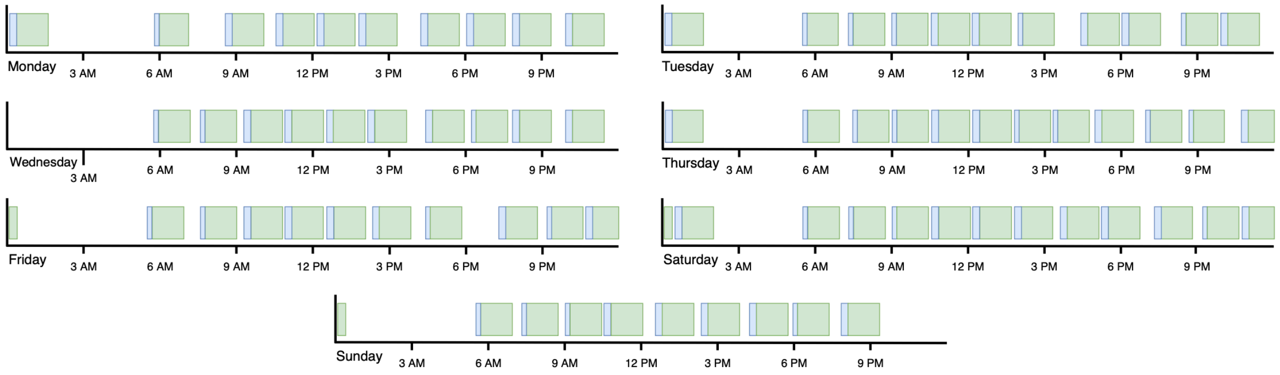

Figure 13: Schedule of EV-LFPG-0 for alliance scenario under *hybrid electric taxiing system* case. Green boxes represent charging times and blue boxes operational times of the external vehicles.

6.2 Sensitivity Analysis of Assessment Model Results

The results obtained in the assessment model will be validated in a similar way as in the preliminary design: by carrying out a local sensitivity analysis. A thorough explanation of the method can be found in Section 3.5. The parameters that have led to high sensitivity values will now be presented, together with the analysis performed to ensure the validity of the parameter and, subsequently, the model outcomes.

As expected, the model is very sensitive to all input data given, as the flight schedule solely depends on it. All values, including airport taxi times, have been retrieved from reliable sources such as the corresponding airline or EUROCONTROL and it is assumed that no other sources will be more reliable than the aforementioned. The weight of the electric motors (W_{EM}) has been taken from a reliable source that took such value as an average. It is known that there are lighter and heavier electric motors available but it a design decision was made to take the average value. It is known that the cost of kerosene (C_k) varies on a time basis depending on the market. As this value is directly related to the fuel savings, the model is very sensitive to the parameter. An average of the fuel values of the last months has been taken from IATA. It is believed that this technique can lead to the most accurate high-level estimations. Lastly, the 25% of the average lifetime of an aircraft limit imposed on profit calculations was an assumption made in this research. It does have an impact on the number of aircraft profitable to have electric motors incorporated. However, utilisation of the aircraft has a much bigger impact on this, and only two aircraft with a utilisation higher than 50% were not able to exceed the profit requirement. Thus, it is concluded that the impact of this assumption is negligible.

A box plot depicting the average profit after the implementation of the electric motors is presented in Figure 14. It can be seen that the outputs do not vary largely when exposed to a local sensitivity analysis. Furthermore, a box plot for the average utilisation of external vehicles was intended to be added under this section. However, due to most values being equal, it was not possible to construct a meaningful box plot. Taking the Tarom dataset for simulation time purposes, the mean value is equal to 18.7603% and the minimum and maximum values are 17.3306% and 20.5940%, respectively.

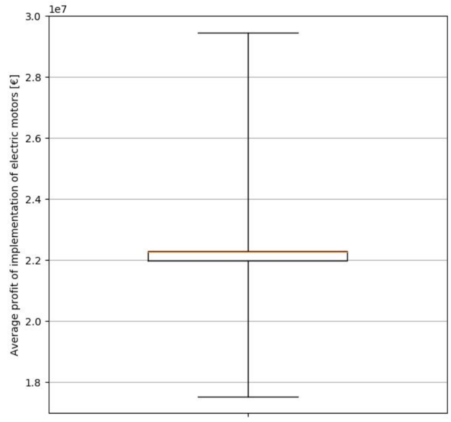

Figure 14: Box plot on average profit of implementation of electric motors.

7 Conclusions

The goal of this research was to assess the economic and operational feasibility of Hybrid Electric Taxiing Systems (HETS). A preliminary design of the system was carried out, determining that the most optimal configuration of the HETS would be to have a battery-powered external truck providing power to the electric motors located in the Main Landing Gear (MLG). Two scenarios were then studied: the feasibility of the system at an airline level and at an alliance level. After conducting the assessment model, the results were only promising at hub airports. Namely, destination airports were not making use of the HETS, leading to the conclusion that such a system requires multiple airlines to make use of it in order to yield profitable results on a network level.

Due to the high demand in air transportation, utilisation of aircraft reaches high values, making the use of electric motors profitable in a wide range of aircraft in the fleet. This would increase the profit of the airline by vastly reducing fuel consumption, emissions and noise at airports. When it comes to the external vehicles, as a maximum of five airlines were studied in this research, the flow of aircraft was not sufficient to attain high utilisation values. Moreover, charging times were too high compared to the operational time of the external vehicles, making them inoperable for a considerable part of the day.

If the research was to be continued in the future, it would be useful to extend the scope of the scenarios and include a greater amount of airlines. Additionally, the preliminary design of the vehicle could be made into more detail and, if compressed hydrogen technologies are developed further, a change in power system could be considered, leading to lower charging times and more operation cycles per charging.

Overall, it can be concluded that the implementation of HETS depends on a wide variety of factors (e.g. available technologies, number of airlines and airports willing to include this technology in their operation, investment costs, etc.), which cannot be done at a small scale. Therefore, the operational and economic implementation of HETS cannot be justified at the proposed scope.

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Appendices

A Extract of Flight Information Dataset

Table 6: Example of data gathered from airline flight schedule.

Day of Week	**Flight Number**	**Arrival Time**	**Arrival Airport**	**Departure Time**	**Departure Airport**	**Aircraft Used**
Monday	KL1720	07:00	EHAM	06:15	EBBR	Embraer 190
Monday	KL1721	07:35	EBBR	06:50	EHAM	Embraer 175

B Extract of Airport Information Dataset

Table 7: Example of data gathered from hub and destination airports.

Airport ICAO Code	**Number of Runways**	**Avg. Taxi-In Time [min]**	**Avg. Taxi-Out Time [min]**	**Time Difference [h]**
SAEZ	2	6	15	-5
LOWW	2	5.7	9.5	0

C Extract of Fleet Information Dataset

Table 8: Example of data gathered from airline fleet.

Aircraft Name	**Aircraft Type**	**Quantity**	**Turnaround Time [min]**
Airbus A330-200	Wide	6	31
Boeing 737-700	Narrow	10	20

D External Vehicle Utilisation Tables

Table 9: External vehicle utilisation for airline scenario under *external vehicle only* case.

External Vehicle ID	Utilisation [%]
EV-EHAM-N0	11.47
EV-SBGR-W0	8.61
EV-CYUL-W0	3.87
EV-CYYZ-W0	7.08
EV-SCEL-W0	2.08
EV-HECA-W0	2.44
EV-VHHH-W0	2.48
EV-VIDP-W0	3.26
EV-VIDP-W1	0.61
EV-VABB-W0	3.72
EV-RJAA-W0	1.98
EV-OKBK-W0	1.14
EV-OKBK-W1	1.30
EV-MMUN-W0	5.04
EV-MMMX-W0	4.88
EV-EHAM-W0	35.34
EV-EHAM-W1	29.03
EV-EHAM-W2	22.48
EV-EHAM-W3	16.99
EV-EHAM-W4	12.25
EV-EHAM-W5	8.85
EV-EHAM-W6	8.15
EV-EHAM-W7	5.24
EV-EHAM-W8	4.10
EV-EHAM-W9	2.87
EV-EHAM-W10	0.57
EV-DNMM-W0	6.31
EV-FAOR-W0	5.22
EV-RKSI-W0	6.98
EV-OMDB-W0	8.02
EV-OMDB-W1	1.14
EV-KATL-W0	15.13
EV-KORD-W0	5.18
EV-KIAH-W0	3.30
EV-KLAX-W0	5.21
EV-KJFK-W0	11.20
EV-KJFK-W1	1.79
EV-KSFO-W0	4.04

Table 10: External vehicle utilisation for airline scenario under *hybrid electric taxiing system* case.

External Vehicle ID	Utilisation [%]
EV-EHAM-N0	6.88
EV-EHAM-N1	1.72
EV-SBGR-W0	8.61
EV-CYUL-W0	2.58
EV-CYYZ-W0	5.82
EV-SCEL-W0	0.69
EV-HECA-W0	1.22
EV-VIDP-W0	1.93
EV-VABB-W0	3.72
EV-RJAA-W0	1.32
EV-OKBK-W0	1.22
EV-MMUN-W0	3.78
EV-MMMX-W0	2.09
EV-EHAM-W0	42.96
EV-EHAM-W1	32.59
EV-EHAM-W2	21.70
EV-EHAM-W3	11.63
EV-EHAM-W4	3.03
EV-EHAM-W5	0.57
EV-DNMM-W0	3.79
EV-FAOR-W0	5.22
EV-RKSI-W0	5.72
EV-OMDB-W0	8.59
EV-KATL-W0	13.87
EV-KORD-W0	4.58
EV-KIAH-W0	2.64
EV-KLAX-W0	5.21
EV-KJFK-W0	12.39
EV-KJFK-W1	0.59
EV-KSFO-W0	3.37

Table 11: External vehicle utilisation for alliance scenario under *external vehicle only* case.

External Vehicle ID	**Utilisation** [%]
EV-LFPG-N0	36.85
EV-LFPG-N1	5.59
EV-LFPG-N2	0.59
EV-EHAM-N0	13.88
EV-EHAM-N1	2.33
EV-LROP-N0	0.58
EV-LEMD-N0	32.23
EV-LEMD-N1	9.25
EV-LEMD-N2	1.82
EV-LEMD-N3	0.66
EV-SBGR-W0	16.65
EV-SBGR-W1	16.65
EV-SBGR-W2	6.88
EV-CYUL-W0	13.48
EV-CYUL-W1	6.30
EV-CYUL-W2	2.17
EV-CYYZ-W0	8.83
EV-CYYZ-W1	7.08
EV-SCEL-W0	10.99
EV-HECA-W0	8.53
EV-HECA-W1	2.44
EV-LFPG-W0	54.11
EV-LFPG-W1	50.76
EV-LFPG-W2	44.14
EV-LFPG-W3	34.66
EV-LFPG-W4	32.47
EV-LFPG-W5	28.87
EV-LFPG-W6	24.57
EV-LFPG-W7	22.30
EV-LFPG-W8	19.19
EV-LFPG-W9	13.70
EV-LFPG-W10	8.76
EV-LFPG-W11	7.96
EV-LFPG-W12	7.26
EV-LFPG-W13	7.26
EV-LFPG-W14	7.26
EV-LFPG-W15	6.03
EV-LFPG-W16	6.18
EV-LFPG-W17	2.96
EV-LFPG-W18	2.52
EV-VHHH-W0	10.58
EV-VIDP-W0	9.77
EV-VIDP-W1	3.37
EV-VIDP-W2	1.32
EV-VIDP-W3	0.61
EV-VABB-W0	6.21
EV-VABB-W1	3.72
EV-RJAA-W0	9.33
EV-RJAA-W1	0.66
EV-OKBK-W0	1.14
EV-OKBK-W1	1.30
EV-MMUN-W0	11.41
EV-MMUN-W1	3.71
EV-MMMX-W0	13.82
EV-MMMX-W1	2.55
EV-EHAM-W0	35.22
EV-EHAM-W1	28.83
EV-EHAM-W2	24.86
EV-EHAM-W3	17.81
EV-EHAM-W4	14.13
EV-EHAM-W5	11.26
EV-EHAM-W6	8.72
EV-EHAM-W7	5.82
EV-EHAM-W8	4.10
EV-EHAM-W9	2.87
EV-EHAM-W10	0.57
EV-DNMM-W0	6.31
EV-FAOR-W0	13.27
EV-RKSI-W0	18.34
EV-RKSI-W1	2.52
EV-LEMD-W0	33.49
EV-LEMD-W1	28.86
EV-LEMD-W2	17.44
EV-LEMD-W3	8.84
EV-LEMD-W4	6.61
EV-LEMD-W5	2.64
EV-LEMD-W6	0.66
EV-LEMD-W7	0.66
EV-OMDB-W0	12.03
EV-OMDB-W1	5.08
EV-KATL-W0	18.15
EV-KATL-W1	14.32
EV-KATL-W2	5.36
EV-KORD-W0	9.07
EV-KORD-W1	5.18
EV-KIAH-W0	8.66
EV-KIAH-W1	3.30
EV-KLAX-W0	13.91
EV-KLAX-W1	8.70
EV-KLAX-W2	6.22
EV-KJFK-W0	30.49
EV-KJFK-W1	18.86
EV-KJFK-W2	14.01
EV-KJFK-W3	13.17
EV-KJFK-W4	11.62
EV-KJFK-W5	2.81
EV-KSFO-W0	14.95
EV-KSFO-W1	4.04
EV-MDPC-W0	7.31
EV-MDPC-W1	1.13
EV-KMIA-W0	17.63
EV-KMIA-W1	8.85
EV-KMIA-W2	2.29
EV-FNLU-W0	1.78
EV-ZBAA-W0	3.24
EV-ZBAA-W1	0.71
EV-ZSPD-W0	2.69
EV-KDTW-W0	8.99

Table 12: External vehicle utilisation for alliance scenario under *hybrid electric taxiing system* case.

External Vehicle ID	**Utilisation** [%]
EV-LFPG-N0	29.10
EV-LFPG-N1	1.18
EV-EHAM-N0	9.83
EV-EHAM-N1	2.33
EV-LEMD-N0	22.73
EV-LEMD-N1	9.66
EV-LEMD-N2	0.58
EV-SBGR-W0	15.99
EV-SBGR-W1	11.73
EV-SBGR-W2	2.46
EV-CYUL-W0	12.76
EV-CYUL-W1	5.17
EV-CYUL-W2	1.45
EV-CYYZ-W0	8.83
EV-CYYZ-W1	5.82
EV-SCEL-W0	9.60
EV-HECA-W0	6.09
EV-HECA-W1	1.22
EV-LFPG-W0	52.38
EV-LFPG-W1	46.20
EV-LFPG-W2	38.11
EV-LFPG-W3	32.27
EV-LFPG-W4	26.50
EV-LFPG-W5	23.54
EV-LFPG-W6	18.49
EV-LFPG-W7	16.22
EV-LFPG-W8	13.65
EV-LFPG-W9	10.04
EV-LFPG-W10	7.96
EV-LFPG-W11	7.96
EV-LFPG-W12	7.11
EV-LFPG-W13	7.31
EV-LFPG-W14	6.72
EV-LFPG-W15	4.94
EV-LFPG-W16	2.42
EV-LFPG-W17	0.64
EV-VHHH-W0	5.63
EV-VIDP-W0	7.73
EV-VIDP-W1	2.15
EV-VIDP-W2	0.61
EV-VABB-W0	6.21
EV-VABB-W1	3.72
EV-RJAA-W0	9.33
EV-OKBK-W0	0.57
EV-OKBK-W1	0.65
EV-MMUN-W0	8.82
EV-MMMX-W0	11.03
EV-EHAM-W0	32.88
EV-EHAM-W1	25.35
EV-EHAM-W2	21.95
EV-EHAM-W3	15.36
EV-EHAM-W4	11.22
EV-EHAM-W5	7.04
EV-EHAM-W6	3.48
EV-EHAM-W7	2.33
EV-DNMM-W0	3.79
EV-FAOR-W0	12.04
EV-RKSI-W0	14.56
EV-RKSI-W1	1.94
EV-LEMD-W0	22.66
EV-LEMD-W1	11.32
EV-LEMD-W2	2.64
EV-OMDB-W0	10.89
EV-OMDB-W1	3.20
EV-KATL-W0	17.48
EV-KATL-W1	13.73
EV-KATL-W1	5.36
EV-KORD-W0	9.07
EV-KORD-W1	4.58
EV-KIAH-W0	8.66
EV-KIAH-W1	2.64
EV-KLAX-W0	13.91
EV-KLAX-W1	8.70
EV-KLAX-W2	2.49
EV-KJFK-W0	26.98
EV-KJFK-W1	14.86
EV-KJFK-W2	12.33
EV-KJFK-W3	9.31
EV-KJFK-W3	2.81
EV-KSFO-W0	13.71
EV-KSFO-W1	3.37
EV-MDPC-W0	5.47
EV-MDPC-W1	0.57
EV-KMIA-W0	12.89
EV-KMIA-W1	3.79
EV-KMIA-W2	1.14
EV-FNLU-W0	1.19
EV-ZBAA-W0	1.32
EV-ZSPD-W0	2.69
EV-KDTW-W0	8.99

II

Literature Study

previously graded under AE4020

1

Introduction

The continuous yearly increase in air transportation users, excluding the numbers experienced in 2020, leads to the economic growth of countries, job creation and fast transport of goods, amongst other advantages. However, it also brings some downsides such as an increase in carbon emissions, air pollutants and noise. Although the airborne phase is the biggest contributor to such emissions, when the aircraft are on the ground the engines are highly inefficient and therefore attain high emission levels. Thus, sustainable taxiing solutions should be implemented to reduce such impact and also reduce the fuel consumption, which would result in great economic savings for airlines. The aviation sector is mainly researching on on-board or external electric taxiing systems. However, the idea of a hybrid system that combines both on-board and external technologies has not been widely researched yet.

The goal of this report is to find the specific research gap that can be fulfilled by this thesis project in order to decrease the emissions, noise and fuel consumption produced during taxiing. This will be done by performing a literature survey on the state of the art of electric taxiing systems that will be followed by a market study to identify the specific research gap. The findings obtained will then lead to the formulation of the research goal and questions.

This report is structured as follows. Firstly, a brief summary on the current situation in air transport will be given in Chapter 2. Here, predictions on how the pandemic has affected this sector as well as facts on how aviation environmentally impacts the world will be addressed. Then, the most relevant findings on the state of the art of electric taxiing systems will be summarised in Chapter 3. A market study will follow in Chapter 4, where the market gap will be identified and a stakeholder and competitor analysis will be performed. Once the research gap is clear, the methodology that will be followed throughout the project will be presented in Chapter 5. Lastly, the research objective and questions are introduced in Chapter 6.

2

Current Situation in Air Transport

In this chapter, an introduction to the current situation in the air transport industry in Europe will be given. First, different forecasts on how the COVID pandemic has affected aviation will be presented, and predictions following from all scenarios will be given. Then, the advantages and disadvantages that this ever-increasing industry has globally will be mentioned. Lastly, the chapter will focus on the environmental impact that the taxiing phase has on air transport.

The use of air transport keeps increasing every year and is expected to double every 15 years [19]. In 2019, 4.5 billion passengers were carried by the world's airlines [3], meaning that in 2034 a total of 9 billion passengers would be travelling around the globe on a yearly basis. However, due to the COVID pandemic that started in March 2020 and is still affecting air transport, it is difficult to predict how the number of passengers will evolve in the upcoming years and if it will be able to meet the predictions stated in [19]. A five-year forecast made by EUROCONTROL for the period 2020-2024 states three different forecast scenarios for European air transport due to the uncertainty left by the pandemic [12]. The most optimistic scenario predicts that the number of travellers in 2019 will be reached again in 2024, while the most pessimistic states that recovery back to 2019 numbers will only be achieved at least in 2029. As can be seen in Figure 2.1 [12], there is a third scenario that is mid-way between the most optimistic and the most pessimistic, which estimates recovery by approximately 2026. By taking a conservative approach and assuming that levels in air transport will have recovered by 2029, this would mean that in 2044 the number of passengers throughout the world would be approximately equal to 9 billion. On the contrary, if the most optimistic vision is taken into account, this number of passengers would be reached in 2039.

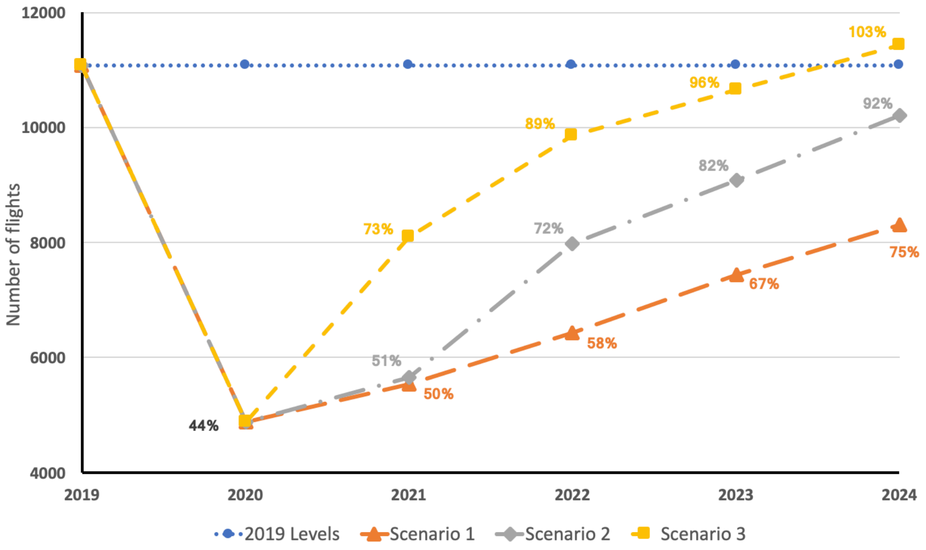


Figure 2.1: Forecast scenarios of flights in Europe for the period 2020-2024 (Adapted from [12]).

This increase in the use of air transport will evidently have a positive impact on the economic growth of airports, airlines and the cities nearby. Moreover, as air traffic increases, so will the job opportunities in the aviation sector, which in 2019 already generated 65.5 million jobs globally (through direct, indirect, induced and catalytic impacts) and was predicted to reach 97.8 million jobs in 2036 before the pandemic hit the aviation sector [1]. Additionally, in 2019 around 90% of Business to Consumer (B2C) e-commerce parcels were carried by air, which highlights the importance of aviation in worldwide companies' sales [1]. On the social side, air transport improves the quality of life by expanding the range that people can reach, enriching their culture. It also promotes social inclusion, by bringing tourism to countries that are affected by poverty [2]. Another benefit that was seen in the last months is the facilitation of the delivery of emergency and humanitarian aid relief anywhere on earth [2], as experienced with the vaccines and other equipment needed during the COVID-19 pandemic.

Although there are many benefits linked to the increase in air transportation, not all outcomes are positive. If the number of flight movements doubles in the next decades, so will the emissions and fuel consumption associated to aircraft. Currently, the global aviation industry already produces 2% of all human-induced carbon dioxide (CO_2) emissions and aviation is responsible for 12% of CO_2 emissions from all transport sources [3]. These numbers are expected to increase if no sustainable solutions are implemented to reduce pollution. Moreover, the noise levels at airports and neighbouring areas will also rise, possibly attaining levels that are harmful for the population. On a more operational side, congestion at airports will be difficult to deal with, as some of the biggest airports are already reaching maximum capacity and expansion of some of these airports will not be possible. Numerous research projects and policies are being carried by organisations throughout the globe. An example of this is Flight Path 2050, a plan carried by the European Union to develop a vision for Europe's aviation system and industry by 2050 [6]. This plan has the following environmental objectives to be reached by 2050: 70% reduction of CO_2, 90% reduction of nitrogen oxide (NO_x) compared to 2000 levels, minimisation of noise and all taxiing procedures are required to be carbon neutral [6]. Currently, research is mostly focused on the airborne phase, where the benefits of More-Electric Aircraft (MEA) and All-Electric Aircraft (AEA), amongst others, are being studied. Experts believe that the implementation of such aircraft would result in a 10% decrease in aircraft weight and 9% decrease in fuel consumption [19]. However, in order to meet the Flight Path 2050 objectives, more solutions have to be implemented. Techniques that reduce noise, emissions and fuel consumption on the ground also need to be executed. Currently, the most popular research field related to the minimisation of emissions on the ground phase is taxiing due to the great fuel savings and pollution reduction that could be achieved by optimising this phase of flight.

Taxiing is described as the phase of flight in which movement of an aircraft under its own power occurs on the surface of an aerodrome, excluding take-off and landing [19]. This phase of the flight cycle is highly inefficient since the engines are optimised for cruising speed. This makes taxiing be one of the biggest contributors to the pollution and noise at airports [19]. The pushback phase is specifically the most significant contributor of slowing down the total ground procedure [20], which leads to significant delays of departing and arriving aircraft, greater fuel consumption and greenhouse gasses emitted. Currently, in Europe, aviation accounts for 3% of the total greenhouse emissions, while this share is especially high in the United Kingdom with a 6% [5]. Moreover, European flights spend up to 30% of the time and consume 5% to 10% of the entire mission fuel for ground operations and taxi [24]. Taking this into account and knowing that aviation fuel comprises 25% or more of airline costs [10], it can be assumed that airlines would be very interested in making air transport greener to then greatly reduce fuel consumption and subsequently reduce operational costs. The optimisation of ground movements and reduction of fuel consumption and emissions can be carried out by the implementation of different methods, which will be tackled in the next chapter.

3

State of the Art

The taxiing phase is currently widely performed with the use of all engines. However, some airports and airlines are starting to implement alternative ground propulsion systems in order to mitigate noise and emissions and reduce fuel consumption. The most popular solutions are depicted in Figure 3.1. They are initially divided in operational and technological solutions. The former involve improvement of operations at airport level and still require engines to taxi, while the latter focus on the employment of engineless-based approaches that allow for smarter and greener taxiing [20].

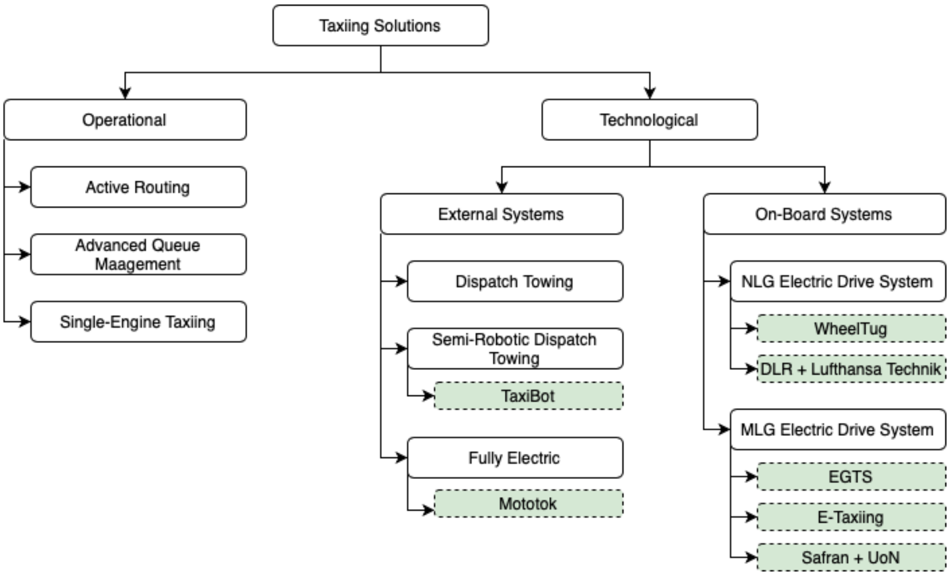


Figure 3.1: Diagram of the currently most popular technologies to replace the conventional taxiing procedure (Adapted from [20]).

Throughout this chapter, the different solutions will be explained. Moreover, some information will be given on the current state of the art and on the most popular and reliable prototypes to replace conventional taxiing. The advantages and disadvantages of each solution will be presented and a comparison of all techniques will close up this chapter.

3.1. Operational Solutions

On the operational side, different strategies such as active routing, advanced queue management and single-engine taxiing could be implemented as the new form of taxiing. The two first techniques focus mainly on reducing congestion and delays at airports while the third one is an attempt to reduce noise, emissions and fuel consumption at airports and neighbouring areas. As the focus of this research is on the last-mentioned topics, only single-engine taxiing will be addressed in this study.

This taxiing alternative consists in using only one engine for taxiing twin-engine aircraft or two engines for four-engine aircraft [14]. It has the potential to reduce fuel burn and carbon dioxide emissions by 20-40% and emissions of nitrogen oxides by 10-30% [23]. The upside of using this technique is that its implementation would not suppose any big changes in airport infrastructure or aircraft design, leading to an earlier execution. However, there are several points of attention that should be taken into account when studying the feasibility of such system. First of all, the manoeuvrability and balance of the aircraft would be affected if thrust power is only coming from one side. Also, depending on the weather conditions and the shape of the taxiway, it is sometimes not possible to have half of the engines turned off. These safety and technical constraints make single-engine taxiing forbidden at certain airports and not recommended by aircraft manufacturers [23].

3.2. Technological Solutions

The technological strategies to greatly improve sustainability on the ground phase of flight can be distinguished between external and on-board solutions. Both depart from the same principle: engineless-based taxiing. However, external systems consist in having towing tractors that carry the aircraft from the gate until the runway and on-board systems consist in installing electric motors on the aircraft wheels to electrically power the aircraft from gate to runway.

3.2.1. External Systems

First of all, the easiest and cheapest external system technique to apply, and also the least sustainable, is dispatch towing. It consists in using the standard towing tractors that are already used for pushback to carry the aircraft throughout the whole taxiing path. These tractors burn diesel, gasoline or natural gas and they show fewer emissions on average compared with conventional aircraft engine-based taxiing [8].

A similar method to dispatch towing but slightly more sustainable is semi-robotic dispatched towing, which employs more efficient and environmentally friendly electric (fully or hybrid) trucks for towing purposes [20]. An example of this is TaxiBot, a semi-autonomous hybrid electric tractor developed by Israeli Aerospace Industries [19], which is one of the few certified and commercially-operational alternative taxiing solutions up to date. The system is designed in such a way that it allows the tractor to slightly lift up the aircraft's front wheel and lock it up in a position, with the possibility to control the wheel from the cockpit [15]. Braking is also achieved as in conventional taxiing, using brake pedals that control the brake system in the main landing gear [19]. The main technical characteristics are the following: the powertrain of the tractor consists of two diesel engines each driving a separate electric generator which supplies 8 electric motors installed in 4 wheels; the maximum power to the road is 500kW with a maximum achievable torque of 45kNm; and the

TaxiBot is able to reach speeds up to 23 knots (42.6 km/h) on a Boeing 737 [19], which is approximately 75% of the speed achieved in conventional taxiing. This system is currently being used by airports and airlines throughout the world, such as Lufthansa, Air France, China Eastern and New Delhi International Airport [29][28]. However, it still does not fully comply with the carbon-neutral objective of Flight Path 2050. Thus, further development of taxi systems is needed.

The third alternative for external electric systems is the use of Electric Pushback (EP) systems. These are designed to replace conventional fuel towing tugs with electrical ones. An example of EP system is Mototok, which requires no driver and thus has lower operating costs in addition to no emissions and comparatively low noise during pushback procedures. The towing trucks are smaller compared with conventional tractors, which makes storage and manoeuvring at airport hangars more accessible and flexible. The main drawback is that EP systems can only achieve very low speeds, making them only acceptable for pushback operations [20].

The main advantages of external systems are that they do not add any weight on-board, modifications done to the aircraft are minor and Foreign Object Damage (FOD) risk is reduced by 50% [27]. When compared to the other taxiing solutions, external systems lead to the maximum fuel savings. Also, the certification process is considerably easier compared to other Electric Taxiing Systems (ETS) solutions [19]. The drawbacks that come with the implementation of these systems are the following: congestion at airports would increase as the aircraft would have to stop and wait a few minutes to be attached and detached from the tractor after landing and take-off, respectively. Also, the airport infrastructure should face some major modifications as secondary roads for the movement of the tractors should be built. Each vehicle should have a human driver or an automatic guidance system, which would result in additional operational costs [19]. On the economic side, the use of external systems would mean a great investment from airports and airlines. For example, the price of one single TaxiBot is $1.5M for narrow-body aircraft and $3M for wide-body aircraft [18]. Moreover, the cost for additional concrete tracks is approximately $240 per square meter, or if asphalt tracks are created, the cost would roughly be $190 [20]. It is estimated that the average operational usage of tow tractors on regional airports is 500h/year and 5000h/year on hub airports, leading to a Return on Investment (ROI) of 2 years [15].

3.2.2. On-Board Systems

As it can be implied by the name, these systems are placed on board of the aircraft. They typically include an electrical drive concept with an electric motor, power converter and an electric energy source [19]. Due to the complexity of this system, several options are being studied to determine the optimal location of the motors, the method of wheel integration and the electrical energy source.

The motor can be located either in the Nose Landing Gear (NLG) or in the Main Landing Gear (MLG). Placing it in the NLG allows for larger space and a simpler structure due to the absence of brakes. However, as the centre of gravity of the aircraft is relatively far from the NLG, the weight on the nose gear might be too small to ensure the needed friction between the tire and the ground in all surface conditions [24]. Carrying the motor on the MLG is very appealing due to the possible high tractive forces, as the main gear carries approximately 90% of the aircraft's weight [19]. Also, as the MLG consists of four wheels, reliability, redundancy and design flexibility are increased because the requirements can be scaled down by four times. Even if the placement of the motor on the MLG can result in many advantages, it also implies a series of downsides. First of all, the brakes generate a lot of heat that could impact the motors. Thus, cooling systems for the motors should be put in place [19]. Secondly, adding mechanical linkages to the gear strut supposes great mechanical complexity and causes architecture changes on the design of the landing gear [24].

There are two different methods of wheel integration, direct drive or geared system. The advantages of implementing the first technique are the simpler drive train construction, the higher overall efficiency of the system, the possibly reduced weight and the increased reliability. When it comes to geared systems, it is important to mention that they would simplify the installation of clutch systems as the clutch could be integrated within the gearbox, potentially solving the problem of Counter-Electromotive Force (CEMF), and they enable a lower Traction Motor (TM)'s torque rating and thus allow for more compact TM design. However, geared systems lead to jamming and complex mechanical drive train systems [19].

In order to supply energy to the motors, sources that are already available on the aircraft can be used, such as the Auxiliary Power Unit (APU) or the Integrated Drive Generator (IDG), which is driven by the main engine [21]. The first option is usually preferred, as the second one implies the use of the engines, which directly makes this solution less sustainable. However, currently the APUs located on aircraft cannot provide sufficient power to carry the aircraft to the runway by itself, while maintaining its current functions (e.g. main engine starting, providing cooling are for aircraft secondary systems, supplying electrical power when main engines are shut down, etc.) at the same time. In order to use the APU exclusively, some modifications would be required on this system. Another option would be to supply energy through localised batteries and fuel cells, or a combination of both. This solution is however not yet feasible, as fuel cells are not technologically fully developed for mobile applications [20].

On-board systems lead to the maximum carbon monoxide (CO) reductions, compared with other taxiing alternatives. In addition, the implementation of these systems minimises the airport surface movements created by towing tractors and decreases push-back times significantly [19]. Another important upside is that on-board systems can be used by the same aircraft on all airports, so if an airline decides to make an investment, it will not depend on the airport but only on the aircraft they choose for that route. The drawback of carrying the motors at all times supposes an increase on the total aircraft weights, as well as a change in the aircraft's architecture [19]. Moreover, as previously mentioned, cooling for the additional systems (e.g. generator, electric motors) might be needed [24]. In order to offset the additional weight caused by the on-board systems, a reduction of two or more passengers and/or stricter baggage allowance restrictions might be imposed [20].

Several systems have been designed and presented to the public in the last years. The first company to develop an on-board ETS was WheelTug. Its system consists of two induction machines located at the NLG and powered with the help of the APU [19]. The additional weight included in the aircraft is 130 kg [26] and it can reach a maximum speed of 9 kt (16.7 km/h) [20], which is relatively low compared to the 30 kt (55.6 km/h) normally reached in conventional taxiing. WheelTug initiated the manufacturing process in July 2021 and it is predicted that it will be available for the Boeing 737NG family in 2022 [30]. The DLR and Lufthansa Technik also worked on a joint project to design an on-board system located at the NLG and powered by fuel cells. The speed reached was higher than that of WheelTug, with a maximum of 13.5 kt (25 km/h) [19]. However, it is difficult to predict when this system could be put in place as fuel cells are still technologically immature. The most promising design was the Electric Green Taxiing System (EGTS) developed by Safran and Honeywell Aerospace. It was located at the MLG and powered through the APU. It was a relatively light system with a total weight of 36 kg, including the cooling fan [20] and it could reach speeds of up to 20 kt (37 km/h) [19]. However, for undisclosed reasons, this project was terminated in 2016. Safran has however kept working on other projects such as e-taxiing with Airbus, which intends to offer a market-ready APU powered product for the future versions of the A320neo [20], and a joint project with the University of Nottingham on the design of an optimum energy storage system for electric taxiing [19].

3.3. Comparison of Alternative Taxiing Procedures

Now that the most promising taxiing solutions up to date have been introduced, it is time to perform a comparison between them. Table 3.1 provides an overview of the different taxiing solutions with the respective system configuration and the advantages and disadvantages that they offer. Although some of the facts have already been mentioned throughout this chapter, this overview also contains more specific and numerical data about each taxiing solution.

As external and on-board systems have been extensively researched, it is time to look for alternative solutions. In the next chapter, a research gap will be looked for, which will lead to the main topic of this research.

Table 3.1: Comparison of the most promising operational and technological solutions up to date [20][19][24][14][26][18][22][13][25][11].

	System Configuration	Advantages	Disadvantages
Single-Engine	Twin-Engine A/C: 1 engine on Four-Engine A/C: 2 engines on	- 20-30% in CO2 emissions; - 10-30% in NOx emissions; System is already available; No pilot training needed; No changes in infrastructure or aircraft design.	Bad manoeuvrability and balance; Aircraft manufacturers are concerned about this technique; Not operable under special taxiing conditions; Safety concerns such as jet blast and FOD risk.
TaxiBot	External (Semi-Robotic Dispatch Towing)	- 98% in CO2 emissions; - 98% in overall taxi fuel; Operational since 2014; $5.4M pd py saved; Highest maximum speed; Highest maximum power.	Highest purchase cost (1.5$M-3$M per device); It does not comply with carbon neutrality objective.
Mototok	External (EP System)	- 100% in pushback fuel; - 54 % in pushback time; Low operational costs; More compact trucks.	Lowest savings as it is only used for pushback operations; Low speed.
WheelTug	On-Board (NLG + Geared)	- 60% of total emissions; - 50% in overall taxi fuel; 6 min. of overall taxi time savings per cycle; Highest money savings w.r.t. other on-board systems; Lightest on-board system.	Not operational yet; Lowest maximum speed of all on-board systems.
DLR and Lufthansa Technik	On-Board (NLG + Geared)	Low on-ground noise; Low fuel consumption.	Fuel cells are not technologically ready yet; Low speed; Lowest maximum power.
EGTS	On-Board (MLG + Geared)	- 47% in NOx emissions; - 62% in CO2 emissions; - 74% in HC emissions; - 74% in CO emissions; - 3% of block fuel; 2 minutes time savings on pushback per cycle.	Lowest money savings for on-board systems; Heaviest on-board system (400 kg); Project was terminated.
E-Taxiing and Safran/UoN	On-Board (MLG + Geared)	- 51% in NOx emissions; - 62% in HC emissions; - 61% in CO2 emissions; - 73% in CO emissions; - 4% of block fuel; 2 minutes time savings on pushback per cycle.	Heavy (320-380 kg); Newest development, Entry Into Service (EIS) might be late.

4

Market Study

This chapter focuses on getting to know the market in which the developed product will be deployed. First, a market segmentation analysis will be conducted in order to identify the main sectors in which the product can be helpful. Once this is done, the size of the market will be estimated as well as the research gap that still needs to be filled, so that the developed concept is unique and satisfies specific needs that are not tackled yet by the industry. A stakeholder analysis will also be provided in the chapter in order to identify the main parties of interest. Finally, the chapter will be concluded by a SWOT analysis of the concept, together with an analysis of the potential main competitors.

4.1. Market Segmentation

It is clear that the product is being developed as part of a thesis in aerospace engineering, which implies that the industry in which the research will be conducted is the aviation industry. Figure 4.1 shows how this industry can be subdivided in different segments. Commercial aviation has been chosen as the main target of this research, as the implementation of such system would take place in commercial aviation airports.

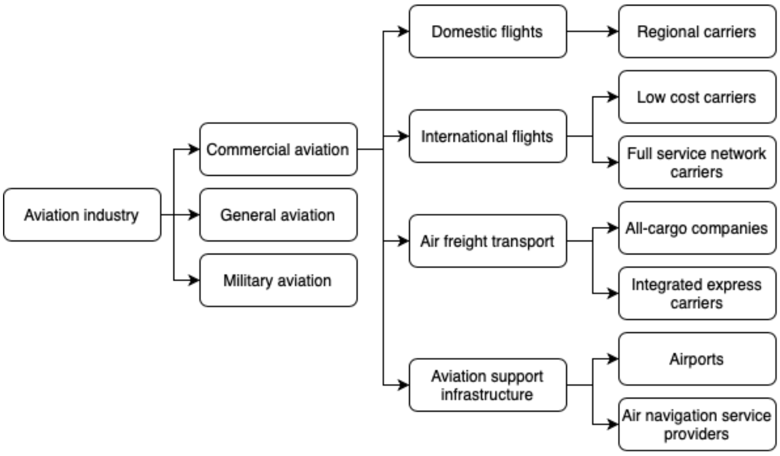


Figure 4.1: Diagram of market segmentation.

4.2. Market Gap

Alternative taxiing solutions are being researched by many institutions and companies worldwide. As it has been described in this study previously, most companies are focusing on either on-board or external taxiing systems. However, a downside that both options share is that such systems cannot be used in all types of airports. For example, when the taxiing time is lower than 5 minutes, it is not beneficial to use these systems, as the time it would take to heat the engine can double the taxiing time, increasing congestion at the airport [19].

Developing a system that could combine characteristics of both on-board and external systems, while minimising the downsides and maximising the advantages, would be an interesting area of research. Hybrid Electric Taxiing Systems (HETS) have not been widely researched yet, making it an interesting and innovative research topic to explore.

4.3. Market Size

Estimating the market size is a very important and useful technique to understand the target customer. This estimation represents the number of users and/or buyers of the product that is going to be developed. In this case, it is likely that in the far future, every airport and airline will want to invest in such fuel consumption reduction techniques. However, in the near future, not all airlines and airports will be willing to invest in such systems, as their success has not been widely proved and the purchasing costs are still very high.

As the design phase has just started and the development, certification and manufacturing phases could take decades, the target customers considered in this report will be airports and airlines throughout the globe. Although international big airports are more likely to use the system due to congestion and high emission levels issues, all airport sizes will be considered as the system will try to be as flexible as possible to accommodate all airport types. Also, it is expected that network carriers will be the first ones to implement ETS in their operations. However, as environmental fees will increase and government regulations will become more strict, all airlines will have to shift towards a more sustainable flying in the future.

4.4. Stakeholder Identification

Stakeholders can be classified into two main groups: primary and secondary stakeholders. In the case of a HETS, the primary stakeholders can be taken from the deepest level of detail in Figure 4.1, as they represent the entities that would be directly affected by the system. Following this logic, the secondary stakeholders represent the main parties that would be be indirectly impacted by the system.

4.4.1. Primary Stakeholders

- Airlines: They are the main benefiters of such system, as fuel consumption reductions during taxi suppose great money savings for an airline, knowing that fuel accounts for 22.1% of the operating expenses [17]. Moreover, the reduction on noise and emissions will also decrease the environmental airport fees that are present in many European airports nowadays and that represent 15-20% of low cost carrier costs and 4-8% of network carrier costs [9]. However, these advantages will come at the cost of the potential training of pilots to use the system and the purchasing of the on-board systems needed.

- Airports: As it has been previously mentioned in this report, the external part of a hybrid system will suppose a significant change in an airport's infrastructure. Thus, airport operators must account for this and, if needed, redesign the road network across the airport. Moreover, they will be the ones purchasing the external systems, which would suppose additional costs. It must be noted that these one-time payments could be evened out by the drastic decrease in carbon emissions and air pollutants, as well as noise. This would also mean that biodiversity around the airport could be better protected.

- Air navigation service providers: If taxiing becomes slower, congestion at airports will increase, making the job of air traffic controllers more complex. Moreover, if a certain period of time is required to heat up the engines before take-off, this will also make the navigation network more intricate.

- Aircraft manufacturers: The design of the aircraft will probably be impacted by the placement of the on-board systems. Thus, manufacturers must keep this into account when placing the electrical system, for example. Moreover, the additional weight carried on board might also alter the design of the aircraft, such that the performance attained still remains the same. Lastly, certification of such aircraft will be more difficult, which should be taken into account in the development timeline of an aircraft.

4.4.2. Secondary Stakeholders

- Government: Countries are heading towards a more sustainable development. Having their national airlines and airports implementing sustainable solutions is of interest for them, as it would help decrease a country's environmental footprint.

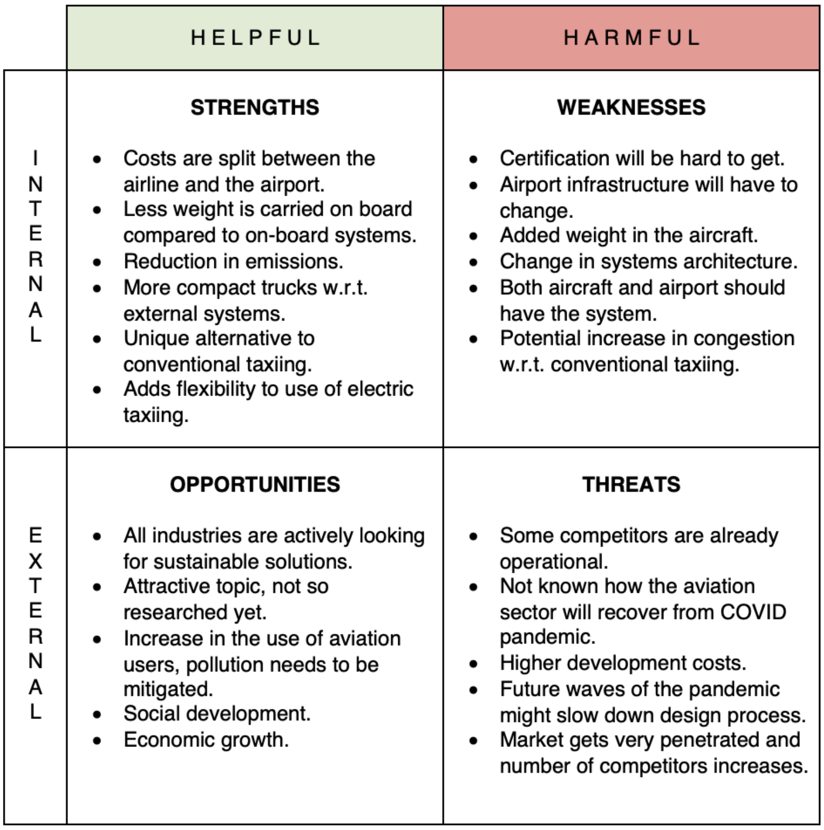
- Employees: The health of the ground operations employees is harmed by the noise and pollution emitted by aircraft when the engines are running. By mitigating these, workers will have improved health conditions.

- Customers: Nowadays, people are becoming more aware of the environmental impact their actions might have. Knowing that they can fly by emitting less pollution will potentially be a factor that will guide them towards choosing airlines that use this solution. This is also applicable for companies that ship their cargo.

4.5. Competitor Analysis

When entering a competitive market, it is important to know very well the strengths, but most importantly the weaknesses, of the product that will be developed as well as those of competitor products. First, an analysis on the factors that can help or harm this research internally as well as externally is covered in Figure 4.2. As the project is still at an early stage, the facts included are rather general. However, once the design and other data of the final concept are known, a more detailed SWOT analysis will be carried.

The competitors of the HETS developed in this research will not only be the aforementioned companies working on on-board and external systems, but also those researching into HETS. Currently, none of the big entities that lead this research sector have come up with any successful findings on the use of hybrid systems. However, it is known that Safran is interested in assessing the feasibility of such technologies, which can make them either a competitor or a partner of this project. Throughout the project, if any other companies express their desire to research on this technology, a more elaborate competitor analysis will be performed. A comment on the companies that have developed successful on-board and external systems will not be included in this section, as their working principle, together with their strengths and weaknesses, has already been extensively covered in Chapter 3.



	HELPFUL	HARMFUL
INTERNAL	**STRENGTHS** • Costs are split between the airline and the airport. • Less weight is carried on board compared to on-board systems. • Reduction in emissions. • More compact trucks w.r.t. external systems. • Unique alternative to conventional taxiing. • Adds flexibility to use of electric taxiing.	**WEAKNESSES** • Certification will be hard to get. • Airport infrastructure will have to change. • Added weight in the aircraft. • Change in systems architecture. • Both aircraft and airport should have the system. • Potential increase in congestion w.r.t. conventional taxiing.
EXTERNAL	**OPPORTUNITIES** • All industries are actively looking for sustainable solutions. • Attractive topic, not so researched yet. • Increase in the use of aviation users, pollution needs to be mitigated. • Social development. • Economic growth.	**THREATS** • Some competitors are already operational. • Not known how the aviation sector will recover from COVID pandemic. • Higher development costs. • Future waves of the pandemic might slow down design process. • Market gets very penetrated and number of competitors increases.

Figure 4.2: SWOT Analysis on Hybrid Electric Taxiing Systems.

5

Methodology

In this chapter, the methodology that will be used during the next stage of the project will be described step by step. Although it aims to be as specific as possible, it might be the case that throughout the project some steps will be changed due to the current uncertainty on the concepts that will be chosen. If this is the case, a note will be made to the reader explaining the reasons of the change in method. A map of the main steps taken throughout the project is depicted in Figure 5.1.

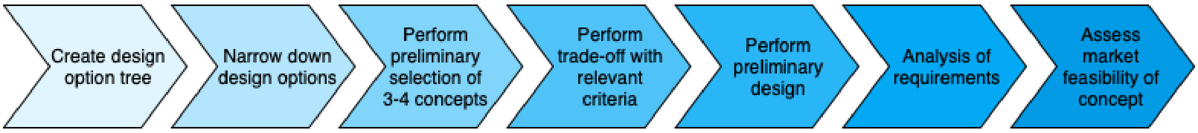


Figure 5.1: Main steps of the design process throughout this project.

First of all, a design option tree will be created with all the design options that can be thought of. In this diagram, innovative and unrealistic designs will be welcome. This will serve as a way of looking for out-of-the-box solutions that might be possible sometime in the future. However, as the scope of this project is relatively short, the design solutions will be narrowed down to less than 10 concepts that would be feasible to incorporate in the aviation sector in the near future. A preliminary analysis will then be performed to select a maximum of 4 concepts that will then be subjected to a trade-off process. The preliminary analysis will consist in conducting a feasibility study on which concepts can be put in place in the next decade according to the technical requirements.

Once the final concepts are selected, the trade-off process will start. For this, we must select some criteria in which all concepts will be evaluated and ranked. At the end of the ranking procedure, the concept with the highest score will then be selected as the hybrid electric taxiing system for this research. The following trade-off criteria have been chosen, together with the weight of each:

- Technical complexity [35%]: it has been selected as a criterion because the architecture of the aircraft systems and the airport's infrastructure might greatly change and its technical characteristics will impact the amount of future customers and attention given to the product. It has been given the highest weight as it will also lead to the greatest changes.

- Profit [25%]: stakeholders will play an important role and if the system is not interesting for them economically, they will go for other taxiing solutions even if their technical characteristics are slightly less promising than the ones obtained for this system.

- Sustainability [20%]: this criterion is important because the aim of such system and the project itself is to make aviation more sustainable. Also, this will indirectly lead to money savings as environmental fees will be mitigated.

- Technology Readiness Level (TRL) [10%]: it is important to consider this aspect as airlines and airports want to implement such systems as soon as possible and some competitors are operational and creating partnerships.

- Delay caused [10%]: as stated in [7], "a design improvement that reduces taxiing time by 1 minute, on average, translates to savings of 5000 aircraft-hours and over 400,000 passenger-hours per year. If the average direct operating cost for taxiing is $2000 per aircraft-hour, saving a minute of average taxi times saves about $10 million per year in direct airline costs alone".

Each criterion will be subdivided in different categories. This will then lead to solving separate trade-offs that will then be combined into the main trade-off. Table 5.1 summarises the five main criteria, together with the subdivisions of each of them and their respective allocated weight.

Table 5.1: Trade-off criteria, subcriteria and respective weights.

Technical Complexity [35%]	**Profit [25%]**	**Sustainability [20%]**	**Technology Readiness Level [10%]**	**Delay Caused [10%]**
Added Weight (20%) On-board architecture changes (40%) Airport infrastructure changes (40%)	N/A	Emissions (40%) Noise (40%) Health of workers (20%)	Time to adapt airport (30%) Availability of materials and power source used (70%)	N/A

Profit and delayed caused will not follow a preliminary trade-off procedure. In order to assess the economic capabilities of the different concepts, the method carried in [16] will be used. In that scientific article, J. Hospodka describes how to perform a cost-benefit analysis of electric taxi systems for aircraft. As the analysis is extensive, only the variables that affect profit the most will be included in this study. The variables used and an extensive explanation of this method will be provided in the thesis report that will follow this literature survey. The way in which the scoring for delay will be assessed is based on a model that will simulate the taxiing time and delay caused by each concept. This model will be developed as part of the main thesis project.

One scoring method must be decided in order to get a consistent grading scale for the different parameters to be combined into one trade-off. Linear scaling is found to be the best fitting option for this. Methods that transform the grades, for example by rooting and scaling, are dismissed, because the values would lose their distinct meaning and its complexity might lead to confusion. A ranking between the concepts for each parameter was dismissed, because it would hide the small or large difference between the concepts. The same applies for having the best and worst concepts graded 1 and 5 respectively. These methods would result in concepts having a 1% difference in performance, have a 25% difference in grade in the case of having four concepts.

It must also be mentioned that the trade-off procedure will be submitted to a verification and validation process to ensure that the results obtained can be taken for further analysis. If the verification and validation tools determine that the method implemented is not accurate enough, this design step will be started from the beginning with a new methodology. Once the trade-off is performed, there will be a winning concept. Then, a preliminary design will be done on this concept. Due to time constraints of this project, the analysis will be rather superficial and will mainly focus on the main changes to the aircraft components and to the airport infrastructure. These changes will also be subjected to a verification and validation process to ensure that the numbers obtained can be trusted.

Once the main technical characteristics of the system will be known, an analysis on the requirements needed for the functioning of the HETS will be carried out. This will take into account both requirements needed as part of the aircraft design as well as any infrastructure requirements.

The last step that will be performed in this research project will be to assess the feasibility of such system compared to its main competitors. This will be done at an operational and economic level. On the operational level, the complexity of the systems, the reduction in emissions and fuel consumption, the TRL and the expected delays caused will be tackled, whilst on the economic side, the profit will be the main variable.

6

Research Objective and Research Questions

This chapter will close up the literature survey by presenting the research goal and questions that have been developed from the findings.

From the research performed in this review, it is possible to find a research gap that has not been fulfilled yet: the use of a hybrid electric taxiing system to mitigate pollution and reduce fuel consumption at airports and their surroundings. In order to assess the feasibility of such system in the aviation market and ensure the success of this concept against its competitors, it is necessary to assess the economical and operational capabilities of the designed HETS. The research objective can be summarised as follows:

To assess the operational and economic feasibility of hybrid electric taxiing systems by designing a mixed on-board and external electric system and comparing its characteristics with other existing electric taxiing solutions.

With the research objective being identified, the research questions and subquestions that follow and that will be carefully addressed throughout this research project are stated below:

1. What is the working principle of the hybrid system?
    (a) How is the system powered?
    (b) What will be the changes in the aircraft system's architecture?
    (c) How will airport infrastructure change to accommodate the HETS?
2. What are the benefits and downsides of such system?
    (a) What will be the environmental footprint of the system?
    (b) Will congestion issues arise due to the implementation of the system?
    (c) Would the research and development costs involved in this project justified?
    (d) Is the performance of the system better than the one of its competitors?
3. What will be the feasibility margins of the HETS?

(a) Will it be able to penetrate in low-cost carriers markets or solely in network carriers?

(b) In which type of airports will the product be implemented: international hub, international or regional airports?

7

Conclusion

The goal of this report was to find the specific research gap that can be fulfilled by this thesis project in order to decrease the emissions, noise and fuel consumption produced during taxiing. The importance of the implementation of such system was highlighted in a background study on the current aviation sector's facts and figures. It was seen that the pollution emitted by air transport must be drastically reduced in order to promote a more sustainable development of countries.

A literature study on the state of the art of electric taxiing solutions was carried out, highlighting the advantages and disadvantages that every system has. It was seen that although the current situation would already be highly improved with the implementation of on-board or external systems, there are still some drawbacks that these systems pose that have to be mitigated. For this, a research gap was found: the potential implementation of Hybrid Electric Taxiing Systems (HETS), that would combine and optimise the operational and economic characteristics of on-board and external systems.

The report was then concluded by listing the methodology steps to be followed throughout the project in order to achieve the successful design of such system. The areas in which the project will mainly focus on were described by the research objective and questions. This denotes the end of the literature survey carried out and it is now time to implement the knowledge gained throughout this period and start the design process.

III

Supporting work

A

Detailed Results

The figures presented in this chapter present the utilisation of each aircraft in KLM's fleet after carrying out the flight schedule heuristic. As it can be seen, in most cases utilisation decreases as the number of aircraft increases. This makes sense, as the heuristic is designed to have maximum aircraft utilisation.

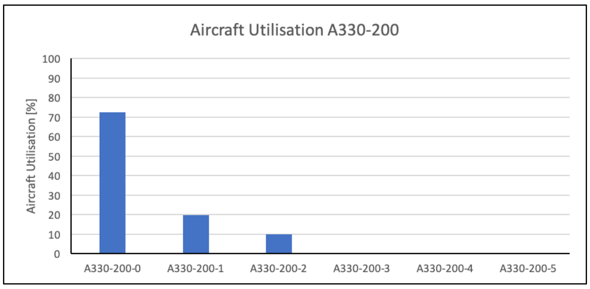


Figure A.1: Aircraft utilisation of all Airbus A330-200 in KLM's fleet.

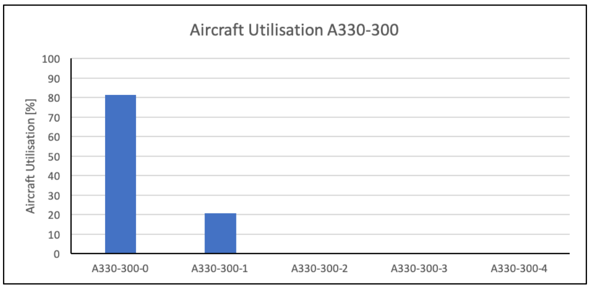


Figure A.2: Aircraft utilisation of all Airbus A330-300 in KLM's fleet.

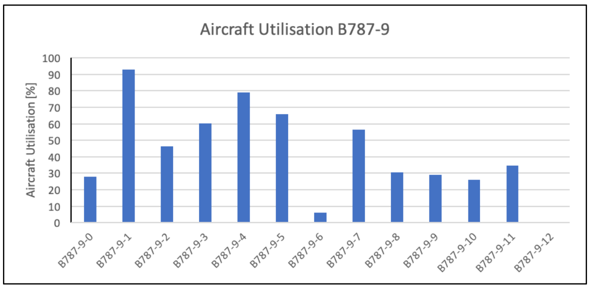


Figure A.3: Aircraft utilisation of all Boeing 787-9 in KLM's fleet.

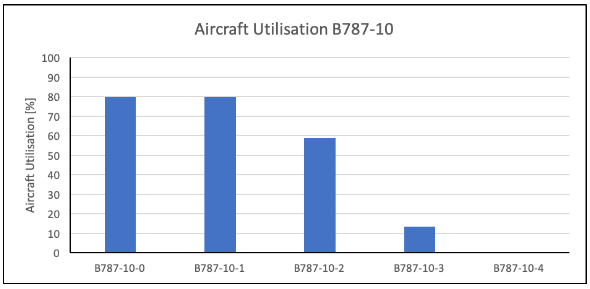


Figure A.4: Aircraft utilisation of all Boeing 787-10 in KLM's fleet.

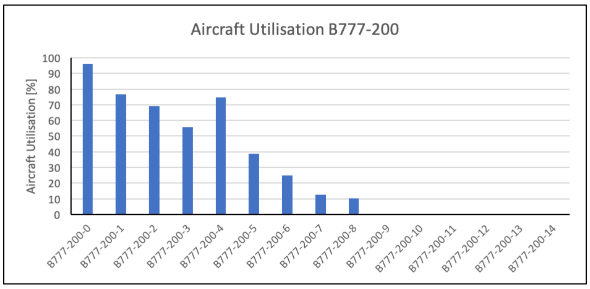


Figure A.5: Aircraft utilisation of all Boeing 777-200 in KLM's fleet.

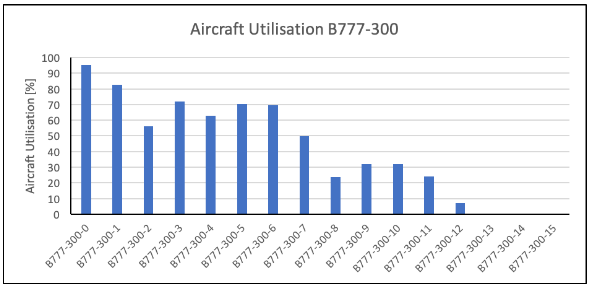


Figure A.6: Aircraft utilisation of all Boeing 777-300 in KLM's fleet.

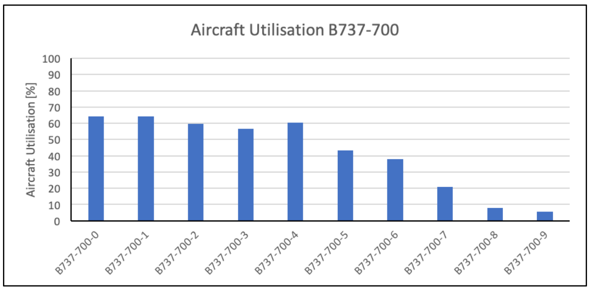


Figure A.7: Aircraft utilisation of all Boeing 737-700 in KLM's fleet.

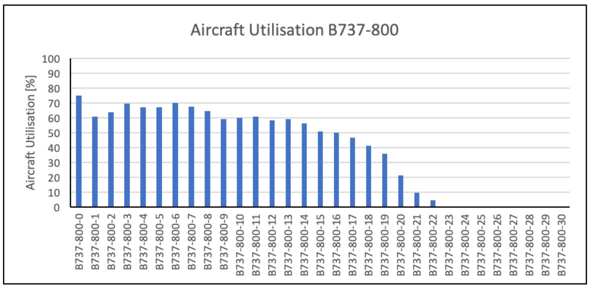


Figure A.8: Aircraft utilisation of all Boeing 737-800 in KLM's fleet.

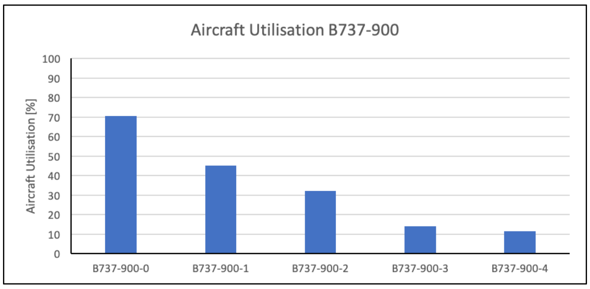


Figure A.9: Aircraft utilisation of all Boeing 737-900 in KLM's fleet.

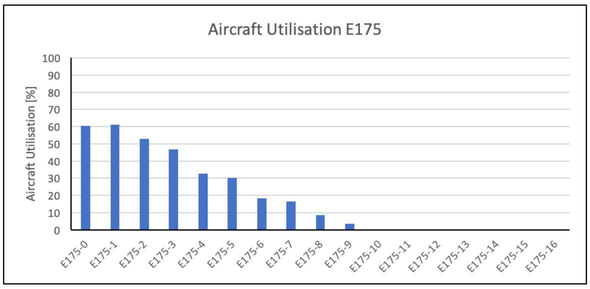


Figure A.10: Aircraft utilisation of all Embraer 175 in KLM's fleet.

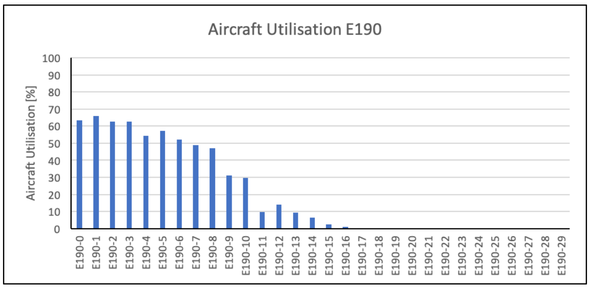


Figure A.11: Aircraft utilisation of all Embraer 190 in KLM's fleet.

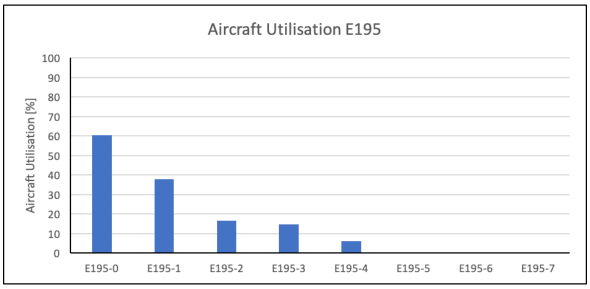


Figure A.12: Aircraft utilisation of all Embraer 195 in KLM's fleet.

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