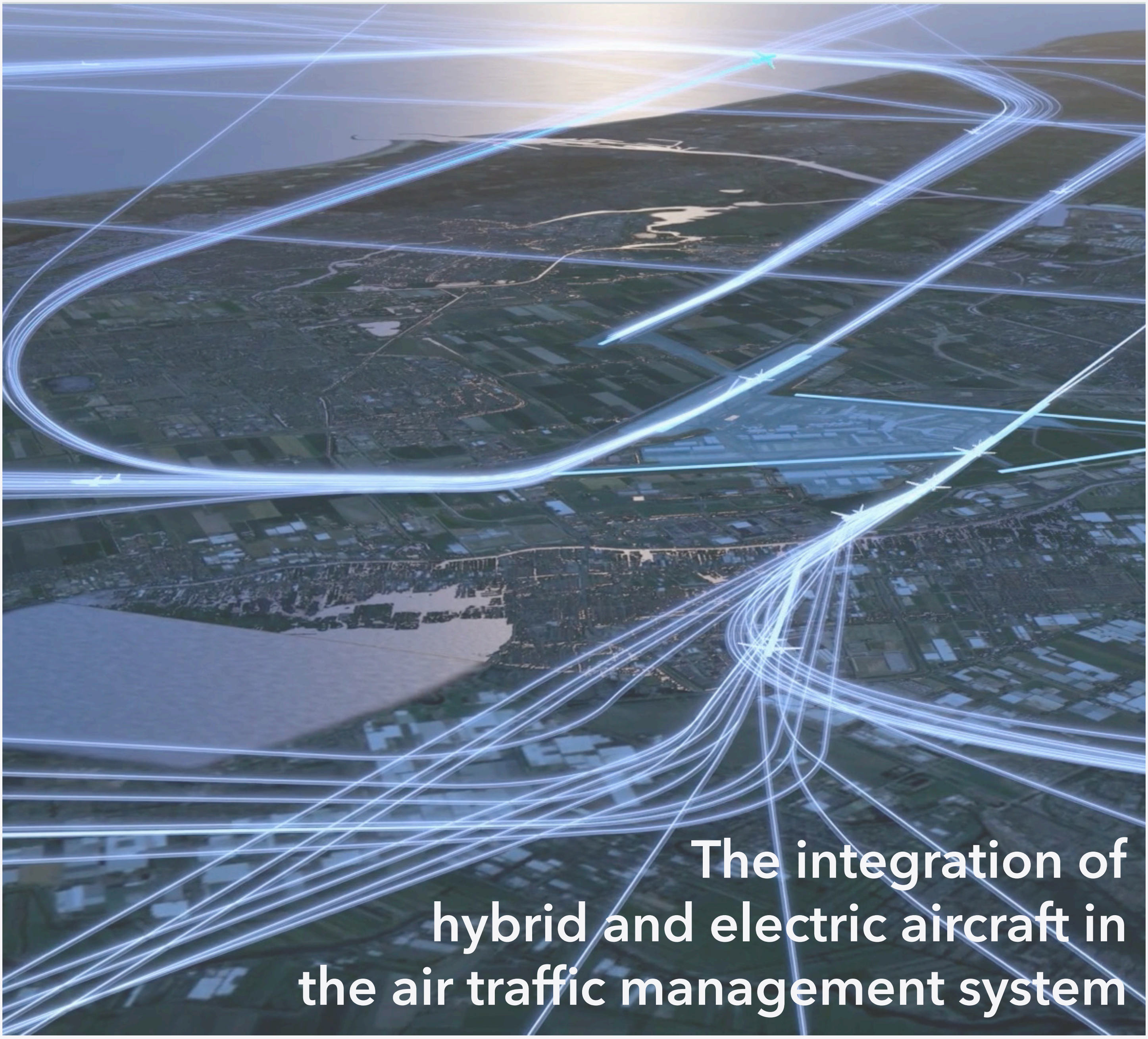

The integration of hybrid and electric aircraft in the air traffic management system

A case study on hybrid and electric aircraft in Dutch TWR and APP operations

Master thesis of:
M.N.A. (Nanette) Lim

TUDelft

LVNL

THE INTEGRATION OF HYBRID AND ELECTRIC AIRCRAFT IN THE AIR TRAFFIC MANAGEMENT SYSTEM

A thesis to obtain the degree of Master of Science at the Delft University of Technology, to be defended publicly on Wednesday June 24th, 2020 at 15:00h

Master of Science in Transport, Infrastructure and Logistics

Thesis committee:
Prof.dr. G.P. van Wee, TU Delft, committee chair
Dr. J.A. Annema, TU Delft, supervisor
Dr.ir. J.H. Baggen, TU Delft, supervisor
Dr. F. Oliviero, TU Delft, supervisor
Drs. B. de Wit , LVNL, strategy expert

by

M.N.A. (Nanette) Lim
4223128

June 2020

ACKNOWLEDGEMENTS

This report is the final product of my MSc Thesis before I graduate as Engineer from the Delft University of Technology. In collaboration with *Luchtverkeersleiding Nederland* (LVNL), I researched potential concepts of operations to integrate hybrid and electric aircraft (HEA) in the air traffic management system. I hope the results of this thesis will be of use to LVNL and the aviation sector in general.

The great thing about aviation is that it brings people together. How wondrous is it that 800 persons can be transferred at such a height. Yet, something got in my way. Is it ethical to work in a sector that I am passionate about, but at the same time is responsible for so many emissions? I deliberately chose to graduate on the subject of sustainable aviation. Finding a thesis internship did not become easier because of this, but I am grateful that LVNL also understands the importance of this.

I experienced the process of my thesis as positive. Mainly because of all the people I spoke to for my thesis. Everyone shared the passion for sustainable aviation and the hope that HEA will become reality. A saying that was mentioned during an interview has stayed with me all along. ”If you want to build a ship, do not gather people to collect wood and assign them tasks and work. Rather, teach them to long for the endless immense sea.” This saying fits in perfectly with this subject.I wanted to contribute more to the arrival of HEA. But more importantly, we all have to believe in the arrival of HEA.

I would like to thank some people. First of all, thanks to Ferdinand Dijkstra, who answered every time I called him and gave me the opportunity to do my thesis at LVNL. Thanks to Bianca de Wit, who was always there for guidance. You took the time to go through my drafts every week. Thank you to all LVNL colleagues who I could always ask questions and for participating in the brainstorm. I would like to thank Arjan van Vliet for the input of my thesis and the pleasant coffee hours that often extended to two hours. And thank you to all the interviewees, who, in addition to providing valuable input, also believe in the arrival of HEA.

Of course I would also like to thank my committee. Jan Anne, in the beginning you gave me courage that I would find an internship with which I could contribute to sustainable aviation. You helped me to structure my thesis and I was always enthusiastic about writing the thesis after talking to you. John, thank you for your critical eye. Even over the weekend you sent me e-mails that there had been a test flight of an electric aircraft. Our meetings always ended in interesting and pleasant conversations. Fabrizio, thank you for the knowledge you gave me about the technical aspects of aircraft. When I really did not know anymore how to make an assumption, you were the one that could help me. And last but not least, thank you Bert for reading my thesis and your critical point of view.

Of course I want to thank my friends who are always there for me, in good and bad times. Thank you Valentijn, for making me laugh when I needed it and always being there for me. You made sure I took my walks, even if I did not realize these are important. A special thanks to my dad, mom, Eliza and Michelle who have always had the utmost confidence and trust in me.

Marie Nanette Alexandra Lim
Amsterdam, June 2020

EXECUTIVE SUMMARY

This research is about the integration of hybrid and electric aircraft (HEA) in the air traffic management (ATM) system. It is a response to the letter regarding the development of Schiphol Airport and the outlines of the *Luchtvaartnota* 2020-2050. The Dutch minister of Infrastructure and Water Management states that "the aviation sector can earn growth through demonstrable reduction of nuisance" [60]. Dutch airlines are responsible for 13 billion kilos of CO_2 and 57 billion kilos of NO_x [8]. The arrival of HEA can decrease emissions and noise nuisance for residents. This research studies potential concepts of operations (CONOPS) to integrate HEA in the ATM-system. Therefore, the research question of this thesis is:

What are potential concepts of operations for the integration of HEA in the air traffic management system in 2035?

Methodology

This research is divided into four phases. The aim of phase I is to structure the context of this problem. With the information found in literature research, interviews and observations, a data analysis and stakeholder analysis were performed.

Since the aim of this research is to find potential CONOPS per scenario, three types of input are needed: KPIs, scenarios and CONOPS. In phase II of this research, these three types of input were explored. The CONOPS are defined with a morphological analysis and a brainstorm. The KPIs are determined in the design space and a scenario analysis defined five scenarios based on exogenous factors. However, since a scorecard consists of two axes and there are three types of input, the scenarios and CONOPS were combined in phase III of this research. In the last phase, the scenario-CONOPS-combinations are assessed on the KPIs. The scores are assigned to the KPIs based on absolute numbers that are calculated with the outcome of the data analysis. With these absolute numbers, normalized scores are given to the KPIs per CONOPS.

Phase I. Structure the context

In the first part of this research a data-analysis and stakeholder analysis were performed. The outcome of the data-analysis defined the deviating performances and effects of HEA compared to conventional aircraft. The main difference between a conventional aircraft and HEA is the replacement of fuel with a battery. Since the power-to-weight ratio of batteries is different compared to fuel, the powertrain of HEA is heavier. This influences three technical performances, namely a decreased passenger capacity, increased landing weight and shorter range. These deviating performances and characteristics of HEA lead to differences in effects. First, a decrease of 80 gram/passenger/km CO_2-emissions. For NO_x a value of 1222 gram/aircraft applies. This means that the implementation of HEA leads to less aviation emissions. In addition, the noise nuisance also decreases with 10 dBa per commercial aircraft. For private jets a noise reduction of 19 EPNdB applies. Indirect effects are as followed: the shift in aviation network from hub-and-spoke to more point-to-point traffic changes due to the minimal range and passenger capacity. Secondly, the operational cost decreases by 20 percent since the cost of fuel no longer have to be paid. Lastly, because of a heavier landing weight, the runway capacity decreases due to an increased Runway Occupancy Time (ROT).

Since many are stakeholders related to this problem, a stakeholder analysis was performed. The constraints, requirements and objectives of stakeholders with high power are taken into account in the design space. It is remarkable that all stakeholders share the same goal to make aviation more sustainable. However, they all have a different interest.

Phase II. Explore types of input assessment

In this part of the research the three types of input for the assessment are explored. This concerns the design space, scenarios and CONOPS.

Design space: The design space is based on the objective, constraints, requirements and KPIs of the air navigation service provider (ANSP) and important stakeholders. The objective states that the CONOPS should be able to handle conventional, hybrid and electric aircraft. That means that the CONOPS should be able to handle both the take-off and landing of these three types of aircraft. The constraints say something about the capacity, safety, regulations or technical performances that the CONOPS must meet. Next to the objective, requirements and constraints the KPIs are determined. These KPIs help to assess the CONOPS per scenario. The KPIs are: runway capacity, complexity of implementation, noise-, CO_2-reduction and NO_x-reduction, possibility to grow, operation cost reduction and total travel time.

Scenarios: The dependent variables of the performances of HEA are still uncertain. That is why five scenarios are determined in a scenario analysis. The scenarios consist of a combination between the exogenous factors technology breakthrough and the decisions of regulations regarding HEA. For each scenario, consisting of a specific combination between the exogenous factors, absolute values are given to the dependent variables. The five scenarios and their corresponding performances and characteristics can be found in figure 0.1.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Positive regulations regarding HEA	None	Positive	None	Medium	Positive
	Technology breakthrough	Low	Low	High	Medium	High
	Percentage HEA in ATM-system [%]	0	5	10	20	25
	Range [km]	0	500	1000	500	1000
	Passengers capacity [pax/HEA]	0	19	100	50	100
	Type of aircraft	N.A.	Private jets	Private jets, airlines	Private jets, airlines	Private jets, airlines
	Type of electrificiation	N.A.	Hybrid and electric aircraft	Electric aircraft	Hybrid and electric aircraft	Electric aircraft
Hybrid aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1	1 (compared to conventional, 100-passengers)	1
Electric aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1,15	1,1 (compared to conventional, 100-passengers)	1,15

Figure 0.1: Performances per scenario

CONOPS: Many ideas for CONOPS have been devised in a brainstorm. The brainstorm was performed with ATM and HEA experts. Three important variables were the outcome of this brainstorm: time, airport and runway. A morphological analysis was applied in order to make all combinations between these three variables. CONOPS that were not feasible or did not meet the constraints were filtered out. The outcome contains of nine CONOPS (A to I), that can be found in figure 0.2.

The aim of phase II is to determine the KPIs, scenarios and CONOPS as input for the assessment. Now that these are determined, phase II can be completed.

Phase III.

Since there are three types of input and a scorecard only has two axes, the scenarios and CONOPS must be combined. The result consists of 27 combinations. However, only the vertices are chosen to do further research on. The vertices are the most interesting combinations that cause the most friction in the ATM-system. They are chosen in a scorecard, based on the constraints and the characteristics of the scenario-CONOPS-combinations. Nine combinations are determined as vertices.

	Time	Airport	Runway
A	Peak hours	Schiphol Airport	Integration
B	off-peak hours	Schiphol Airport	Integration
C	all day	Schiphol Airport	Integration
D	Peak hours	Regional airport	Integration
E	off-peak hours	Regional airport	Integration
F	all day	Regional airport	Integration
G	Peak hours	Schiphol Airport	Integration extra runway
H	off-peak hours	Schiphol Airport	Integration extra runway
I	all day	Schiphol Airport	Integration extra runway

Figure 0.2: Outcome morphological analysis

These combinations are from now on called CONOPS and given a name, as can be seen in figure 0.3. Phase III has now been completed.

CONOPS	Linked to CONOPS	Percentage HEA	Range	Passengers capacity per HEA	Airport	Time	Runway
Bell	1	0	N.A.	N.A.	N.A.	N.A.	N.A.
Edison	2	5	500	19	Schiphol	All day	Oostbaan
Ferraris	3	10	1000	100	Schiphol	Peak-hours	Current runways
Tesla	3	10	1000	100	Schiphol	Peak-hours	Current runways + 1
Siemens	4	20	500	50	Schiphol	Off-peak hours	Current runways
Thompson	4	20	500	50	Schiphol	Off-peak hours	Current runways + 1
Volta	5	25	1000	100	Schiphol	All day	Current runways
Franklin	5	25	1000	100	Regional airport	All day	Current runways
Kelvin	5	25	1000	100	Schiphol	All day	Current runways + 1

Figure 0.3: Characteristics per CONOPS

Phase IV.

The input for the assessments consists of the CONOPS (related to a scenario) and KPIs. Each CONOPS is assessed on the KPIs by first calculating the absolute numbers of the KPIs. This is done by implementing the performances and effects of HEA. Based on the absolute numbers, normalized scores are given to the KPIs per CONOPS. The final score per CONOPS shows which CONOPS fits best per scenario. It was already clear that CONOPS Bell and CONOPS Edison are the best fit in case respectively scenario 1 and 2 become reality. For scenario 3, CONOPS Ferraris has the highest final score. In case scenario 4 becomes reality, it is recommended to implement CONOPS Siemens. For scenario 5, it was also researched what the effect is of implementing HEA at regional airports. This CONOPS Franklin scores best of the three. However, it was striking that CONOPS Volta scores second best. The difference in final scores between CONOPS Franklin and Volta is around 0.5 on a total score around 100. This means that both CONOPS can be implemented.

Conclusion

The outcome of the scorecard answers the main research question. Overall, it can be seen that it is not needed to make use of an extra runway at Schiphol Airport. The decrease in runway capacity is minimal and does not outweight the complexity of the new CONOPS. This conclusion only applies to a maximum of 25 percent of HEA in the ATM-system. It is also possible to relocate up to 25 percent HEA to regional airports as Lelystad Airport and RTHA. Since HEA produce significantly less emissions and noise, HEA make it possible for regional airports to grow without harming residents.

Main recommendations

Since aircraft manufacturers are still exploring the maximum power-to-weight ratio, there is a lack of exact data of the performances of HEA. A data-analysis attempts to make the performances of HEA as robust as possible. However, this does not change the fact that assumptions had to be made for independent variables. It is therefore recommended to repeat this research again in the future with more reliable data. When the maximum power-to-weight-ratio is more reliable, the performances of HEA become subsequently more reliable as well. This mainly concerns the performances MTOW, passengers capacity of HEA, increased ROT of HEA, noise-reduction, range and operational costs. When these data from aircraft manufacturers are more reliable, the CONOPS can also be designed more in detail. In addition, stakeholders used in this study will have a stronger opinion of HEA when the exact data of performances and effects are known.

When the independent variables are more reliable, the outcome of this research becomes more reliable as well. At that moment, it is important to do more detailed research per KPI. Calculations in the scorecard of this research are done roughly which can influence the outcome of the scorecard. These detailed studies also ensure that the results per KPI do not depend on the number of HEA per CONOPS to a great extent. In this research, the number of HEA in the ATM-system has too much influence on the outcome of the scorecard. These recommendations also apply for ANSPs abroad who want to integrate HEA in the ATM-system. The same structure of this research can be used for the specific airports they want to examine.

CONTENTS

LIST OF FIGURES

ACRONYMS

AHEV = *Nationaal Actieprogramma Hybride Elektrische Vliegtuigen*
ANSP = Air Navigation Service Provider
APP = Approach
ATC = Air Traffic Control
ATCO = Air Traffic Controller
ATM = Air traffic Management
CONOPS = Concepts of Operations
HEA = Hybrid and Electric Aircraft
IFR = Instrument flight rules
KLM = *Koninklijke Luchtvaart Maatschappij*
KPI = Key Performance Indicator
LTO = Landing and Take-Off
LVNL = *Luchtverkeersleiding Nederland*
MTOW = Maximum Take-Off Weight
ROT = Runway Occupancy time
TWR = Tower
RTHA = Rotterdam-The Hague Airport

1 INTRODUCTION

This research is about the integration of hybrid and electric aircraft (HEA) in the air traffic management (ATM) system. It is a response to the letter regarding the development of Schiphol Airport and the outlines of the *Luchtvaartnota* 2020-2050. The minister of Infrastructure and Water Management of the Netherlands states that "the aviation sector can earn growth through demonstrable reduction of nuisance" [60]. In her letter, the minister emphasizes that there can no longer be any question of unconditional growth when the advantages and disadvantages of aviation are not balanced for residents. The disadvantages refer to the emissions and noise nuisance of aviation. Dutch airlines are responsible for 13 billion kilos of CO_2 and 57 billion kilos of NO_x [8]. This has led to the continuation of the *Nieuwe Normen- en Handhavingsstelsel* until 2021. Schiphol Airport is restricted to 500,000 air traffic movements per year [60]. This introduction describes the research context, problem and challenges of the study on how to integrate HEA in the ATM-system.

1.1 RESEARCH CONTEXT

One of the solutions to decrease noise, CO_2- and NO_x-emissions is the replacement of conventional aircraft with HEA. At the moment, a lot of research is done by aircraft manufacturers into the technical aspects of these aircraft. This research of aircraft manufacturers is a reaction to the awareness of the negative impacts of aviation and the aim to make aviation sustainable. This awareness has grown with the growth of aviation. 8.2 billion air travelers in 2037 were forecast by IATA [25] but due to the COVID-19-crisis, this growth is uncertain. Nonetheless, the urge for sustainable aviation still remains. Looking at the Netherlands, the *Koninklijke Luchtvaart Maatschappij* (KLM) received state aid in return for more sustainable aviation [47]. In addition, the *Luchtvaartnota*, issued during the crisis, still states that Dutch aviation can no longer emit greenhouse gases in 2070 [41]. That means that a sustainable recovery is of importance after the COVID-19-crisis.

Since the demand for environmental sustainability is growing, *Luchtverkeersleiding Nederland* (LVNL), *Schiphol Group* and other aviation parties such as airlines joined their forces and started the *Nationaal Actieprogramma Hybride Elektrische Vliegtuigen* (AHEV) early 2019. 26 important Dutch aviation parties have joined to make aviation more sustainable. The intention of AHEV is to have reduced the CO_2-emissions in 2030 to the level of emissions in 2005 [61][8]. This is an accelerated route compared to the *Luchtvaartnota* [41]. One of the actions to achieve this goal is to renew the aircraft fleet with HEA. The first generation HEA is expected to take-off and land in 2035 [1].

Many aircraft manufacturers have launched sustainable projects to bring HEA to the market. Boeing started the Boeing SUGAR VOLT program with the aim to design a hybrid aircraft that can transport 135 passengers [7]. Airbus is working on the E-fan X, which is a large commercial aircraft for 100 passengers, is planned to take its first commercial flight within the 2030's timeframe [2]. Since Easyjet wants to own a fully electric short-distance fleet in 2030, they have partnered up with Wright Electric to design the first electric, large commercial aircraft [16]. In a shorter period of time, Eviation aims to have their aircraft Alice certified in one year. Alice is a nine-seater fully-electric aircraft that can fly up to 1000 kilometers [4]. While aircraft manufacturers are engaged in the technical aspects of HEA, this research contributes to the integration of these aircraft in the ATM-system.

1.2 PROBLEM STATEMENT

The problem is that a concept of operations (CONOPS) that integrates HEA in the ATM-system, does not exist. There is little to no knowledge about the integration of HEA on (crowded) airports. To the best of the authors' knowledge, no literature research has been conducted to this issue. This means there is a knowledge gap. In contrast, the architecture and design of HEA is studied widely. But in order to implement HEA on a large scale, it is necessary to study the integration of these aircraft as well. For air navigation service providers (ANSPs) it is important to know what adjustments need to be made to the operation to allow HEA to land at and take-off from (crowded) airports.

1.3 RESEARCH OBJECTIVES

The objective of this research is to close the gap by finding feasible CONOPS for the integration of HEA in the ATM-system in 2035. A CONOPS aims to several proposals for conceptual solutions. It contains a purpose and scope definition, ideas to solve the identified problems, and the consequences for the human, machine and procedures in the ATM-system. In this research a CONOPS means a first assessment of the possibilities of integrating HEA in the ATM-system [28]. Since it is expected that HEA have deviating performances compared to conventional aircraft [24], the technical performances and effects of HEA are analysed (see chapter 4). These (deviating performances of) HEA have to be fitted in between (performance of) conventional aircraft in the ATM-system. It is therefore important to understand the ATM-system which is part the context of this problem. Since there is still a lot of uncertainty regarding HEA, this is an explorative research.

To close the gap, the objective is defined as "Find the potential concepts of operations that integrate HEA in the air traffic management system".

The core task for LVNL is providing air traffic services. Constraints for decisions are safety, efficiency and environment. Safety has the highest priority. These three constraints are also of importance for this study. First of all, safety relates to prevention of incidents in the air and on the ground [35]. Secondly, efficiency will be calculated in air traffic movements per year. Decreasing the emissions and nuisance by integrating HEA in the ATM-system, leads to the possibility to increase the number of movements [60]. Lastly, environment is calculated by the emissions of CO_2, NO_x and noise-nuisance. For these first two key performance indicators (KPIs) it is important to take into account the predicted smaller capacity [passengers per aircraft] of HEA. This means that one aircraft can be quieter but when the total passenger capacity stays equal or increases, more HEA have to take-off and land, which can affect the total noise emissions.

1.4 SCOPE

This study looks into Tower (TWR) and Approach (APP) Air Traffic Control (ATC) operations. These operations consist of take-off and departure, climb, descent, approach and landing. The process of parking, taxi, cruise and taxi to the gate is out of scope. These operations can be seen in figure 1.1. APP accompanies aircraft from the air route to the airport and vice versa for around 50 kilometers around the airport and hand them over to TWR. TWR air traffic controllers (ATCOs) are responsible for aircraft within 15 kilometer around the airport [34] [33].

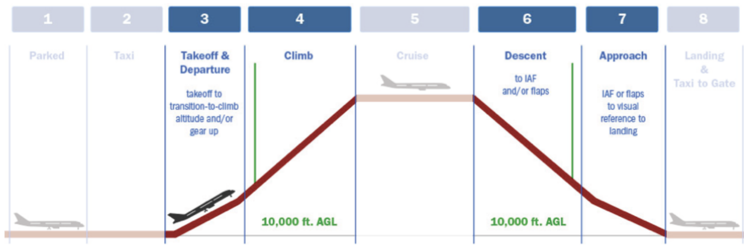

Figure 1.1: Take-off to landing processes

LVNL is also the service provider for Rotterdam-The Hague Airport (RTHA), Lelystad Airport, Groningen Airport Eelde and Maastricht Aachen Airport. As the latter two airports are not within an accessible range for potential transfers to Schiphol Airport (the hub) within 15 years, only Schiphol, Rotterdam-The Hague Airport and Lelystad Airport are within the scope of this research.

HEA consist of passenger flights of large commercial airlines or private jets. Cargo aircraft are out of scope as the current HEA projects focus on passengers, due to the weight they have to take into account. These aircraft fly under Instrument Flight Rules (IFR) where ATCO are responsible for providing separation instructions.

Both hybrid and electric aircraft are part of this research as hybrid aircraft are seen as the intermediate step to electric aircraft [61]. There are three types of electrified aircraft. The first type is the all electric aircraft which no longer uses fossil fuel. The turbo-electric aircraft uses gas turbines to drive electric generators. The third electrified aircraft is the hybrid aircraft that operates partly on fossil fuel and partly on a battery [18][36]. Vertical Take-off and Landing (VTOL) aircraft are out of scope as the aim of these VTOLs are to transfer passengers within cities and do not make use of airports. Hydrogen-powered aircraft are out of scope as well, due to a completely different technical architecture of the aircraft.

Lastly, the integration of HEA in the ATM-system are suitable for both peak- and off-peak hours. Night flights between 23:00h and 06:00h are out of scope.

1.5 RESEARCH QUESTIONS

The problem statement and research objective lead to the following main research question and sub research questions.

What are potential concepts of operations for the integration of HEA in the air traffic management system in 2035?

To be able to answer the main research question, the following sub questions are defined:

1. What are the deviating performances and effects of HEA (compared to conventional aircraft) and the associated consequences for the ATM-system?

2. What is the objective and what are the requirements, constraints and KPIs of the design space?

3. What are possible future scenarios to take into account?

4. What are feasible CONOPS per scenario that are interesting to do further research on?

1.6 RELEVANCE

This study has societal, scientific and company (LVNL) relevance. As is mentioned earlier, it is expected that HEA have positive effects on emissions and noise. The following points indicate the relevance:

Societal importance:

- The result of this research could make it possible that aviation becomes more sustainable as HEA can be integrated in the ATM-system. This is in line with the climate targets that are presented in the *Luchtvaartnota* [41].

- This study contributes to sustainable mobility by connecting countries/cities in a sustainable way.

- The ability to take-off and land with a HEA motivates airlines to purchase more sustainable aircraft.

Scientific importance:

- This is one of the first studies into the implementation of HEA in the ATM-system.

- The methodology used in this study (see chapter 3) is an example for other ANSPs on how HEA can be introduced in the ATM-system. Since it is a first assessment of the possibilities of integrating HEA in the ATM-system, LVNL and ANSPs abroad can start a follow-up research to study more specifically the possibilities for their airport.

- Aircraft manufacturers and knowledge centers can learn from the results what is important for the aircraft design, performances and effects to enter HEA on a large scale in the ATM-system.

Company relevance:

- Since LVNL is a service provider for airlines, they can offer them to take-off and land with a HEA at Dutch airports.

- When the Dutch aviation sector proves that the nuisance decreases for residents, LVNL can facilitate the possible growth of air traffic movement within the framework of the minister.

- Increase the expertise of the company in sustainable aviation.

1.7 RESEARCH APPROACH

The structure of this research is based on system engineering [14] and is adjusted to fit this specific problem. A simplified structure diagram can be found in figure 1.2. The aim of is research is to find potential CONOPS per scenario where HEA are integrated in the ATM-system, based on KPIs. In order to find these, this research is divided into four parts. Firstly, it is important that the context of the problem is clear. Information is gathered with literature research, interviews and participatory observations and structured with a data analysis and stakeholder analysis in phase I.

In phase II of the research, three types of input are explored and defined:

- CONOPS: In order to find CONOPS, a brainstorm with aviation experts was held. The input for the brainstorm consists of the deviating performances To structure the many ideas that came up during the brainstorm, a morphological analysis is applied. (see chapter 7). The feasible CONOPS are the input for the scorecard.
- Scenarios: The scenarios are determined with the help of a scenario analysis, based on exogenous factors (see chapter 6). These exogenous factors are partly determined in the stakeholder analysis (see appendix C). The scenarios are input for the scorecard.
- KPIs: The KPIs are part of the design space. Besides the KPIs, requirements, objectives and constraints are the outcome of the design space process. The constraints are used to filter out not feasible CONOPS (see chapter 5). The KPIs are used to assess the CONOPS per scenario in the scorecard.

Since there are three types of input and a scorecard consists of only two axes, the CONOPS and scenarios are combined in phase III. These combinations are assessed on their feasibility and undesirability in a first scorecard. The constraints, determined in the design space, were leading in the feasibility. The outcome consists of feasible scenario-CONOPS-combinations that are the input for the second assessment. From this moment on, the scenario-CONOPS-combinations are called CONOPS.

Now that there are only two types of input, the CONOPS can be assessed in phase IV. The assessment is based on the KPIs that are determined in the design space process. The outcome of the scorecard answers the main research question. In chapter 3 a more comprehensive and precise design framework is explained.

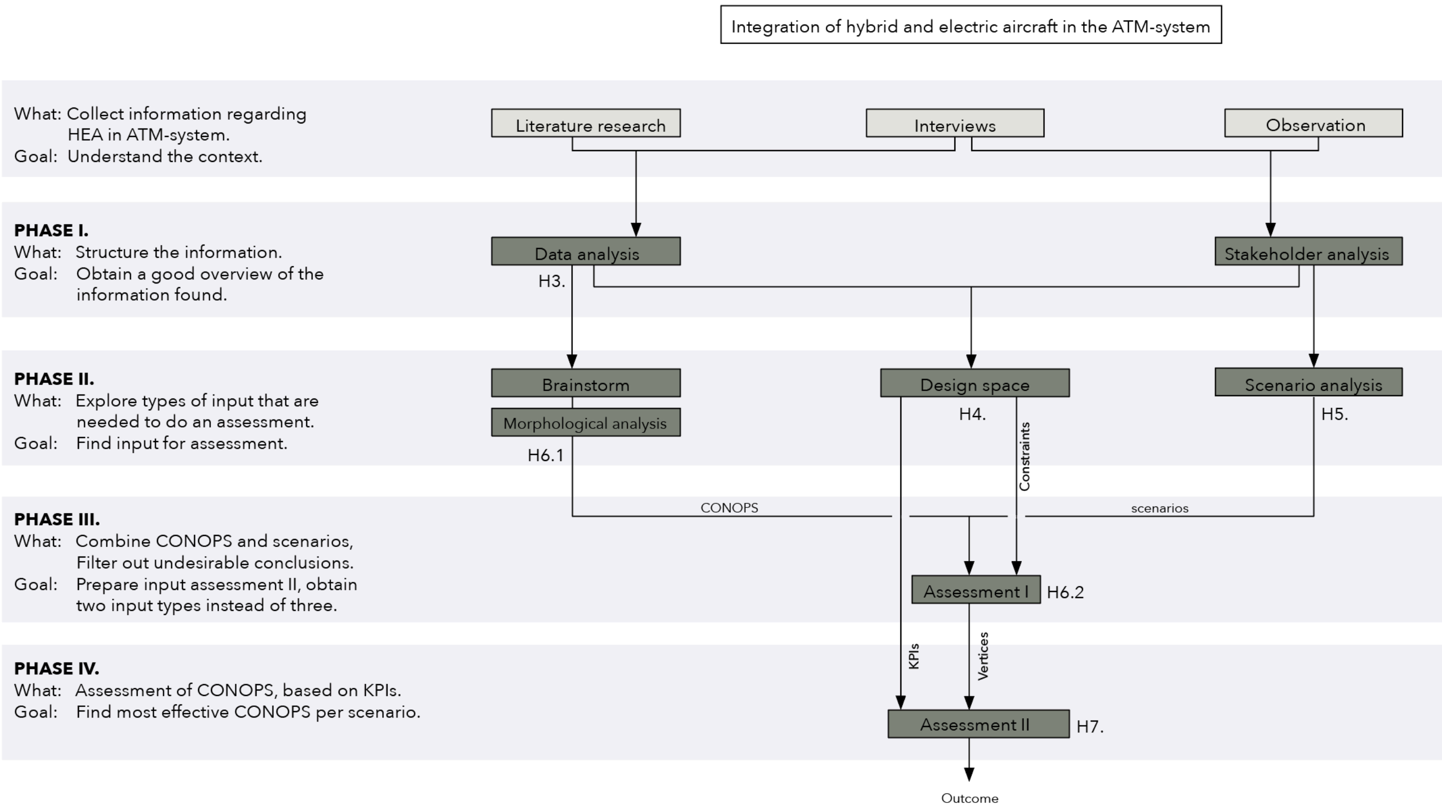

Figure 1.2: Simplified structure diagram

1.8 REPORT OUTLINE

This research starts with an explanation of the methodology in chapter 3. This chapter explains the different methods and tools that are used with the help of a design framework. Chapter 4 explains the deviating performances and effects, the outcome of the data analysis. In order to find the three types of input for the assessment, the design space is determined in chapter 5 and the scenario analysis in chapter 6. In chapter 7, the exploration of different CONOPS is described. Firstly, the outcome of the brainstorm is structured in section 7.2. Secondly, the combinations are made between the scenarios and CONOPS and assessed on feasibility in section 7.3. This section concludes with a description of every chosen combination. In chapter 8 a second assessment is done were the scenarios, CONOPS and KPIs come together in a scorecard. The conclusion of this second assessment shows which CONOPS are potential per scenario. The outcome of this research is repeated in chapter 9 and supplemented with a discussion.

2 THEORETICAL BACKGROUND

This chapter describes the theoretical framework of this research. It shows the analytical concepts and models that have been worked with and their connections. Since there is no clear existing framework that fits this problem, a unique framework is build. In section 2.1, the definitions per model are described that are important in this research. This is followed by chapter 2.2 where the theoretical framework and the connections between the models are explained.

2.1 DEFINITIONS

This section gives the definitions of six concepts that are important in this research. Each concept consists of multiple dependent and independent variables. Dependent variables are the effect of other (independent) variables. Independent variables are variables or which fixes values are established before taking measures, based on literature research.

- Current operations ATM-system: The current operations of the ATM-system are determined based on the performances of conventional aircraft. Since the operations of TWR and APP are dynamic, it still consists of four variables. For example, depending on the wind, time of day, type of aircraft and others, the runway use is determined. They are the input for this research. Since these variables are known and clear, these are dependent variables.

- Performances HEA: The performances of HEA are related to the design and architecture of the aircraft. The performance can also be seen as characteristics. For this research, four important variables are taken into account: the passengers capacity, landing weight, range and RECAT-categories. These variables can be measured in number of passengers, kg, km and categories defined by ICAO [20]. In this study, the variables are the input for further research. This makes these variables independent. For these independent variables, an assumption has been made based on literature research and interviews. A detailed description of the variables and the underlying reasons for determining the assumptions can be found in chapter 4.

- Effects HEA: The effects of HEA are the results or consequences of the performances of HEA. For TWR and APP operations, there are six effects of HEA. These effects can be divided into direct and indirect effects. CO_2, NO_x and noise are direct results of the use of batteries as replacement of fuel. These direct effects are related to the architecture of HEA as well. The indirect effects are the consequences of implementing HEA in the ATM-system on the network, cost for airlines and the operations. The variables are determined based on literature research and interviews and are independent variables. A more detailed description can be found in chapter 4.

- Design space: The design space consist of three variables, namely the constraints, requirements and KPIs. These variables are determined based on the effects of HEA and the current operations of the ATM-system. The variables in the design space are dependent on the variables of the current operations of the ATM-system, the direct and indirect effects of HEA. The design space contributes to this rational decision-making model.

- Scenarios: Scenarios are used to to deal with uncertainties in the future, related to the external environment of the system. Since HEA are expected in 15 years, it is important to take into account various future scenarios. Based on two important external factors, the variables of the scenarios are given an exact value. These variables are dependent on the performances of HEA.

- CONOPS: A concept of operations, also known as CONOPS, is a document that proposes a system. This system is set up from the stakeholders point of view. It is used to communicate the quantitative and qualitative characteristics to management and staff of the company and other stakeholders. After it is approved, the CONOPS will be implemented and used [28]. Since there is a lot of uncertainty in the exact performances and effects of HEA, the aim of this study is to explore which potential CONOPS apply to integrate HEA in TWR and APP operations. This means that the CONOPS in this research have not been worked out in detail. Based on the outcome of this research, potential CONOPS can be further elaborated in a further research. In this study, the four variables runways, airport and time of day for different percentages conventional aircraft and HEA were examined.

2.2 THEORETICAL FRAMEWORK

Figure 2.1 shows the theoretical framework. There are seven concepts in bold which all consist of different variables. The variables are determined in this research and indicated in a rectangle in this theoretical framework. Grey rectangles refer to independent variables, blue rectangles refer to dependent variables. The oval boxes are related to external factors. A distinction has also been made between the connections between models.The dashed arrows and dashed rectangles are connections that are important for the advent of HEA but are excluded in this study. A further statement about these are made in the discussion in chapter 9. In addition, the red arrow related to the constraints indicates that the constraints are decisive. The orange arrow indicates that the requirements can be part of a trade-off.

The aim of this study is to find potential CONOPS for the integration of HEA in the ATM-system in 2035. The details of the CONOPS depend on the outcome of several other concepts. First of all, the current situation of the ATM-system is the existing situation and location in which HEA must be integrated. The important independent variables of the current operations regarding HEA are filtered and are input for the design space. secondly, the design space depends on the constraints, requirements and KPIs of the decision maker and the stakeholders involved. The design space consists of multiple constraints, requirements and KPIs. The design space ensures that the CONOPS are feasible, efficient and sustainable. Lastly, the performances of HEA are of great importance for the CONOPS since HEA are the new type of aircraft that must be integrated. It is determined that the performances of HEA consists of six dependent variables that influence the CONOPS. Based on literature research, it is determined that five variables are important for TWR and APP operations, namely the passenger capacity [5], landing weight [10], range [48], RECAT-categories and approach and landing speed. The range, landing weight passengers capacity and the approach and landing speed are related to each other. A detailed explanation of the variables and their dependency can be found in chapter 4. There is still a lot of uncertainty what the exact values of these five variables are going to be. Therefore, different absolute values are given to these variables per scenario. The scenarios are based on external factors, namely regulations concerning HEA and technological breakthrough. The range, passengers capacity, approach

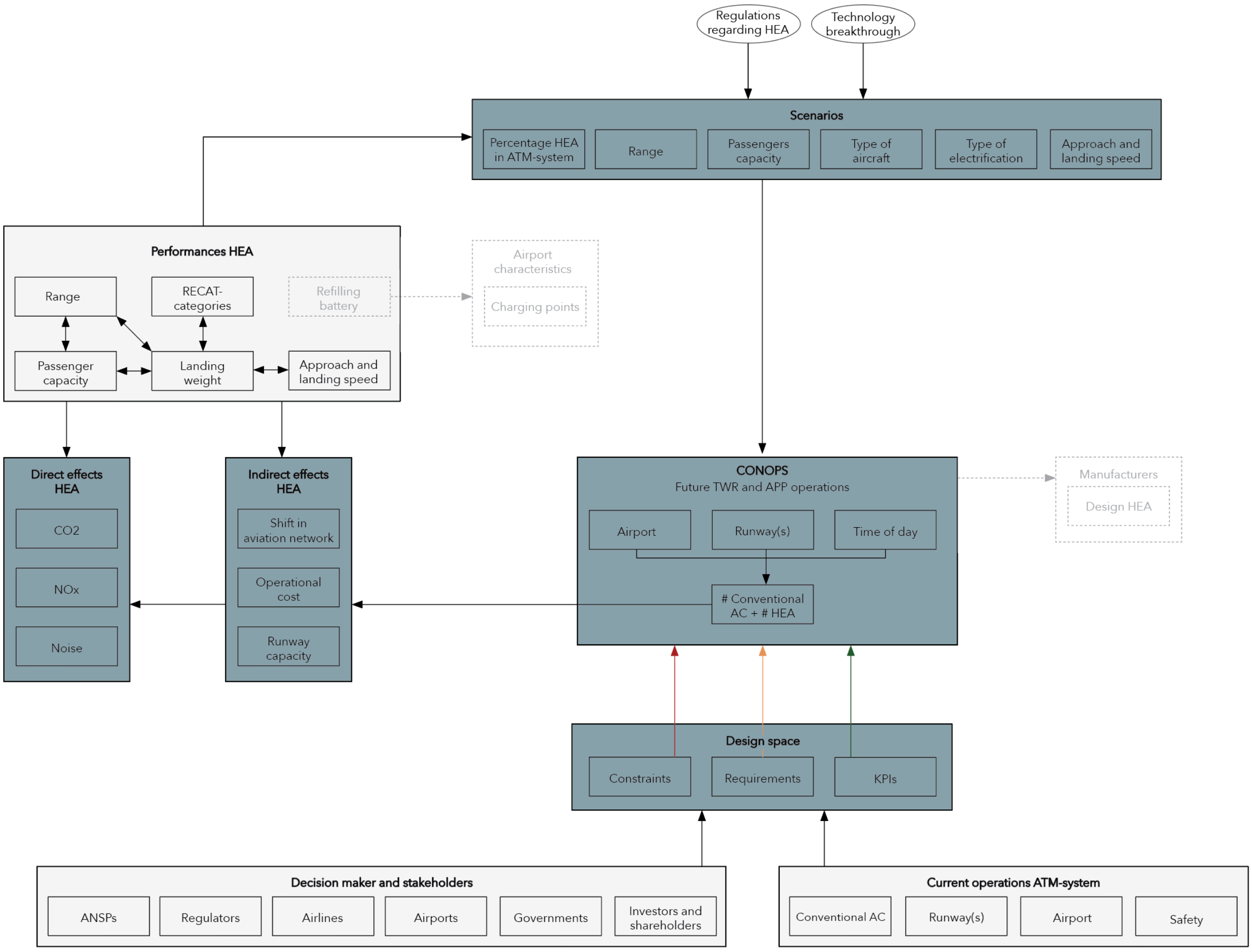

Figure 2.1: Theoretical Framework

and landing speed are reflected directly in the scenario variables. In addition, the percentage of HEA in the ATM-system, type of aircraft and electrification are variables of the scenarios that are based on literature research and interviews. A detailed description of the scenarios and its variables can be found in chapter 6.

Based on the variables of the scenarios and the design space, the independent variables of the CONOPS are determined. The CONOPS contain three independent variables runways, airport and time of day. The interpretation of the variables differ per scenario. The combinations of these variables result in a specific number of conventional aircraft and HEA. The diverging process of finding as many CONOPS possible can be found in chapter 7. In chapter 8, the CONOPS per scenario are converged based on the design space. After the CONOPS are determined, the total effect of these independent variables can be calculated based on the number of conventional aircraft and HEA per CONOPS per scenario. These calculations consists of the number of HEA per CONOPS and the effects per HEA as consequence of the deviating performances. A more detailed description of the latter one can be found in chapter 4. A distinction is made between direct and indirect effects. The effects consists of six independent variables. An explanation can be found in chapter 4. These effects are important for making TWR and APP operations more sustainable and efficient.

3 METHODOLOGY

Now that the research gap is clear, this chapter explains the methodology that is used for this research. Section 3.1 contains an overview of the design framework that is applied in this research. This design framework is based on system engineering. The methods and tools used in this research are explained more in detail in section 3.2.

3.1 DESIGN FRAMEWORK

The design framework (figure 3.1) is specified to come up with concepts of operations where HEA are integrated in the ATM-system. The used methods and tools are indicated in green and the output in blue. The methods and tools marked with a gray square are linked to a chapter. The methods and tools that do not have this gray square are supportive and are explained in an appendix or can be found in the chapter they are supporting. The methodology is based on system engineering [14] and adapted to this specific problem.

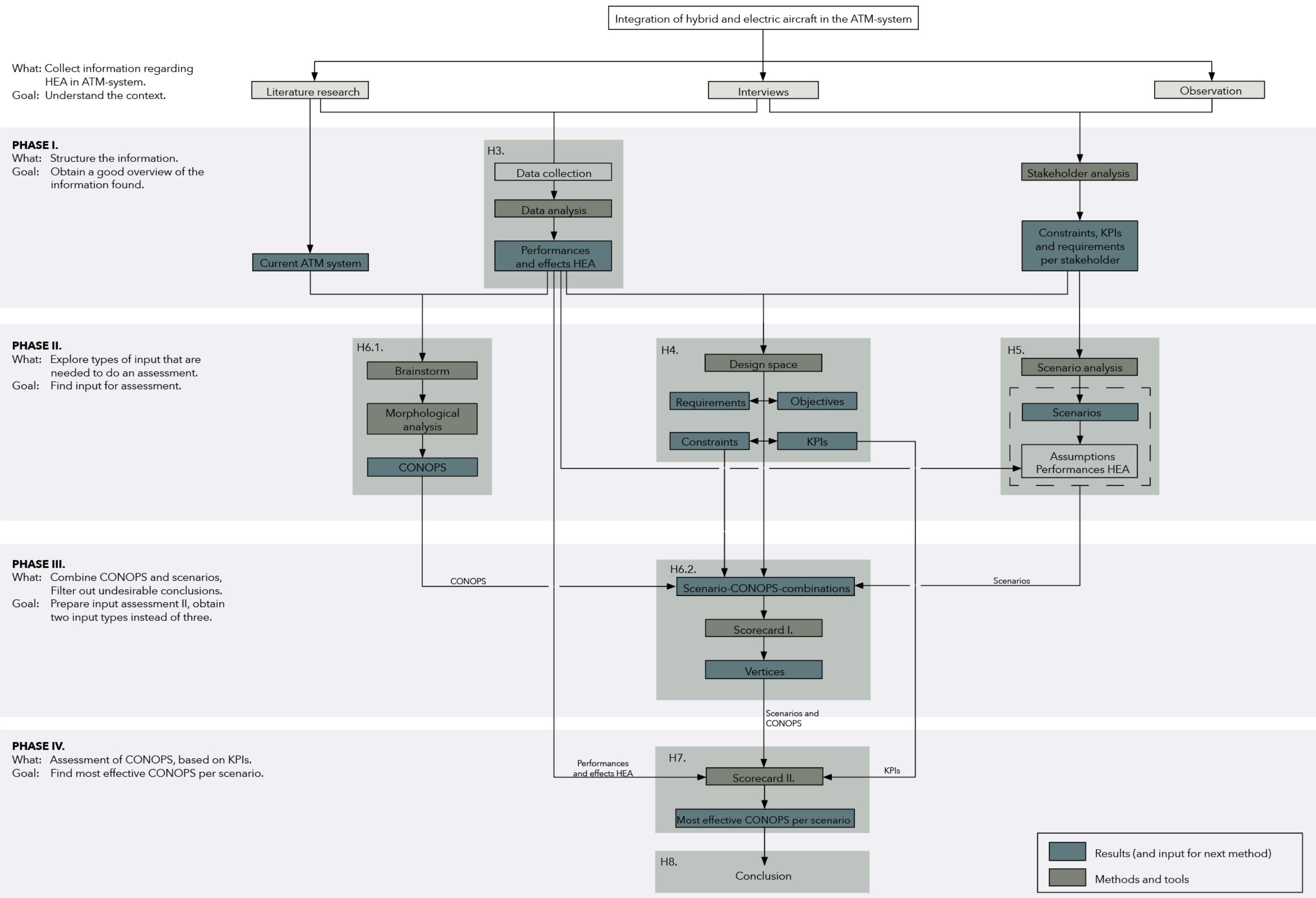

Figure 3.1: Design Framework

Phase I: Context analysis
Methods and tools used: Data analysis, stakeholder analysis
First of all, it is important to understand the context. To do so, a data analysis and stakeholder analysis were performed. Literature research and interviews are used to collect data which form the starting point for the data analysis. This data analysis studies the expected performances and effects of HEA in 2035 (see chapter 4). A stakeholder analysis is carried out based on interviews and participatory observations (appendix C). The ATM-system is complex and many stakeholders are associated with this subject. The stakeholder analysis gives insight into the constraints, objectives and requirements of stakeholders. Now that the context is clear, the stakeholder analysis, performances and effects are the input for the design space (chapter 5), scenario analysis (chapter 6, brainstorm (appendix F) and scorecard (chapter 8).

Phase II: Determine input assessment
Methods and tools used: Design space, scenario analysis and brainstorm
The aim of this research is to find potential CONOPS per scenario where HEA are integrated in the ATM-system, based on KPIs. This assessment is done with a scorecard that consists of KPIs, scenarios and CONOPS. The second phase consists of determining these three types of input, based on the context analysis that is done before. These three types of input are:

1. KPIs: the KPIs are determined in a design space, along with the constraints, requirements and objectives (chapter 5). The integration of HEA is dependent on many stakeholders. It is therefore important to include the constraints, requirements and objectives of (the important) stakeholders. That is why the stakeholder analysis forms the input for the design space. The performances and effects that are the output of the data analysis are also important for the design space. The deviating performances indicate which constraints and KPIs are important.

2. Scenarios: the scenarios are determined with the help of a scenario analysis (chapter 6). The scenario analysis is based on exogenous factors. It is therefore important to include the viewpoint of all stakeholders that are determined in the stakeholder analysis. However, it is considered what the power and interest are per stakeholder.

3. CONOPS: a brainstorm was carried out in order to design multiple CONOPS for integrating HEA in the ATM-system (appendix F). The outcome of the brainstorm consists of three variables: time, airport and runway. A morphological analysis was used to find all possible combinations of these three variables. In addition, the combinations between the three variables that are not feasible based on the constraints, were filtered out (chapter 7, section 7.2). The outcome contains of 9 different CONOPS.

Phase III: Preparation final assessment
Methods and tools used: Scorecards I
A problem that came up is that a scorecard only has two axes, while there are three types of input (CONOPS, scenarios and KPIs). It is therefore important to combine the scenarios and CONOPS in order to receive two types of input for the scorecard (chapter 7, section 7.3). The outcome concerns 27 combinations. A first scorecard was applied to find the vertices of these scenario-CONOPS-combinations, since it is not usefull to assess all 27 combinations. The choice of vertices is based on the pressure on the ATM-system and not feasible combinations between scenario and CONOPS are filtered out.

Phase IV: Final assessment
Methods and tools used: Scorecards II
From this moment on there are two types of input: The KPIs that are the outcome of the design space and the scenario-CONOPS-combinations. The latter one is called from this moment on CONOPS. This means that a scorecard can be applied to find potential CONOPS per scenario where HEA are integrated in the ATM-system, based on KPIs (chapter 8). Using the performances and effects that are determined in the data analysis, absolute numbers are given to each KPI per CONOPS. Based on these absolute numbers, the CONOPS are assessed with normalizes scores. The outcome of this scorecard answers the main research question.

3.2 METHODS AND TOOLS

This sections describes the methods and tools that are used during this research in detail.

Literature study
Researching literature has been done by using several search engines as Scopus, Google Scholar and WorldCat. To find relevant scientific articles, (combinations of) keywords were used as: hybrid aircraft, electric aircraft, HEA, Air Traffic Management, approach, tower, aeroplane, aircraft, plane, performances, effects, integration, application, operations strategies, concept of operation. When results came up, first they were studied based on a quick scan of the content, source, journal, citations and year of publication. When these were positive, secondly the abstract was viewed and eventually the paper was read in a more detailed way. In the latter case, other relevant papers where found due to the references used in the paper. The number of scientific papers related to the integration of HEA in the ATM-system was limited. The limited amount of scientific papers that were useful are part of this research. In addition, the literature study is supplemented with non-scientific papers. Examples are commercial websites of aircraft manufacturers, articles in aviation magazines and articles of airlines and aviation regulators.

Interviews
The complex situation in which the problem is situated was partially determined with the use of semi-structured interviews, held with experts in the aviation field. These interviewees are chosen based on the stakeholder analysis, their importance and interest in HEA. A semi-structured interview was prepared beforehand with questions where there was still room for flexibility during the interview [19]. This way, necessary information was provided by the interviewee and possibly unknown information that could be important for the research came to light. For example, it has occurred that interviewees came up with certain subjects, topics or projects that are related to HEA or the ATM-system. These were further explained during the interview and studied in detail after the interview using literature research. Experts and stakeholders that were interviewed are presented in the table below, including the sub-questions (see section 1.5) they helped to answer. The figure includes the participatory observations as well.

Participatory observation
To obtain the most in-depth information possible, interviews with ATCOs and pilots were held during participatory observation. For example, during a shift of an ATCO, an interview was held in between his proceedings. This way, the air traffic controller could also explain the acts he performed and why they are important. Participatory observation has also been done during a flight. The pilot and co-pilot explained in detail what they were doing during a flight and reflected on the differences when it would be a HEA. The work procedures of ATCOs and pilots have

Company	Function	Stakeholder/expert	Interview/observation	SQ
KLM	Captain and co-pilot	Expert	Participatory observation	1
LVNL	ATCO TWR/APP	Expert	Participatory observation	1
LVNL	ATCO ACC	Expert	Participatory observation	1, 4
LVNL	ATCO TWR/APP	Expert	Interview	4
KLM	Director Fleet evaluation	Stakeholder	Interview	2, 3
DEAC	CEO	Stakeholder	Interview	2, 3
	Public Relations manager	Expert	Participatory observation	2, 3
Boeing	Team leader Boeing Sugar Volt	Stakeholder	Interview	1, 2, 3
Airbus	Vice President, Head of Global Innovation Network Power & Flight Propulsion, Energy & Control	Stakeholder	Interview	1, 3
TU Delft	Professor CNS/ATM	Expert	Interview	2, 3
Advisor	Lucht- en Ruimtevaart Nederland	Expert	Interview	1, 2, 3, 4
NLR	Electric flight programme manager	Expert	Interview	1, 2, 3, 4

Figure 3.2: Interviews and observations

also shown what is important for them to deliver good (and therefore safe) work. This has been included in the stakeholder analysis. The interviews and participatory observations can be found in appendix A.1

Stakeholder analysis
The outcome of the interviews and participatory observations are used as input for the stakeholder analysis. The introduction of HEA brings along a big impact on many stakeholders in the aviation sector and each stakeholder has different problems, interests and solutions to deal with HEA. The stakeholder analysis gives a clear image of the context of the problem. Firstly, a list of stakeholders has been compiled. Secondly, their formal relations are identified in a map. In the next step of the stakeholder analysis the interests, objective, causes and possible solutions per stakeholder are described. Lastly, the stakeholder are classified into a power-interest grid. The steps taken in the stakeholder analysis are based on Enserink's methodology [17] and can be found in appendix C.

Data analysis
To retrieve the performances of HEA, a data analysis was carried out using a data analysis. The data-input consists of expected performances of HEA that have been found in scientific papers, websites of aircraft manufacturers and interviews with Airbus (see A.8) and Boeing (see A.4). Since there is still a lot of uncertainty, it was decided to look at the performances per passenger capacity and the RECAT-category of HEA. RECAT-categories are based on the characteristics of an aircraft and are used to determine the minimal separation between two aircraft [20].

The performances of HEA for commercial use were mainly used, as they are the most interesting for this research. It is also important to know what the performances of conventional aircraft are, since conventional aircraft (and their performances) are also part of the new CONOPS. A data set has been delivered by LVNL that contains all aircraft that have landed or taken off from Schiphol airport, including aircraft type, layers, indicated airspeed and rate of climb per aircraft. Based on their RECAT categorization, the important averages of performances of conventional aircraft were determined. These were compared with the expected performances of HEA. The conclusions of the data analysis can be found in chapter 4.

Scenario analysis
The scenario analysis explores the possible future scenarios of HEA. Contextual factors, driving forces and their impacts and uncertainty are determined and scenarios are sketched, based on the stakeholder analysis. The process of the scenarios analysis is based on the scenario analysis steps described by Enserink et al [17]. The future scenarios can be influenced by economic, political and technical aspects by

actors as the Ministry of Infrastructure and Water management, aircraft manufacturers and airlines. The scenarios that are the output of this analysis consists of characteristics like the percentage of HEA in the ATM-system and characteristics of HEA. A detailed description can be found in chapter 6.

Brainstorm
To come up with different CONOPS, a design thinking method is applied in the form of a brainstorm session. During the brainstorm it is important to diverge and come up with many possibilities. The participants of the brainstorm are experts out of the field, e.g. employees of LVNL and experts in HEA. Since the participants know how the current air traffic management system works, it is important to encourage participants to look broadly and to think about not-obvious designs. Due to circumstances, the brainstorm was held individually at first. The participants received a form that guided them during their individual brainstorming. In order to keep control over a brainstorm at a distance, the brainstorm consisted of a case study that was constructed of four parts. An advantage of an individual brainstorm is that there is an absence of criticism and negative feedback. This stimulates the creativity of the participants which increases the quality of the outcome of this brainstorm [42]. The outcome of the individual brainstorm was discussed during a meeting with the participants. After each round, the question was asked if someone came up with new CONOPS. The final outcome of the brainstorm showed that there were three different variables (time, airport and runway) that came back in every CONOPS. These variables are the input of the morphological chart. The process of the brainstorm can be found in appendix F.

Morphological analysis
After the brainstorm, the morphological chart is created, based on the steps of Ostertagová et al. [43]. The morphological chart combined the three variables that came up during the brainstorm. Each variable consists of different building elements that were though of during the brainstorm. An identification of all combinations of building elements was made which lead to multiple combinations. These combinations were analysed and the ones that are not feasible, were eliminated. The outcome of the morphological analysis can be found in chapter 7.

Scorecard I: scenario-CONOPS-combinations
Since the aim of this research is to find potential CONOPS per scenario, a first scorecard is applied to make all combinations between CONOPS and scenarios. Based on the pressure on the ATM-system of each combination, not feasible combinations are filtered out and vertices are chosen with the help of ATCOs. Vertices are the most interesting combinations to do further research on. The pressure on the ATM-system is calculated based on the following characteristics:

1. Number of runways (characteristic of CONOPS)
2. Percentage HEA (characteristic of scenario)
3. Specific time (characteristic of CONOPS)
4. Current pressure on ATM-system (characteristic of CONOPS)

Scorecard II: CONOPS - KPIs
The vertices of the scenario-CONOPS-combinations, from now on called CONOPS, are assessed with the help of a scorecard. The CONOPS are assessed based on different KPIs that are determined in the design space. First the absolute numbers per KPI are determined. This was possible to do with the performances and effects of HEA. Based on these absolute numbers per KPI, a normalized score between 0 and 1 is given, where zero is the lowest score (worst performing CONOPS per KPI) and 1 the highest (best performing CONOPS per KPI). The KPIs are also given a

weight of importance, to make the scorecard more reliable. ATM experts and ATCOs helped assessing the CONOPS. The final scores per CONOPS indicates which of the CONOPS is a potential CONOPS to integrate HEA in the ATM-system. The CONOPS can be compared with each other per scenario. In addition, there is also the option to compare all CONOPS with each other (regardless of the scenarios).

4 PERFORMANCES AND EFFECTS OF HEA

CONOPS are to a large extend based on the technical performances of aircraft. In order to integrate HEA in the ATM-system, it is important to know what the performances of these aircraft are. The effects of HEA can show what the consequences are per CONOPS. The performances and effects that are important for the CONOPS are determined based on literature research and interviews and supported with the data-analysis. The data-analysis can be found in appendix B. This chapter starts with a short description of the data-analysis that is performed in section 4.1. In section 4.2 the deviating technical performances of HEA are explained. The performances lead to effects of HEA that are described in section 4.3.

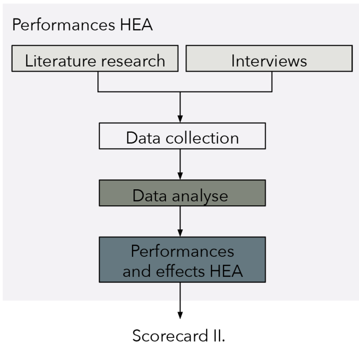

Figure 4.1: Technical performances HEA

4.1 DESCRIPTION DATA-ANALYSIS

A short description of the data-analysis is given before a statement can be made about the exact deviating performances and effects. Based on the literature research, it can be concluded that there is still a lot of uncertainty in the exact values of deviating performances and effects since the maximum power-to-weight ratio of batteries has not yet been reached [57]. In order to use the right results, a data analysis is performed on the performances of 36 concept HEA. These performances are collected from Roland Berger [57], ICAO [27] and complemented with information online from aircraft manufacturers and from interviews with Airbus (A.8) and Boeing (A.4). These performances were adjusted several times by the manufacturers during this research, which shows the dynamics and speed in improvements of this innovation. However, since not all companies and start-ups publish the data of all performances, there are some gaps in the overview. This makes the analysis a complementary and supportive tool to substantiate the literature research and interviews.

The data analysis also checked whether the results of the literature research and interviews correspond with the data in the overview. Overall this was the case. In addition, the data analysis determined if there is a correlation between multiple variables. These correlations can be found in the next section. The full data-analysis can be found in appendix B.

4.2 TECHNICAL PERFORMANCES AND CHARACTERISTICS

The main difference between a conventional aircraft and HEA is the replacement of fuel with a battery. One of the barriers for enabling new propulsion systems is the battery density. Research shows that there is potential to close this technology gap. At the moment, the battery density is beneath the needed performances. For example, a 50 kg electric motor with a power output of 260 kW is developed. However, the required power for a commercial aircraft is 2-50 MW [3]. The weight of a lithium battery-ion battery pack is expected to decrease by 60 percent before 2030 [57]. In order to reach this goal, more research is needed to find the optimal power-to-weight-ratio. The difference in weight of the powertrain leads to (technical) performances that differ from the performances of conventional aircraft:

- **Passenger capacity per HEA:** Even though it is expected that the weight of the battery decreases, the powertrain will still be heavier compared to conventional aircraft [55][50][22][9][46]. In order to compensate this extra weight, the weight of the passengers is reduced. This means that HEA can transfer fewer passengers per aircraft [5]. This is confirmed by Boeing as well (see interview A.4). The data analysis shows that the majority of the concept HEA can transfer up to 19 passengers. These are often concept HEA that are used by aircraft manufacturers to study the possibilities of HEA with a bigger passenger capacity. Only five concept HEA can transfer 40 to 135 passengers (see appendix B, figure B.2).

- **Landing weight:** Another difference compared to conventional aircraft is that the weight of the powertrain does not decrease over the flight [10]. Due to the increased landing weight, the approach and landing speed increases as well. This means that HEA need a longer landing field on the runway and a longer Runway Occupancy Time (ROT). Figure 4.2 shows he sequence as effect of the increased powertrain weight.

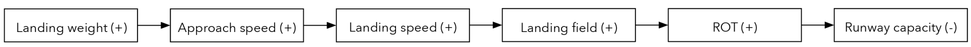

Figure 4.2: Sequential effects of increased landing weight

  In case of HEA that have a passenger capacity of 19 persons or less, the assumption is made that the approach speed of HEA is equal to the approach speed of conventional aircraft. The assumptions are also made for HEA with a passenger capacity of 19-50, 50-70 and 70-120 passengers. In that case the increase in approach speed is respectively 5, 10 and 15 percent. The assumptions are based on the difference between Maximum take-off weight (MTOW) HEA and the landing weight of conventional aircraft. In section 4.3 a further explanation is given about the effects (increased landing field, ROT and decreased runway capacity).

- **Range:** The power-to-weight ratio effects the range of the aircraft [5][48]. Since the power is limited, the maximum range of the aircraft is expected to be around 1000km. This is endorsed by aircraft manufacturers (see interview A.4 and A.8) and can also be seen in the data-analysis. Regulations require that there will be enough fuel on board for the flight to be completed safely and for the alternate airport specified in the navigation plan to be reached, in case of unexpected events [44]. These guidelines were also followed during the observation flight that can be found in appendix A.1. It is expected that these rules will also apply to HEA, which means that these aircraft can fly up to about 750km. The percentage of flights up to 750 km with conventional aircraft equals 38 percent of the total aircraft at Schiphol Airport [13]. HEA with a smaller range of 500 km, can only reach destinations within 300 km.

Aircraft manufacturers aim to design HEA with as limited outstanding technical performances as possible compared to conventional aircraft (see interview A.8). This means that a 33 percent increase of the powertrain weight must be compensated with other characteristics [12]. The data-analysis proves that the total weight of HEA increases compared to conventional aircraft but are still assigned the same RECAT-category D or E. This means that the wake-vortex separation is similar as well [20]. The coherence between the characteristics of HEA due to the powertrain can be found in figure 4.3. This coherence can also be seen in the data-analysis (see appendix B, figure 6.4), where aircraft with a relatively high passenger capacity have a low range and vice versa.

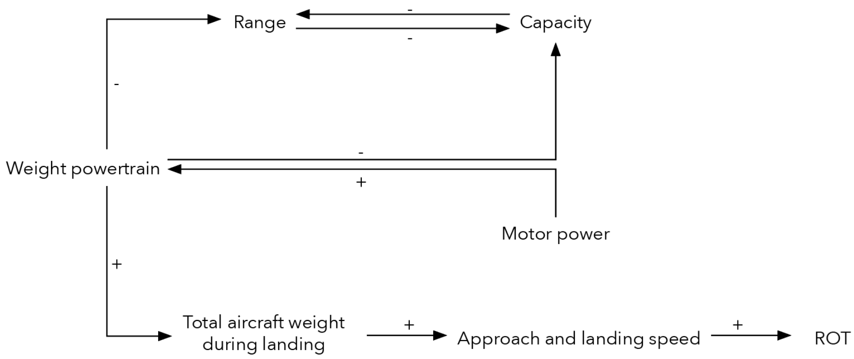

Figure 4.3: Performances and their connections [5]

4.3 EFFECTS OF HEA

The deviating performances and characteristics of HEA lead to differences in effects of HEA, compared to conventional aircraft. One of the main advantages of HEA is that it leads to reduction of CO_2-emissions, NO_x-emissions and noise. In addition, the arrival of HEA also influences the shift in the aviation network and operational costs of airlines.

- **CO_2:** Air-France-KLM found out that in 2018, CO_2-emissions per passenger-km is 80 gram. The revenue passenger-kilometers in that year was 107,676 million [29]. In case of electric aircraft, CO_2-reduction is 100 percent, since these are specific emissions for combustion engines. For hybrid aircraft applies that the fuel consumption decreases up to 40 percent [62]. That means that the CO_2-emissions decreases with 48 gram/passenger/km.

- **NO_x:** NO_x-emissions are also a specific emissions for combustion engines. The NO_x-mass is calculated for the (LTO) flight phases TWR and APP and equals 1222.14 gram [15][5].

- **Noise:** The higher mass flow and lower exhaust speed of the electric propulsors compared with conventional turbofan engines lead to less noise. UTC studies conclude that commercial hybrid and electric propulsion reduces aircraft noise by up to 85 percent [62]. Looking more in detail, the American Institute of Aeronautics and Astronautics calculated that electric aircraft have a noise decrease of -10 dBA compared to conventional aircraft of similar size (for outside sound pressure levels). For private jets the noise decrease is 19 EPNdB [37].

- **Shift in aviation network:** The shift in the aviation network is an indirect effect of HEA. Due to the short range and limited passenger capacity, it is likely that HEA are mainly used for point-to-point traffic. This also has to do with the expectations of passengers and the general efficiency of aviation. The European Union set the goal for 2050 that passengers can travel door-to-door within a 4-hours time limit [11]. The share of HEA in this concept is confirmed by experts, as can be seen in the interviews A.3, A.5, A.6, A.7 and A.8. The importance of regional airports increases due to the 4-hours door-to-door concept. Regional airports are often easier to reach and the expected arrival time of passengers for the flight departures is shorter. However, the nuisance caused by aircraft and the accompanying resistance from the residents is what holding back growth at regional airports. HEA solve this problem as they cause less nuisance. The shift occurs from hub-and-spoke-network to more point-to-point flights.

- **Operational costs:** Another indirect effect of HEA is the operational cost for airlines. The total operating cost for an aircraft is the sum of the costs for insurance, cabin crew, landing and ATC fees, fuel, maintenance, ownership and others [56]. In case of HEA, airlines do not have to pay the high price for fuel anymore. Because of this, the airlines operating cost for HEA are reduced by up to 20 percent [62].

- **Runway capacity:** It is determined in section 4.2 that the landing weight does not decrease over the flight [10]. This is also confirmed by Boeing and Airbus (see interview A.4 and A.8). The consequence is that the runway capacity decreases as can be seen in figure 4.2. Looking at only the TWR operations of Schiphol Airport, the capacity of aircraft per hour is 120 aircraft for peak-hours and 80 for off-peak hours [38]. This allows a total maximum capacity of 540,000 movements per year. The effect of an increased approach and landing speed is an increase in landing field and ROT. Similar increased percentages can be applied on the landing field and ROT. The landing field length of a conventional aircraft, for example an 100 passengers Embraer190, is 1226m. That means that one HEA with 100 passengers needs a landing field length of 1410m. This is still within the lengths of the runways of Schiphol and the regional airports [52]. Based on the maximum capacity of a runway, the average ROT plus wake-vortex separation of a conventional aircraft is 1.5 minutes. In case of a HEA with 70 to 120 passengers, the ROT becomes 1.725 minutes. In the end, the increase of ROT and the wake-vortex separation lead to a capacity decrease [31]. The absolute numbers of the increased ROT and the needed landing field length are important to complete the scorecard in chapter 8.

As is mentioned before, the reduction in CO_2, NO_x and noise, is less for hybrid aircraft compared to electric aircraft since the powertrain still runs on fuel. The emissions and noise pollution of hybrid aircraft vary per mode of operation. A pilot can choose for the noise- and CO_2-reduction mode or the economic mode. When a pilot chooses for the first mode, the aircraft will use the battery for take-off and landing which means that residents experience less nuisance. When the pilot chooses for the economic-mode, the noise and CO_2 nuisance will not reduce (see interview A.4) [6]. In this research, the assumption is made that pilots choose to use the noise- and CO_2-reduction mode. This means that the noise-, CO_2- and NO_x-reduction is similar to electric aircraft during TWR and APP.

4.4 CONCLUSION

This chapter described the performances and effects of HEA. The difference in weight of the powertrain due to the power-to-weight ratio of the batteries, results in deviating performances of HEA. The performances that differ are the passenger capacity per aircraft, the landing weight and the range. Besides the performances, there is a positive effect on noise, CO_2- and NO_x-emissions. Indirectly, the advent of HEA also influences a shift in aviation network, the operational costs for airlines and the runway capacity. The deviating performances are important for the interpretation and determination of the scenarios and CONOPS in chapter 6 and chapter 7. The effects are used to determine the scores of the scorecard in chapter 8. Now that the deviating performances and effects have been determined, phase II of this research can be started in the next chapter.

5 DESIGN SPACE

The ATM-system in which HEA are integrated, is complex and HEA are a complete new innovation in the aviation sector. Many stakeholders are involved, each with different problems, interests and situations related to these HEA. Each stakeholder has its own objectives, requirements and constraints of which some are passed on to the ANSP. Therefore it is important to define a design space. In order to know what the boundaries are of the design space, the objective, requirements, constraints and KPIs are determined. In figure 5.1 it can be seen that literature research, interviews and participatory observations are used in order to perform a data analysis (see chapter 4) and stakeholder analysis (see appendix C). The outcome of these two analyses are the input for the design space. This chapter starts with an introduction of the stakeholders in section 5.1. This is followed by the objectives and requirements in section 5.2. In section 5.3 the constraints are determined. Section 5.4 describes the KPIs.

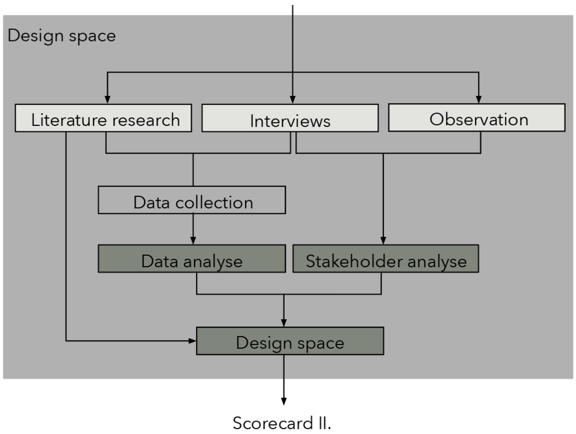

Figure 5.1: Design Space

5.1 STAKEHOLDERS

In order to answer the research question successfully, it is important to find all stakeholders related to this problem and their associated power and interest and their constraints, objectives and requirements. This has been done in the stakeholder analysis based on [49] and can be found in appendix C. The main findings are that there are 12 stakeholders that have an interest in this problem. The interests, constraints, objectives and requirements are, among others, listed in table C.1, table C.2 and table C.3. The objectives and requirements of stakeholders with high power are taken into account in the design space. Even thought stakeholders have a different underlying reason, it is striking that all stakeholders have the same goal to make aviation more sustainable. The interaction between the stakeholders to make aviation more sustainable can be seen in figure 5.2. The figure shows that the government, residents, passengers and NGOs put pressure on executive parties (airlines, airports and ANSPs) to operate more sustainable. The airlines passes this on to the service providers and aircraft manufacturers. The executive parties have to gain approval from investors, regulators and employees to operate more sustainable.

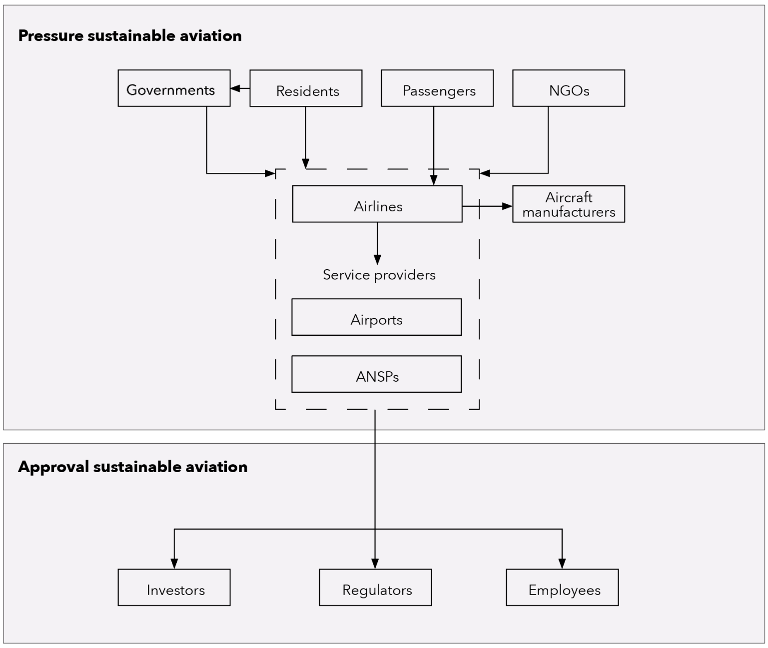

Figure 5.2: Pressure sustainable aviation and stakeholders

5.2 OBJECTIVE AND REQUIREMENTS

The objective comprises the overall goal of the CONOPS. The requirements are the properties that the CONOPS should have. They can be part of a trade-off which makes the requirement different than the constraints in section 5.3. The requirements can be divided into functional and non-functional requirements. Functional requirements refer to what the system should do, non-functional requirements what the system should have.

In chapter 4 it is concluded that the technical aspects of HEA influences the performances of these aircraft. The differences are relatively small since aircraft manufacturers aim to design HEA similar to conventional aircraft, in order to make the integration easier. Nonetheless, there are differences that does require a new CONOPS. This leads to the following objective: "The CONOPS should be able to handle conventional, hybrid and electric aircraft".

The functional requirements are:

- The CONOPS should handle the take-off of conventional, hybrid and electric aircraft.
- The CONOPS should handle the landing of conventional, hybrid and electric aircraft.

The non-functional requirements are:

- The CONOPS should be efficient in passenger capacity [total passengers per year]. According to KLM, they are only willing to purchase HEA when it is economically viable. This means that when one 100 passengers conventional aircraft is replaced with two hybrid or electric 50-passengers aircraft, twice as much HEA must be able to land and take-off (see interview A.2). Other airlines, for example Easyjet [16], share the same requirement. It is also a requirement from the airport who wants to maintain its status, which includes the number of passengers per year (see appendix C). Since LVNL is a service provider (see appendix C, figure C.4 and figure 5.2), it is important to take this requirement into the design space.

- The CONOPS should make use of the runways that are available. That means that there is no possibility to build an extra runway. Regional airports can only make use of the current runway they own. For Schiphol Airport, all runways can be used as long as this is technically feasible and the government approves this. At the moment, the 2+1-runway use is applicable for peak-hours [38].

- The CONOPS should be environmentally friendly in terms of CO_2, NO_x and noise. Figure 5.2 shows that the government, residents, passengers and NGOs all demand a more sustainable aviation of the executive parties (airlines, airports and ATM service providers). Residents aim to experience less nuisance from aircraft and NGOs and governments aim to increase the quality of life and preserve the environment [49]. Passengers value the freedom to travel but want the industry and governments to take action on emissions [26]. This requirement of the stakeholders has led that aircraft manufacturers are exploring the possibilities of HEA. In chapter 4 it is determined that the effect of HEA are positive compared to a CONOPS where only conventional aircraft are included.

5.3 CONSTRAINTS

The constraints of the CONOPS are decisive. This means that when a CONOPS does not meet one of the constraints, the CONOPS is rejected. The constraints of important stakeholders are taken into account as well. These important stakeholders have high power and can be found in figure 5.3.

Power	Level of interest: Low	Level of interest: High
Low	Passengers Employees	Residents NGOs
High	Regulators	Airlines ANSP Schiphol airport Regional airports Investors and shareholders Governments

Figure 5.3: Power and interest of stakeholders

1. The CONOPS shall be safe. Safety is the most important pillar of the ANSP. For LVNL, aviation safety is the prevention of collisions in the air and on the ground [35]. That means that the risks of a CONOPS already must be detected in advance, before implementing the CONOPS.

2. The CONOPS shall be compliant with regulations (Government, EU, EASA, ICAO). One of the most important rules concerns the separation between aircraft. The separation between aircraft is based on the RECAT category of the

aircraft [20]. In addition, examples of rules are the number of flight movements per year and a maximum noise nuisance per year among many others. The CONOPS shall be compliant to all these regulations.

3. The CONOPS shall have a capacity [movements per year] that is equal or higher than a CONOPS where only conventional aircraft are included. Airports want to maintain their status as can be seen in appendix C. The ANSP is a facilitating stakeholder that cannot decide that less aircraft can take-off and land at the airport. The capacity of Schiphol Airport is 540,000 movements per year when the sector can prove that the nuisance has decreased [60]. This can be divided into 120 movements for one peak hour and 80 movements for off-peak hours [38]. The increased ROT (see chapter 4) should also be included in the capacity.

4. The CONOPS shall not exceed the maximum runway capacity. The maximum capacity of the 2+1-runway use is 120 movements per hour. The maximum capacity for off-peak hours at the current runway use is 80 movements per hour. So a maximum runway capacity of 40 movements per hour is assumed. This is equivalent to 540,000 movements per year (see appendix A.9 and [38]). For the *Oostbaan*, the runway capacity is 30 movements per hour. Looking at regional airports, RTHA has a maximum capacity of 15 movements per hour [59]. The maximum capacity of Lelystad Airport is 123 movements per day after the revision of the airspace [39]. The maximum capacity at regional airports is not linked to the minimal ROT per aircraft.

5. The CONOPS shall only integrate aircraft with deviating performances up to 10 percent during peak-hours and 20 percent during off-peak hours (see appendix F). This maximum percentage of HEA can still be manageable with tactical planning. Tactical planning refers to the planning of the traffic per day.

6. The CONOPS shall be compatible with existing aircraft. This means that HEA must adjust to conventional aircraft since they are the exception. Segregation of HEA is not possible since procedures in the past, which segregated types of aircraft, learned that this makes the ATM-system to complex (see interview A.10).

7. The CONOPS shall satisfy the technical aspects and performances of HEA. In chapter 4 it was concluded that the approach and landing speed, landing distance and ROT differ compared to conventional aircraft. These differences in performances must be integrated in the CONOPS.

5.4 KEY PERFORMANCE INDICATORS

KPIs are used in the scorecard to assess the performances of CONOPS (see chapter 8). The KPIs can be assessed in a quantitative and qualitative way and are determined based on the requirements. Figure 5.4 lists the KPIs and the the stakeholders to whom they are related. In appendix G the descriptions and formulas are given to calculate the absolute values of the KPIs.

	KPI	Measurement	Related to:
1	Runway capacity	Movements/hour	ANSPs, airlines, airport
2	Complexity of implementation	N.A.	ANSPs,
3	Passenger capacity HEA	Passengers HEA/(off-)peak-hour	Airlines, airport
4	Noise-reduction	dB/year	Residents, NGOs, governments, passengers
5	CO2-reduction	gram/year	Residents, NGOs, governments, passengers
6	Nox-reduction	gram/year	Residents, NGOs, governments, passengers
7	Possibility to grow	N.A.	ANSPs, airlines, airport, residents, NGOs, governments
8	Operational cost reduction	euro	Airlines
9	Total travel time	hour	Passengers

Figure 5.4: KPIs and stakeholders

5.5 CONCLUSION

This chapter states the design space for this research and is input for the assessment. Based on literature research, interviews and observations, the data analysis and stakeholder analysis were performed. Since there are many stakeholders involved and the ANSP is a facilitating stakeholder, the objectives, constraints and requirements of important stakeholders are included in the design space as well. The outcome of the data analysis helped to determine which constraints and requirement are of importance for the new CONOPS. Now that the design space is determined, the KPIs are input for the scorecard in chapter 8. The CONOPS at the end of this research have to meet all the constraints.

6 SCENARIOS

There is a lot of uncertainty in the field of HEA. In addition, the ATM-system is very complex and there are many stakeholders that can influence the integration of HEA. This chapter explores potential external and contextual factors in the future. Based on these factors, different scenarios are determined that can become reality. This contributes to more accurate CONOPS as a conclusion. The scenarios are defined on the basis of literature research, interviews and observations. This information has been used as input for the stakeholder analysis, which in its turn is input for the scenario analysis. To narrow the uncertainty, different absolute values are given to the performance variables per scenario. These assumption of performances of HEA are based on data analysis. In section 6.1 a short description is given of the scenario planning process. This is followed by section 6.2 that describes the five scenarios in detail. Section 6.3 describes the main takeaways that can be drawn from the scenarios.

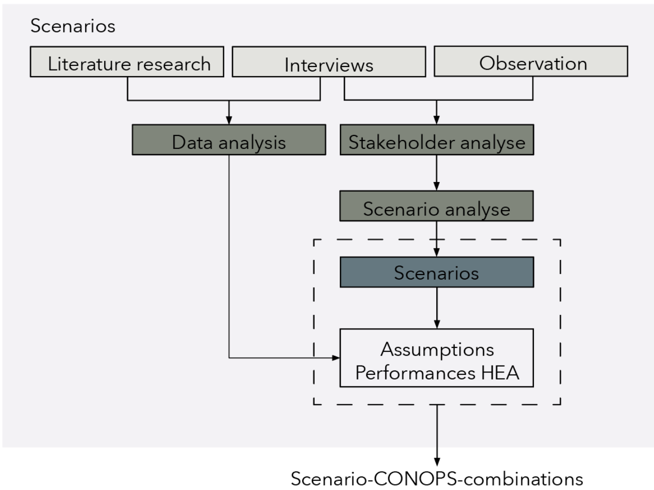

Figure 6.1: Structure chapter Scenarios

6.1 CREATING SCENARIOS

The scenarios are created based on the process of scenario planning of Enserink et al. [17]. First a causal diagram is compiled that describes the context in which the integration of HEA lies. It consists of all factors related to HEA and their connections. Each factor has a number that refers to a stakeholder from the stakeholder analysis. It can be seen that all factors are related to stakeholders except the ANSPs. That proves that they are all contextual factors. This causal diagram can be found in figure 6.5.

The contextual factors are classified into several driving forces. The driving forces are ranked according to their importance and uncertainty as can be seen in figure 6.2. The breakthrough of technologies and the decisions in regulations are the driving forces with the highest uncertainty and impact. These two driving forces form the axes of the scenario space in which five scenarios are determined. Each scenario consists of six variables for which assumptions have been made, based on the contextual factors and previous research. The complete process of the scenario analysis can be found in appendix D. The five scenarios are described in the next chapter.

		Uncertainty	
		Low	High
Impact	Low	"Vliegschaamte" High speed train	Social pressure
	High	Airport possibilities (International) economic development Fuel market Health of global civil aviation Airspace management	Breakthrough of technologies Regulation decisions

Figure 6.2: Importance and uncertainty of driving forces

6.2 DESCRIPTION OF THE SCENARIOS

The five scenarios consist of different levels of the breakthrough of technologies and the decisions in regulations. Figure 6.3 shows the characteristics per scenario. These characteristics are based on the performances of HEA (see chapter 4) that are related to the regulations regarding HEA and the technology breakthrough. Appendix D describes the assumptions per driving force. A combination between the two is made below. Appendix E contains a list of the effects of the scenarios on the KPIs.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Positive regulations regarding HEA	None	Positive	None	Medium	Positive
	Technology breakthrough	Low	Low	High	Medium	High
	Percentage HEA in ATM-system [%]	0	5	10	20	25
	Range [km]	0	500	1000	500	1000
	Passenger capacity [pax/HEA]	0	19	100	50	100
	Type of aircraft	N.A.	Private jets	Private jets, airlines	Private jets, airlines	Private jets, airlines
	Type of electrificiation	N.A.	Hybrid and electric aircraft	Electric aircraft	Hybrid and electric aircraft	Electric aircraft
Hybrid aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1	1 (compared to conventional, 100-passengers)	1
Electric aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1,15	1,1 (compared to conventional, 100-passengers)	1,15

Figure 6.3: Performances per scenario

Scenario 1. No positive regulations – low technological breakthrough
This scenario equals the base scenario as the technological breakthrough is low and there are no motivating regulations for airlines to purchase HEA. This leads to a zero percentage of HEA in the ATM-system. The base case does not take future changes into account that are unrelated to HEA.

Scenario 2. Positive regulations – low technological breakthrough
Regulators motivate airlines to purchase HEA, but no major technological breakthrough has occurred. This means that there are HEA but with minimal performances. The data-analysis shows that the majority of HEA concepts are within a range of 500 km. This can be seen in figure 6.4. This also applies to a passenger capacity of 19 passengers. HEA with this range and passenger capacity ratio expect to become certified within 2 years, for example the Eviation Alice [4]. In case

of this scenario, the technological breakthrough entails that the power-to-weight ratio does not increase which means that aircraft with a larger range and higher passenger capacity are not feasible.

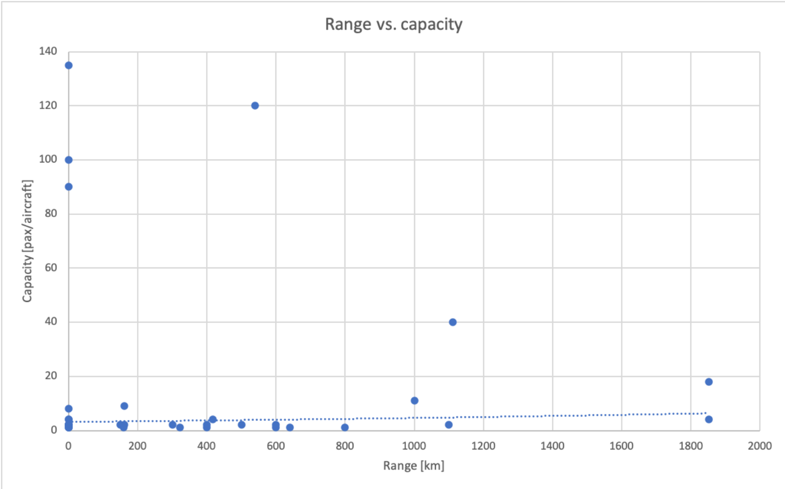

Figure 6.4: Range [km] - capacity [pax/aircraft]

The consequence is that it is not attractive for airlines to purchase HEA since it is not economically viable to transfer only 19 passengers in one aircraft (see interview A.2). However, there are positive regulations for HEA. HEA do not have to pay airport charges [54], take-off and landing charges are based on emissions and noise. This ensures that five percent of the private jets in the ATM-system becomes electric. These private jets have similar performances compared to conventional private jets. The biggest difference is that the range of the HEA is shorter (see chapter 4).

Scenario 3. No positive regulations – high technological breakthrough Aircraft manufacturers managed to design electric aircraft that are certified, with a range of 1000km and a capacity of 100 passengers. This assumption is based on the five promising HEA concepts that have a similar range-passenger capacity ratio. However, there are no positive regulations regarding HEA. The government does not implement special taxes for emissions and noise-nuisance. Airlines do not (financially) benefit from HEA at the airport as there are no landing- and parking fees based on the emissions and noise-nuisance [54]. This means that it is less attractive for airlines to fly electrified. Due to the lack of positive regulations, airlines can only purchase a minimum number of electric aircraft which equals ten percent of the aircraft in the ATM-system. To determine the percentage of HEA in the ATM system, research has been done to the number of flights up to 750 km. For Schiphol Airport applies a percentage of 38. For RTHA applies 25 percent [13]. The percentage of HEA in the ATM-system cannot exceed this. In addition, it is unlikely that the entire fleet will be traded in with the advent of HEA. In combination with the willingness of airlines to become more sustainable, the maximum percentage of HEA is therefore 25 percent. From here, the assumptions of the percentages are based on the combination between the technology breakthrough and the positive regulations regarding HEA. Nonetheless, the airlines decide to purchase these electric aircraft based on social pressure (see figure 5.2) and operational cost [45] (see interview A.2). These aircraft have similar performances compared to conventional aircraft except for the approach and landing speed. The increased speed has negative consequences for the runway capacity as is determined earlier in chapter 4.

Scenario 4. Medium positive regulations – medium technological breakthrough The development of HEA is up and running. This leads to medium performances since the maximum power-to-weight-ratio has not been reached. The aircraft can fly up to 500 km. This assumption is based on the data analysis. The vast majority of the concept HEA lie in this area. This can be seen in figure 6.4. The passengers capacity per HEA is 50, since a slightly greater technological breakthrough has taken place compared to scenario two. Airlines can purchase HEA but due to the aircraft's capacity, one smaller aircraft has to be replaced by two electric aircraft. This scenario can only become reality when airlines change their business model in order to maintain the total passenger capacity (see interview A.9). This is a constraints that can be found in chapter 5. However, this is already in line with KLM's fly responsibly campaign, which is asking passengers to cut back [30]. Even with a smaller passenger capacity, it is economically viable for airlines to purchase HEA due to the positive regulations. This leads to 20 percent of HEA in the ATM-system which can only be used for destinations within 300 km (see chapter 4). Even with a relatively small passenger capacity, the MTOW of HEA is equal to a 100-passengers conventional aircraft. This has to do with the power-to-weight-ratio. Compared to a 100-passengers conventional aircraft, the approach and landing speed is higher. This leads to decrease of the runway capacity.

Scenario 5. Positive regulations – high technological breakthrough
This scenario is the most positive scenario with positive regulations and high technological breakthrough. Technology allows that 100 passengers can fly up to 1000 km in an electric aircraft. This is equal to the range-passenger capacity-ratio of the five promising HEA in figure 6.4. Electric aircraft have lower operational cost compared to conventional and hybrid aircraft [45]. This makes it attractive for airlines to trade in conventional aircraft with electric aircraft with the same capacity (e.g. Embraer 190) and a destination within the range. On top of that, there are also positive regulations regarding HEA which means that distinctions are made in regulations based on the emissions and noise nuisance. These regulations come from governments (taxes), airports (landing- and parking fees) [54] and regulators as the EU, EASA and ICAO. This positive scenario leads to 25 percent of electric aircraft in the ATM-system. The performances of these electric aircraft are generally equal to the performances of conventional aircraft. However, the approach and landing speed is higher which has a negative consequence for the runway capacity. Since the percentage of HEA in this scenario is labeled high, the runway capacity is lowest of all five scenarios.

6.3 MAIN TAKEAWAYS SCENARIO ANALYSIS

Now that the interpretation of the scenarios is clear, the following conclusions can be drawn:

- Scenario 1 does not include HEA.
- In case of scenario 2, 3 and 5 HEA are compared with conventional aircraft of similar size.
- In case of scenario 4, the performances are compared to a 100-passengers conventional aircraft. This comparison is much more interesting since a conventional, 100-passengers aircraft will be replaced by two 50-passengers hybrid or electric aircraft. Besides that, it is not common that a 50-passengers aircraft takes-off and lands at Schiphol Airport regularly.
- Scenario 2 and 4 contain hybrid and electric aircraft. Scenario 3 and 5 contain only electric aircraft as there is a high technology breakthrough. Hybrid aircraft are available as well but less attractive to purchase by airlines due to higher operational cost (see appendix C).

- HEA in scenario 2 do not differ in performances compared to a conventional aircraft. This can be seen in chapter 4.
- HEA in scenario 3, 4 and 5 differ in performances compared to a conventional aircraft. The hybrid aircraft has a longer ROT than a 100-passengers conventional aircraft as can be seen in chapter 4.
- The percentages of HEA in the ATM-system are based on the purchase of airlines. the HEA percentage is only applied to flights up to 750 km which equals 38 percent of the total number of flights [13]. In addition, airlines like Easyjet aims to have an all-electric fleet in 2035 [16] and KLM is willing to buy electric aircraft when they are economically viable (see A.2).
- The differences in performances are assumed in percentages based on the performance analysis in chapter 4.

6.4 conclusion

This chapter describes the five different scenarios that are the outcome of the scenario analysis. These scenarios lie in the design space that is composed of two axes. These axes represent the technology breakthrough and positive regulations regarding HEA. The characteristics of the scenarios are the percentage of HEA in the ATM-system, range, passenger capacity and type of aircraft and electrification. It can be said that the most positive scenario is scenario 5. This gradually decreases with scenario 1 as the most negative scenario, which also represents the base case. The scenarios are combined in chapter 7 with the CONOPS (outcome of the morphological analysis). These combinations are the input for the assessment.

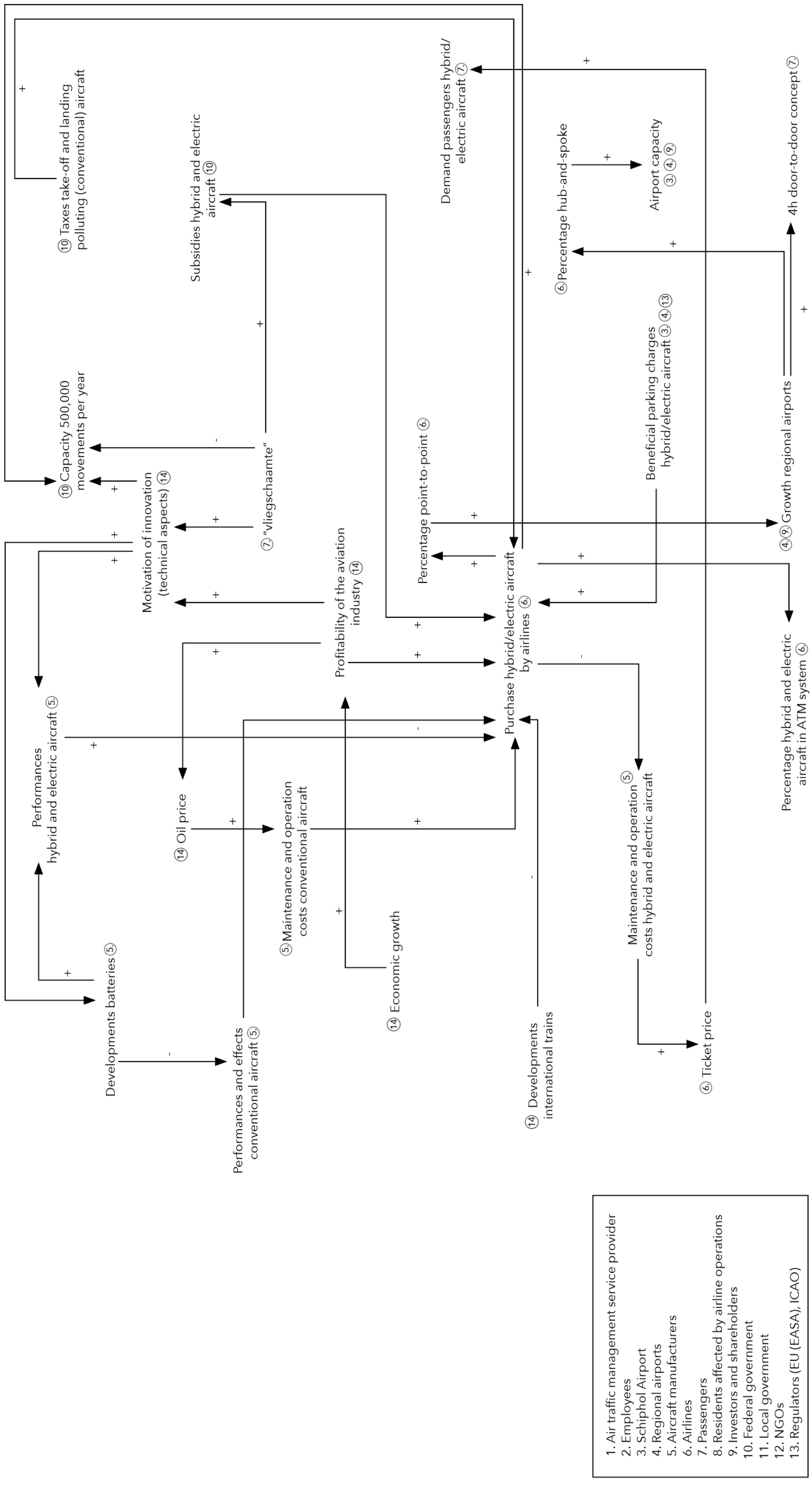

Figure 6.5: Causal Diagram

7 EXPLORING CONOPS

This research aims to find potential CONOPS per scenario. In order to find these CONOPS, a brainstorm is applied to diverge and find as many CONOPS as possible. After the brainstorm, convergence is done by means of a morphological analysis. In section 7.1 the brainstorm is briefly explained. The outcome of the morphological analysis can be found in section 7.2. At this moment in the research, the KPIs, scenarios and CONOPS are determined. This means that phase II of the research is completed. Since a scorecard only has two axes, the CONOPS and scenarios have to be combined in phase III. However, this yields too many combinations. That is why only the vertices of these combinations are studied further. The process of combining scenarios and CONOPS and find the vertices can be found in section 7.3. The vertices are from this moment in the research called CONOPS and are the input for the scorecard.

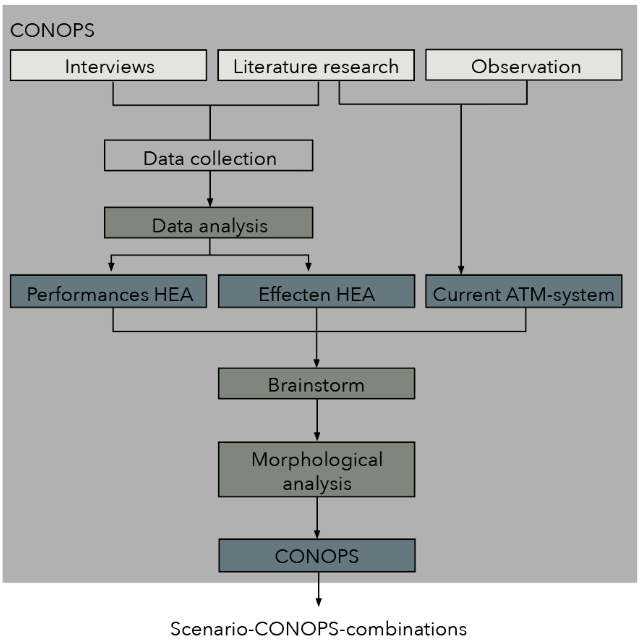

Figure 7.1: Exploring CONOPS

7.1 BRAINSTORM

The design process started with a brainstorm in which six aviation experts participated. The brainstorm mainly focused on scenario 3, 4 and 5. Scenario 1 represents the base case. The CONOPS related to scenario 2 is apparent. These two scenarios are temporarily put aside in this section. The participants of the brainstorm were asked to perform an individual brainstorm before the meeting. A case study was used to make this subject more tangible. The first part of this case study consists of an airline that starts a trial. This trial involves one HEA that flies between The

Netherlands and London. The aircraft takes off and lands once a week. The question was asked in what way this aircraft would land and take-off from a Dutch airport in case of HEA. The intention of this trial is to help participants get a grip on the performances of HEA into the ATM-system.

The second part of the case study focused on the three different scenarios. For each scenario, the participants had to brainstorm about different CONOPS. After the individual brainstorm, the individual conclusions were discussed during a meeting. After each round, the participants were asked if they came up with a new CONOPS. During the brainstorm both segregation and integration were mentioned. Other ideas have been suggested as locating HEA at Schiphol Airport or at regional airports, opening up a fourth runway during peak-hours if the capacity does not allow otherwise and discussions were held about integrating HEA during peak- and/or off-peak hours. These CONOPS ideas can be classified into three variables:

- Time: peak hours, off-peak hours, both
- Airport: Schiphol, regional airports
- Runway: Segregation, integration, integration with an extra runway

These variables are the input for the morphological analysis in the next section. Details of the brainstorm process can be found in appendix F.

7.2 MORPHOLOGICAL ANALYSIS

A morphological analysis helped create different combinations between the three variables which led to 18 different CONOPS. However, segregation of aircraft is not preferred due to the complexity. Segregation has been used in the past and has proven that it does not work (see interview A.10). These CONOPS do not meet the constraints and are removed in the morphological analysis. In addition, CONOPS that are a combination of a regional airport with the opening of an extra runway, are not possible since regional airports only contain one runway. The final outcome of this morphological analysis are nine CONOPS that can be found in figure 7.2. The complete morphological analysis can be found in appendix F, figure F.2.

	Time			Airport		Runway	
A	Peak hours			Schiphol Airport		Integration	
B		off-peak hours		Schiphol Airport		Integration	
C			all day	Schiphol Airport		Integration	
D	Peak hours				Regional airport	Integration	
E		off-peak hours			Regional airport	Integration	
F			all day		Regional airport	Integration	
G	Peak hours			Schiphol Airport			Integration extra runway
H		off-peak hours		Schiphol Airport			Integration extra runway
I			all day	Schiphol Airport			Integration extra runway

Figure 7.2: Outcome morphological analysis

With the outcome of the morphological analysis, the three types of input (KPIs, scenarios and CONOPS) for the scorecard are determined. This means that phase II of the research is completed. In the next section, phase III of the research begins.

7.3 VERTICES SCENARIO-CONOPS-COMBINATIONS

As is said before, there are three types of input for the the scorecard while a scorecard has only two axes. It is therefore important to combine two types of input, so that the scenarios and CONOPS can be assesses correctly in a scorecard. The scenarios (chapter 6) and the CONOPS (section 7.2) that are determined earlier are first combined. Based on the remaining time and to maintain the quality of this study, only the vertices of these scenario-CONOPS-combinations are further researched. The vertices are the most interesting combinations to do further research on. The method of part two can be seen in figure 7.3.

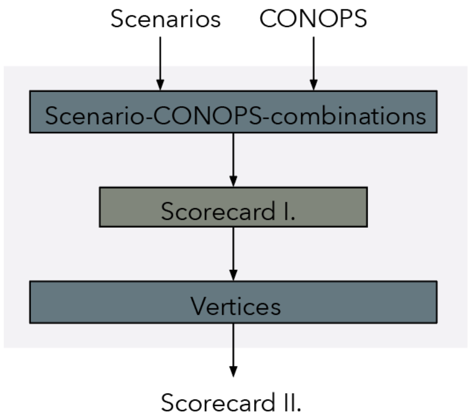

Figure 7.3: Structure - vertices

There are five different scenarios of which scenario 1 and 2 are temporarily put aside. That means that there are three remaining scenarios. Since the morphological analysis concluded nine CONOPS, each of which applies to three scenarios, there are 27 combinations. In figure 7.4, the 27 combinations of scenarios and CONOPS are defined. In order to find the vertices, a distinction is made between CONOPS A-B-C, CONOPS D-E-F and CONOPS G-H-I. The three CONOPS per group share the variables in location and runways but differ in time. First, the variables of the scenario-CONOPS-combination are made more exact by defining the number of runways, number of HEA, the specific time of peak- and off-peak hours [min] [63] and the current pressure on the ATM-system of the location. For the latter variable, regional airports have much more flexibility to integrate aircraft with deviating performances than Schiphol Airport. Hereafter, normalized scores between zero and one are added to these defined variables. The scenario-CONOPS-combination with the highest score per CONOPS is chosen as vertex since this is the most interesting to research more in detail. Thereby, it is also examined whether the scenario-CONOPS-combinations meet the constraints that have been established earlier in chapter 5. The assumption was made that the safety of the ATM-system is not affected by the integration of HEA, from the moment that HEA are certified and the CONOPS meet the requirements of regulators. The determination of the vertices has been carried out in a systematic way as can be seen in figure 7.4, however some exceptions have been made:

- CONOPS A-B-C: there are three combinations that are not feasible. These are scenario-CONOPS-combination 4A, 5A and 5B. These combinations do not meet all the constraints defined in chapter 5, since the maximum percentage of HEA is 10 percent during peak-hours. For CONOPS 3C, 4C and 5C applies that they only meet the constraints when the maximum percentage of HEA is 10 percent during peak-hours

- CONOPS D-E-F: Scenario-CONOPS-combination 5D, 5E and 5F are the CONOPS with the highest score. However, since the current capacity of regional aircraft is flexible, the integration of HEA is not very intriguing. This means that even though combinations 5D and 5E are the ones with the highest score in the column, they are still eliminated for further research.

- CONOPS G-H-I: These combinations consist of CONOPS A-B-C as a base with opening up an extra runway. Combinations 4G, 5G and 5H are not feasible due to exceeding the capacity. This means that scenario-CONOPS-combination 3G, 4H and 5I have the highest scores. For CONOPS 5I applies that only 10 percent of HEA can take-off and land in peak-hours, otherwise the CONOPS does not meet the constraints. With these vertices, the effect of opening a fourth runway can be shown in comparison to combination 3A, 4B and 5C.

	Percentage HEA of all aircraft	Range	Passengers capacity		CONOPS A		CONOPS B		CONOPS C	
				Airport	Schiphol airport		Schiphol airport		Schiphol airport	
				Runway	Integration		Integration		Integration	
				Time	Peak hours		Off-peak hours		All day	
Scenario 3	10%	1000km	100	Number of runways	3	1	2	0,667	Peak hours 3, off-peak 2	1
				Percentage of hybrid/electric aircraft	10%	0,4	10%	0,4	10%	0,4
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system	Ferraris	3,4		3,1		3,4
Scenario 4	20%	500km	50	Number of runways	3	1	2	0,667	Peak hours 3, off-peak 2	1
				Percentage of hybrid/electric aircraft	20%	0,8	20%	0,8	20%	0,8
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system		3,8	Siemens	3,5		3,8
Scenario 5	25%	1000km	100	Number of runways	3	1	2	1	Peak hours 3, off-peak 2	1
				Percentage of hybrid/electric aircraft	25%	1	25%	1	25%	1
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system		4		4	Volta	4

	Percentage HEA of all aircraft	Range	Passengers capacity		CONOPS D		CONOPS E		CONOPS F	
				Airport	Regional airport		Regional airport		Regional airport	
				Runway	Integration		Integration		Integration	
				Time	Peak hours		Off-peak hours		All day	
Scenario 3	10%	1000km	100	Number of runways	1	1	1	1	1	1
				Percentage of hybrid/electric aircraft	10%	0,4	10%	0,4	10%	0,4
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	Low	1	Low	1	Low	1
				Pressure on ATM-system		3,4		3,4		3,4
Scenario 4	20%	500km	50	Number of runways	1	1	1	1	1	1
				Percentage of hybrid/electric aircraft	20%	0,8	20%	0,8	20%	0,8
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	Low	1	Low	1	Low	1
				Pressure on ATM-system		3,8		3,8		3,8
Scenario 5	25%	1000km	100	Number of runways	1	1	1	1	1	1
				Percentage of hybrid/electric aircraft	25%	1	25%	1	25%	1
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	Low	1	Low	1	Low	1
				Pressure on ATM-system		4		4	Franklin	4

	Percentage HEA of all aircraft	Range	Passengers capacity		CONOPS G		CONOPS H		CONOPS I	
				Airport	Schiphol airport		Schiphol airport		Schiphol airport	
				Runway	Integration extra runway		Integration extra runway		Integration extra runway	
				Time	Peak hours		Off-peak hours		All day	
Scenario 3	10%	1000km	100	Number of runways	4	1	3	1	Peak hours 4, off-peak 3	1
				Percentage of hybrid/electric aircraft	10%	0,4	10%	0,4	10%	0,4
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system	Tesla	3,4		3,4		3,4
Scenario 4	20%	500km	50	Number of runways	4	1	3	1	Peak hours 4, off-peak 3	1
				Percentage of hybrid/electric aircraft	20%	0,8	20%	0,8	20%	0,8
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system		3,8	Thompson	3,8		3,8
Scenario 5	25%	1000km	100	Number of runways	4	1	3	1	Peak hours 4, off-peak 3	1
				Percentage of hybrid/electric aircraft	25%	1	25%	1	25%	1
				Specific time [min]	690	1	329	1	1019	1
				Current pressure on ATM-system	High	1	High	1	High	1
				Pressure on ATM-system		4		4	Kelvin	4

Figure 7.4: Combinations Scenarios and CONOPS

From this point on, the vertices are called CONOPS. Since this research aims to find the best CONOPS per scenario, the CONOPS are now ordered per scenario. The combinations that are determined as vertices are CONOPS 1, 2, 3A, 3G, 4B, 4H, 5C, 5F and 5I and are named respectively Bell, Edison, Ferraris, Tesla, Siemens, Thompson, Volta, Franklin and Kelvin. The nine CONOPS have been given a name after scientists, engineers or physicists who have made a major contribution to electrical science or turned electrical science into an essential tool for modern life.

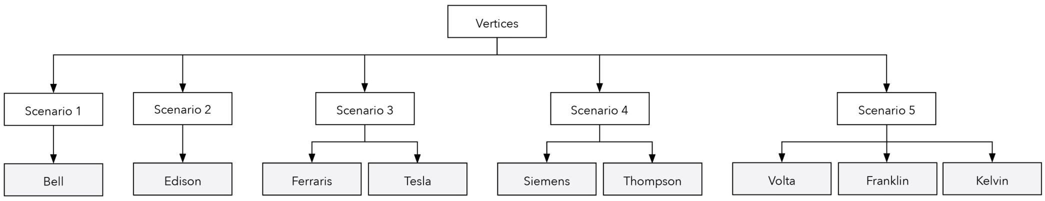

Figure 7.5: Selection vertices per scenario with names

7.4 DESCRIPTION CONOPS

This section describes the nine CONOPS in detail after they have been discussed with ATCOs. The CONOPS related to scenario 1 and 2 are brought in again.

Bell: 0 percent electric aircraft
CONOPS Bell stands for the base case. HEA are not certified in 2035. This means that it is not needed to integrate HEA in the ATM-system. The other CONOPS are compared in the scorecard with the base case to show what the (dis)advantages are of implementing HEA compared to a situation where there are no HEA.

Edison: 5 percent HEA, 19 passengers - Schiphol Airport, all day, integration current runways
CONOPS Edison includes 5 percent of hybrid and electric private jets. These HEA are integrated like conventional aircraft at Schiphol Airport. Since only five percent of the total aircraft is electrified and the occupancy rate of the Oostbaan is lower than the five other runways, it is possible to integrate the hybrid and electric private jets at Schiphol without major problems.

Ferraris: 10 percent HEA, 1000km, 100 passengers - Schiphol Airport, peak hours, integration current runways
HEA will take-off and land from Schiphol Airport during peak hours only, in CONOPS Ferraris. 10 percent electric aircraft equals 12 electric aircraft per hour. That means that there are 138 HEA in total during the peak hours in a day. These have to be divided over three runway which means that there are four HEA per runway per hour. Electric aircraft are not treated differently compared to conventional aircraft (by the means of segregation). This means that 100-passenger conventional aircraft (e.g. Embraer190) are replaced by an electric aircraft with the same capacity. Since ten percent of the total aircraft are HEA, this can still be manageable with tactical planning. Tactical planning refers to the planning of the traffic per day (see F). Since ten percent is defined as the maximum capacity of HEA (see constraints 5), this CONOPS shows what the frictions are. The electric aircraft are part of the hub-and-spoke model and operate as feeders as they only take-off and land during peak hours. In chapter 4 can be seen that ROT of HEA with a passenger capacity of 100 increases with 15 percent. This means that the runway capacity decreases.

Tesla: 10 percent HEA, 1000km, 100 passengers - Schiphol Airport, peak hours, integration + extra runway
CONOPS Tesla consists out of CONOPS Bell as a base and adds an extra fourth runway during peak-hours. So far, using a fourth runway during traffic peaks is limited, since otherwise the nuisance will become too great for the residents. However, HEA cause less emissions and noise pollution which makes it possible to enforce this fourth runway rule less strictly. CONOPS Bell describes that it is still manageable to integrate ten percent of HEA, with the right tactical planning. Open-

ing a fourth runway during peak-hours requires less tactical planning. As twelve HEA are divided over four runways instead of three, there is one HEA less per runway per hour compared to CONOPS Bell. This has, compared to CONOPS Bell, a positive influence on the runway capacity.

Siemens: 20 percent HEA, 500km, 50 passengers - Schiphol Airport, off-peak hours, integration current runways
CONOPS Siemens describes the effect of 20 percent HEA that can transfer up to 50 passengers. These aircraft take-off from and land at Schiphol Airport during off-peak hours and are integrated as conventional aircraft. It is interesting to see what the effect is of smaller aircraft on the ATM-system. The pressure on the ATM-system is high, due to the smaller aircraft, the high percentage or HEA and the fact that one conventional aircraft is replaced by two electric aircraft. This latter one is a requirement that is determined earlier in the research which says that the capacity in passengers per year must remain the same (see interview A.2). Another solution to preserve the total passengers per year is to increase the number of passengers in conventional aircraft. This means that conventional aircraft have to become larger in order to let smaller HEA operate. This is a choice from the airlines to change their business model (see interview A.9). Besides that, during off-peak hours only two runways are used, one for take-off and one for landing. That means that the pressure on the ATM-system is relatively higher during off-peak hours compared to peak-hours and the sensitivity for aircraft with deviating performances is greater. With an increased approach speed of electric aircraft, the runway occupancy time is of interest.

Thompson: 20 percent HEA, 500km, 50 passengers - Schiphol Airport, off-peak hours, integration + extra runway
CONOPS Thompson exists of the CONOPS Siemens as a basis but opens a third runway. During off-peak hours, one runway is used for take-off and one runway for landing of aircraft. The pressure on the ATM-system is relatively high but lower compared to CONOPS Siemens since an extra runway is opened. Similar to CONOPS Tesla, it is possible to use an extra runway since HEA cause less nuisance for residents. This could lead to the decision of the ministry of Infrastructure and Water Management to stop enforcing this rule to open up an extra runway. This CONOPS is linked to scenario 4 where the regulations concerning HEA are defined as medium. This makes an enforcement of this rule more likely than in CONOPS Tesla, related to scenario 3, where there are no positive regulations regarding HEA.

Volta: 25 percent HEA, 1000km, 100 passengers - Schiphol Airport, all day, integration current runways
CONOPS Volta accommodates 25 percent HEA and 75 percent conventional aircraft. They are located at three runways during peak hours and two runways during off-peak hours. For CONOPS Volta the constraint is that there is a maximum of ten percent HEA during peak hours. That means that at least 15 percent must fly during off-peak hours. This leads to 204 HEA per day. The HEA can transfer up to 100 passengers. This means that a conventional single aisle aircraft can be replaced by one HEA. This CONOPS requires tactical planning in both peak and off-peak hours.

Franklin: 25 percent HEA, 1000km, 100 passengers - Regional airports, all day, integration current runways
This CONOPS is chosen as vertex since there is a lot of flexibility at regional airports. In the morning there is an outbound peak that is short in time. HEA are mainly point to point traffic. The maximum capacity of RTHA is 15 movements per hour. The airport operates 16 hours per day which means that there is space for 240 conventional aircraft per day [59]. In case of Lelystad airport, the maximum capacity is 123 movements per day [39]. If 25 percent of HEA are assigned to re-

gional airports, this can also mean that one part is located at RTHA and the other at Lelystad Airport. Since RTHA handeled 52,439 movements in 2019, the airport will grow significantly when (a part of) 25 percent is located here. Since there is currently no clear distinction between peak and off-peak hours, it is therefore assumed that there is no difference between peak- and off-peak hours.

Kelvin: 25 percent HEA, 1000km, 100 passengers - Schiphol Airport, all day, integration + extra runway
CONOPS Kelvin brings along a lot of changes in the current CONOPS where only conventional aircraft make use of Schiphol Airport. The first change is that an extra runway is opened all day. That means that a fourth runway is opened during peak hours and a third runway during off-peak hours. Since there are positive regulations regarding HEA, an enforcement of this fourth runway rule is likely. Secondly, the percentage of HEA in the ATM-system is very high. However, as there is one extra runway, the pressure on TWR and APP is lower compared to CONOPS Volta.

7.5 CONCLUSION

This chapter described the process of designing multiple CONOPS. This process of designing the CONOPS consists of the last type of input of phase II and phase III of this research. In order to find the last type of input, the CONOPS, a brainstorm was performed. The outcome of the brainstorm consists of three variables (time, airport and runway) that are the input for the morphological analysis. This analysis made all the combinations between these variables of which 9 CONOPS were the output. With the CONOPS as output, the three types of input are determined. This means that phase II of the research is finalized.

Since there are three types of input for the scorecard and only two axes, two of them have to be combined. phase III of the research studied the combinations between CONOPS and scenarios. The 9 CONOPS that are the outcome of the morphological analysis (see section 7.2) and the 3 scenarios (scenario 3, 4 and 5) are combined. 27 scenario-CONOPS-combinations are the result. These 27 combinations are assessed based on the defined numbers of runways, percentages of HEA, the specific time of peak- and off-peak hours [min] and the current pressure on the ATM-system of the location. The assessment concluded that there are 9 vertices of scenario-CONOPS-combinations that are further researched. These nine scenario-CONOPS-combinations are from now on called CONOPS. Thet are given the names: Bell, Edison, Ferraris, Tesla, Siemens, Thompson, Volta, Franklin and Kelvin. Now that the CONOPS and scenarios are combined, phase III of the research is completed. In chapter 8, these CONOPS are assessed on the KPIs that determined in the design space to see which CONOPS is potential per scenario.

8 ASSESSMENT

Up to now the performances and effects of HEA, design space and the vertices of the scenario-CONOPS-combinations (also named CONOPS) are determined This means that phase I, II and III of this research is completed and phase IV starts in this chapter. The CONOPS, scenarios (combined) and KPIs are the input for the scorecard, as can be seen in figure 8.1. The scorecard is applied to find potential CONOPS per scenario, what is the aim of this research. In section 8.1 the results that were concluded earlier in this research and that are important for completing the scorecard are repeated briefly. In section 8.2 a description of the KPIs per CONOPS is given. In section 8.3, a general evaluation of the assessment is given. The process of completing the assessment is shown in section G. After the assessment, a sensitivity analysis is applied in section 8.4.

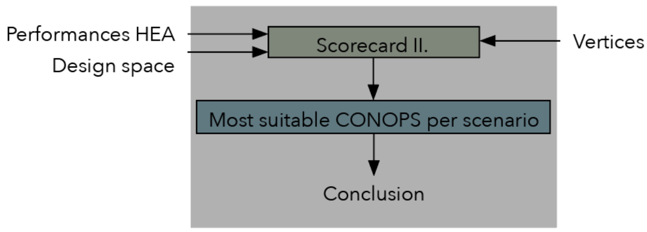

Figure 8.1: CONOPS

8.1 SUMMARY IMPORTANT RESULTS INPUT SCORECARD

This section gives a short summary of important results that are the input for the scorecard:

- The outcome of the design process shows that there are nine different CONOPS. These CONOPS are each linked to one scenario. Since there are multiple CONOPS linked to the same scenario, it is possible to assess which CONOPS is potential for that scenario.
- The CONOPS are assessed based on the KPIs that are determined in chapter 5. In the first scorecard (section 7.3) it was already checked whether the CONOPS meet the constraints.
- The deviating performances and effects are determined in chapter 4. These performances and effects are used to quantify the KPIs per scenarios, before they are given a normalized score.

8.2 EVALUATION ASSESSMENT PER KPI

The results per KPI can be found in the scorecard (appendix G, figure G.3). A simplified scorecard can be found in figure 8.2. The KPIs are determined by the decision maker (ANSP) and stakeholders with high power. However, weights of importance are applied to each KPI from the ANSP's point of view. In addition, the nine CONOPS are once again checked on the constraints. This section described the evaluation of the results per KPI.

	CONOPS	CONOPS 1	CONOPS 2	CONOPS 3A	CONOPS 3G	CONOPS 4B	CONOPS 4H	CONOPS 5C	CONOPS 5F	CONOPS 5I
	Name:	**Bell** (base case)	**Edison**	**Ferraris**	**Tesla**	**Siemens**	**Thompson**	**Volta**	**Franklin**	**Kelvin**
Characteristics	Airport	Schiphol Airport	Schiphol Airport	Schiphol Airport	Schiphol Airport	Schiphol Airport	Schiphol Airport	Schiphol Airport	Regional airport	Schiphol Airport
	Runway	Current runways	Oostbaan	Current runways	Current runways + 1	Current runways	Current runways + 1	Current runways	Current runway	Current runways + 1
	Time	All day	All day	Peak-hours	Peak-hours	Off-peak-hours	Off-peak-hours	All day	All day	All day
	Number of runways	3+2	1	3	4	2	3	3+2	1	4+3
	Percentage of total aircraft [%]	0	5	10	10	20	20	25	25	25
	Range [km]	N.A.	500	1000	1000	500	500	1000	1000	1000
	Passengers capacity [pax/HEA]	N.A.	19	100	100	50	50	100	100	100

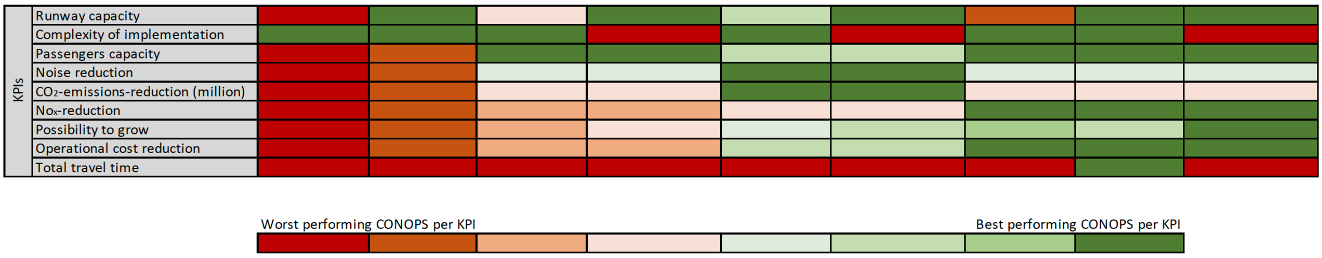

Figure 8.2: Simplified scorecard

- **Runway capacity:** All CONOPS meet the constraint that the runway capacity does not exceed the maximum runway capacity. The number of runway movements is for all CONOPS about equal. This is partly because of a rough estimation of the ROT-increase for HEA and the current ROT plus separation for conventional aircraft. In case of CONOPS Edison, the increase of ROT is five percent. The ROT plus separation on this runway is 2 minutes. For the CONOPS that integrate HEA with 100 passengers, the increase is 15 percent. Since the ROT plus separation for one conventional aircraft is 1.5 minutes on the longer runways, the increase for HEA is only seconds. This leads to a runway capacity decrease of one or two aircraft per hour. Because of this, CONOPS Bell has the highest capacity. In the other CONOPS, the runway capacity is 38 or 39 (rounded down).

- **Complexity of implementation:** The complexity of implementation is a qualitative KPI. The complexity of implementation is related to the opening of an extra runway, and the amount of changes needed in procedures used by ATCOs and in regulations. The complexity of implementation plays in the short term and can be seen as an investment. If a continued growth in HEA is expected, the use of an additional runway may be necessary in the future. When only the current runways are used, the integration of HEA in-between the conventional aircraft is an easier implementation than when one extra runway has to be opened. A simple approach has been chosen for this KPI; if only the current runways are used, a score of 1 is assigned to this KPI. If an extra runway is opened, a score of 0 is given. That means that CONOPS Bell, Edison, Ferraris, Siemens and Volta received a high score. The other CONOPS received a low score.

- **Passenger capacity HEA:** The passenger capacity in HEA is related to the capacity of HEA, the number of passengers that one HEA can transport and the time of day that HEA take-off and land. Per hour, 1200 passengers can be transferred with HEA in CONOPS Ferraris, Tesla, Volta, Franklin and Kelvin. However, the scorecard shows that CONOPS Volta, Franklin and Kelvin can transfer almost 7.5 million passengers per year while CONOPS Ferraris and Tesla can only transfer just over 5 million passengers. This has to do with the duration of peak-hours (11.5 hours) and off-peak hours (5.5 hours) per day. CONOPS Siemens and Thompson are assigned a medium score. Even though the percentage of HEA is higher compared to CONOPS Ferraris and Tesla, the smaller passenger capacity per aircraft and the time of day influences the total passenger capacity. CONOPS Edison and CONOPS Bell are assessed low.

- **Noise reduction:** Noise reduction is related to the number of HEA in the ATM-system per hour and the type of aircraft. It was decided to calculate the noise reduction per hour because the perception of noise nuisance per hour is relatively greater than the noise nuisance per day. The CONOPS with the highest score are CONOPS Siemens and Thompson. These CONOPS integrate the highest number of HEA per hour. The fact that these aircraft can transfer less passengers, does not influence the noise decrease as the MTOW is similar to a 100-passenger HEA in another CONOPS. It is remarkable that CONOPS Edison almost has similar noise reduction compared to CONOPS Ferraris, Tesla, Volta, Franklin and Kelvin. These latter four CONOPS integrate twice as much HEA. However, noise of private jets is reducted with -10 EPNdB, compared to -10 dBA for general aviation [37].
- **CO_2-emissions:** CO_2-emissions are related to the percentage of HEA in the ATM-system, the distance of the flight and the CO_2-emissions in gram/passenger/km [29]. The CONOPS related to scenario 5, CONOPS Volta, Franklin and Kelvin score the highest on CO_2-reduction. From this scenario, the reduction of CO_2-emissions gradually decreases towards the CONOPS related to scenario 1.
- **possibility to grow:** The possibility to grow is scored in a qualitative way. The more HEA are integrated in the ATM-system, the less the nuisance of aircraft will be. In addition, maximum runway capacity is also considered. When an additional runway is put into service, the maximum capacity will increase. These two variables, ensure that CONOPS Kelvin scores highest, CONOPS Volta is next in line. CONOPS Franklin shows that the maximum capacity of HEA is reached at regional airports. However, there is still a possibility to grow at Schiphol Airport with HEA. From scenario Thompson, the possibility to grow gradually decreases towards the CONOPS related to scenario 1.
- **Operational cost-reduction:** The operational cost of HEA decreases by 20 percent [45] per aircraft. This is related to the number of conventional aircraft replaced by HEA and the passenger capacity. In addition, operational costs may decrease even more if regulators choose to calculate costs based on emissions and noise. These three variables cause that CONOPS Volta, Franklin and Kelvin score high on this KPI. These CONOPS contains of 25 percent HEA. Secondly, the passenger capacity of an aircraft is similar to the passenger capacity of convention aircraft. Lastly, the regulations are positive for HEA which means that the operational cost per aircraft decreases even more. CONOPS Siemens and Thompson score second highest even though HEA have a smaller passenger capacity. This has to do with a capacity of HEA that is twice as high compared to CONOPS Tesla and Siemens and medium positive regulations regarding HEA.
- **Total travel time:** The total travel time cannot be calculated based on research done previously in this study. Mainly because it is dependent of the number of destinations, the destination itself, the speed of HEA and other variables that are unknown at this moment. The total travel time is therefore based on the indicated time that you must be present before a flight. In case of Schiphol, you have to be present two hours before your European flight. In case of a regional airport the handling of passengers can be faster. This means that CONOPS Franklin has a higher score for this KPI compared to the other CONOPS.

Constraint 1 (safety), constraint 5 (maximum percentage HEA per (off-)peak hour) and constraint 6 (segregation) were already checked in scorecard I in chapter 7.

The remaining constraints are checked by means of the absolute numbers per KPI in scorecard II. With the outcome of the scorecard, it can be concluded that all CONOPS meet all constraints. That means that all CONOPS can be implemented to integrate HEA in the ATM-system.

8.3 GENERAL EVALUATION ASSESSMENT

This section describes a general evaluation of the assessment.

Scenario 1 - CONOPS Bell
Scenario 1 consists of the base scenario where no HEA are integrated in the ATM-system. The scorecard shows that runway capacity and complexity of implementation are the only KPIs that score points within this CONOPS. Since there are no HEA implemented in the ATM-system, there is no reduction in emissions and noise. This means that there is no possibility to grow, since this is one of the requirements from the minister of Infrastructure and Water Management [60].

Scenario 2 - CONOPS Edison
The outcome of the scorecard shows that even with a small percentage of HEA in the ATM-system, the effects are still of great value. Because of a large noise reduction, the total score of this CONOPS is relatively high compared to other scenarios. The implementation of HEA at the *Oostbaan* is not complex since the runway occupancy with only conventional aircraft is low. In addition, electric private jets can also be easily integrated because they have no outstanding deviating performances. The ROT of hybrid and electric private jets is equal to the ROT of conventional private jets. This means that there is no runway capacity decrease. Since this CONOPS is only located at the *Oostbaan*, it keeps the possibility open to combine this CONOPS with one of the CONOPS in scenarios 3, 4 and 5.

Scenario 3 - CONOPS Ferraris
CONOPS Ferraris received the highest total score of this scenario. The decrease in noise, CO_2- and NO_x-emissions are related to the number of HEA. Since the number of HEA is similar in both CONOPS, the scores for these three KPIs are equal as well. The decrease in nuisance for residents makes it possible for Schiphol Airport to grow to 540,000 movements per year. However, using only the current runways leads to a maximum capacity of 532,444 movements per year. This does not apply to CONOPS Tesla, since an extra runway is used. In addition, the difference in the final score is also based on the complexity of implementation and the possibility to growth. CONOPS Tesla received a lower score for the complexity of implementation. This has to do with opening up an extra runway which leads to bigger changes needed for the procedures of ATCOs and regulations. CONOPS Tesla scores higher for the possibility to grow since opening an extra runway gives the opportunity to make more movements per hour. Based on these KPIs, it is recommended to let 10 percent of HEA in peak-hours take-off and land at Schiphol Airport. These HEA are integrated in between the conventional aircraft on the current runways. It can be concluded that, based on these KPIs, it is not needed to open up an extra runway.

Scenario 4 - CONOPS Siemens
CONOPS Siemens shows that it is not needed to open up an extra runway during off-peak hours as well. Since the number of HEA is equal in both CONOPS, most KPI-scores match. The runway capacity, complexity of opening up an extra runway and the possibility to grow influences the final scores of the CONOPS. Since the noise nuisance, CO_2- and NO_x-emissions decreased, there is a possibility to grow to 540,000 movements per year. In case of CONOPS Siemens, only 536,788 movements per year can be handles. This has to do with the increased ROT of HEA (see chapter

4). Opening up an extra runway ensures that there is an opportunity to increase the number of movements per year. But a fourth runway also causes more complexity. That is why CONOPS Siemens scores higher on this KPI than CONOPS Thompson. It is important to notice that this CONOPS can transfer significantly less passengers (around 2 million per year) compared to CONOPS Ferraris and CONOPS Volta. This has to do with smaller HEA that are part of CONOPS Siemens. The weight of the KPIs are determined from the ANSP's point of view and the passenger capacity is less interesting. However, in chapter 5 one of the requirements states that the total passenger capacity can not decrease. Therefore, this CONOPS can only become reality when airlines choose a different business model (see A.9). To conclude, taking the weights into account, CONOPS Siemens is preferred over CONOPS Thompson.

Scenario 5 - CONOPS Franklin

In the last scenario, three CONOPS are compared that are located at both Schiphol Airport and regional airports. Based on the KPIs, it is recommended to let 25 percent of HEA take-off and land at regional airports during the day. The maximum capacity of RTHA is 87,600 movements per year. In 2019, 52,439 movements were handled [59] which means that there is still space left for around 35,000 movements. Lelystad Airport has a maximum capacity of 45,000 movements per year after the *Luchtruimherziening* [39][40]. This means that CONOPS Franklin does not exceed the maximum capacity of the regional airports. Since the maximum capacity of the runways is not linked to the ROT, the runway capacity can be fully utilized. CONOPS Volta is the only CONOPS of the three that has a decreased runway capacity. CONOPS Franklin scores a bit lower on the possibility to grow but compensates this with a better score on total travel time. In the end, the final scores of this assessment shows that CONOPS Volta and Franklin are good competitors. The final scores of these two CONOPS differ by 0.5 on a score around 100. In comparison with CONOPS Kelvin, it is not needed to open up an extra runway at Schiphol Airport. This will lead to extra complexity. Several final conclusions can be drawn from these three CONOPS. First of all, the maximum capacity of HEA that take-off and land at regional airports is around 25 percent. With this percentage located at regional airports, the maximum runway capacity is reached. Secondly, in CONOPS Franklin it is recommended to locate 25 percent of HEA on a regional airport. However, CONOPS Volta scores close to an equal score.

8.4 SENSITIVITY ANALYSIS

It practice, it can be that the decision maker has a strong preference for a certain CONOPS. The CONOPS can be assessed in a strategical way in order to influence the outcome. It is therefore important to apply a sensitivity analysis. As is said before, the independent variables are based on an assumption. This means that this affects the dependent variables as well. With this sensitivity analysis, it is studied how various sources of uncertainty in a model contribute to the model's overall uncertainty.

The independent variables that are of great influence of the outcome of the assessment are the landing weight, noise nuisance, CO_2- and NO_x-emissions. The landing weight subsequently effects the RECAT-categories, the approach and landing speed, ROT and runway capacity. The increase of the ROT is assumed to be 5, 10 and 15 percent dependent on the HEA's passenger capacity. If the landing weight becomes much heavier than expected, the runway capacity will decrease significantly. In this case, the final scores decrease of CONOPS that include more HEA which shows that it is less attractive for an ANSP to include HEA to a larger extent, based on the runway capacity.

The noise nuisance, CO_2- and NO_x-emissions are assumed as well, based on scientific research [37][29][15]. These three variables are of great importance for the Dutch minister of Infrastructure and Water Management since the aviation sector can only grow through demonstrable reduction of nuisance [60]. By varying these variables, the greatest possible growth can be created. Different values for these four independent variables are applied in the sensitivity analysis. The outcome shows that the final scores change minimally. The adjustments of the variables and the effects on the final scores can be found in table 8.3.

			Assessment	Sensitivity analysis					
			Base case	Small	Δ	Medium	Δ	Large	Δ
Indepent variables	CO2-decrease	gram/passenger/km	80	100	20	120	40	140	60
	NOX-decrease	gram/aircraft	1222,14	1500	277,86	1750	527,86	2000	777,86
	Noise-decrease	dB	10	12,5	3	15	5	20	10
	ROT 50-70p	%	10	15	5	20	10	25	15
	ROT 70-100p	%	15	20	5	25	10	35	20
Outcome	Scenario 3	Ferraris	72,329	72,212	0,161%	72,096	0,322%	71,862	0,645%
		Tesla	63,679	63,679	0,000%	63,679	0,000%	63,679	0,000%
	Scenario 4	Siemens	87,329	87,255	0,085%	87,180	0,170%	87,106	0,255%
		Thompson	78,478	78,478	0,000%	78,478	0,000%	78,478	0,000%
	Scenario 5	Volta	91,733	91,561	0,188%	91,388	0,376%	91,043	0,752%
		Franklin	92,250	92,250	0,000%	92,250	0,000%	92,250	0,000%
		Kelvin	84,250	84,250	0,000%	84,250	0,000%	84,250	0,000%

Figure 8.3: Sensitivity analysis - independent variables

The reason why the final scores do not change that much is because the outcome of the assessment is to a great extent based on the qualitative KPIs. A sensitivity analysis is performed on these KPIs as well. Scenario 3, 4 and 5 are each connected to two CONOPS located at Schiphol. One of these CONOPS makes use of the current runways, the other CONOPS opens up an extra runway. Furthermore, the CONOPS are identical to each other per scenario. This affects the outcome of the scorecard. Since only three KPIs are scored differently between these two CONOPS, namely the runway capacity, complexity of implementation and the possibility to grow. These latter two are KPIs that are scored in a qualitative way. In order to assess these KPIs more detailed, further research is needed (see 9).

It is possible that certain policies affect the scores of these two KPIs. The scores of the possibility to grow are indirect based on the decrease in noise nuisance, CO_2- and NO_x-emissions and the maximum capacity of the used runways. However, it can for example be that future policies state that the maximum capacity of Schiphol Airport cannot exceed 540,000 air traffic movements. In that case, the scores of this KPI should be equal to each other. The scores of the complexity of implementation can differ as well. The complexity of implementation depends on the consequences for human, machine and procedures in the ATM-system. Based on further research on these three, more detailed scores can be given to each CONOPS. This can lead to a CONOPS that integrates HEA at the current runways with a higher complexity to implement, compared to a CONOPS with an extra runway. This sensitivity analysis is applied on CONOPS Ferraris, Tesla, Siemens and Thompson. The final outcomes can be seen in figure 8.4.

			Assessment base case	Sensitivity analysis	
			Scores	Scores	Δ
Complexity of implementation	Scenario 3	Ferraris	10	2	8
		Tesla	0	8	-8
	Scenario 4	Siemens	10	5	5
		Thompson	0	6	-6
Possibility to grow	Scenario 3	Ferraris	3	4	-1
		Tesla	4	4	0
	Scenario 4	Siemens	6	6	0
		Thompson	7	6	1
Final score	Scenario 3	Ferraris	72,329	65,329	-10,715%
		Tesla	63,679	71,679	11,161%
	Scenario 4	Siemens	87,329	82,329	-6,073%
		Thompson	78,478	83,478	5,990%

Figure 8.4: Sensitivity analysis - qualitative KPIs scenario 3 and 4

It is also noteworthy that CONOPS Franklin and CONOPS Volta have a final score with a minimal difference. The KPI-scores that differ between these two CONOPS are the runway capacity, possibility to grow and the total travel time. Further research must be done to the total travel time from door-to-door for passengers. It can be that Schiphol Airport is better accessible for more passengers, due to the better infrastructure and higher population density. In that case, CONOPS Volta is assessed a higher score for this KPI and subsequently for the final score. For example, when the decision maker would like to bring HEA to Schiphol for status, these scores can be influenced by lack of extra research. The final scores in figure 8.5 shows that these different scores of two KPIs can influence the outcome.

		Assessment base case	Sensitivity analysis	
		Scores	Scores	Δ
Possibility to grow	Volta	8	9	-1
	Franklin	7	5	2
	Kelvin	10	10	0
Total travel time	Volta	0	1	-1
	Franklin	1	0	1
	Kelvin	0	1	-1
Final score	Volta	91,733	93,733	2,134%
	Franklin	92,250	89,250	-3,361%
	Kelvin	84,250	85,250	1,173%

Figure 8.5: Sensitivity analysis - qualitative KPIs scenario 5

A third sensitivity analysis is based on the weight of the KPIs. The weights are applied from the decision makers' point of view. However, many stakeholders are involved as is proved earlier in this research. Some KPIs are only related to the ANSP, others are related to important stakeholders. Implementing the weights of importance per KPI can be based on the relationships between the ANSP with other stakeholders. A sensitivity analysis is applied on the relationships with airports, airlines and governments. For airports the passengers capacity, possibility to grow and total travel time are important. Secondly, airlines find the passengers capacity and possibility to grow and operational cost more important. Lastly, the government aims to decrease the nuisance and emissions of the aviation sector. When one of these stakeholders become more important for the decision maker, the weight of the related KPIs will increase. Figure 8.6 shows a summary of the sensitivity analysis with different importance per stakeholders.

			Assessment	Sensitivity analysis					
			Base case	Airports	Δ	Airlines	Δ	Government	Δ
Weights KPIs	Runway capacity		25	16	-9	15	-10	15	-10
	Complexity of implementation		10	8	-2	5	-5	10	0
	Passengers capacity HEA		4	20	16	20	16	4	0
	Noise reduction		15	10	-5	10	-5	20	5
	CO_2-emissions-reduction		15	10	-5	10	-5	20	5
	NO_x-reduction		15	10	-5	10	-5	20	5
	Possibility to grow		10	20	10	20	10	5	-5
	Operational cost reduction		4	2	-2	8	4	2	-2
	Total travel time		2	4	2	2	0	4	2
Outcome	Scenario 3	Ferraris	72,329	64,549	10,756%	61,206	15,378%	71,269	1,465%
		Tesla	63,679	58,773	7,703%	58,416	8,264%	61,979	2,669%
	Scenario 4	Siemens	87,329	74,134	15,110%	74,533	14,653%	86,846	0,553%
		Thompson	78,478	68,229	13,059%	71,622	8,736%	77,435	1,329%
	Scenario 5	Volta	91,733	89,169	2,795%	91,190	0,592%	89,690	2,227%
		Franklin	92,250	88,500	4,065%	90,500	1,897%	90,500	1,897%
		Kelvin	84,250	85,500	-1,484%	90,500	-7,418%	81,000	3,858%

Figure 8.6: Sensitivity analysis - weights KPIs

It can be seen that the final outcome of the assessment does not differ compared to the base case assessment for CONOPS related to scenario 3 and 4. However, it is striking that the results change for the CONOPS related to scenario 5. Firstly. it can be seen that CONOPS Volta scores highest in case of a good relationship between the airports and airlines. This is different compared to the base case assessment where CONOPS Franklin scores best. In that case it is recommended to integrate HEA at Schiphol Airport instead of a regional airport. Secondly, CONOPS Franklin and CONOPS Kelvin score an equal final score when the weights of important KPIs for airlines increase. In that case, CONOPS Volta scores highest and is therefore recommended. Lastly, in case of a good relationship with the government, the recommendation of implementing CONOPS Franklin, remains the same.

8.5 CONCLUSION

In this chapter the nine CONOPS are assessed on the basis of KPIs. The KPIs that have been determined earlier include the desires, like the passenger capacity, of other stakeholders. However, the CONOPS are assessed from the point of view from ANSPs by applying weights of importance to the KPIs. The purpose of this chapter is to determine the CONOPS potential for each scenario, from the ANSP's point of view. Scenario 1 is the base case and for scenario 2 only one CONOPS was established. For this scenario HEA make use of the Oostbaan to take-off and land. CONOPS Ferraris matches scenario 3 best. In this CONOPS a start has been made to reduce emissions and noise without opening up an extra runway. In case of scenario 4, CONOPS Siemens is the potential CONOPS. Emissions decrease significantly but the number of passengers is limited. A requirement is therefore that airlines choose a different business model. This can be a signal in the future; when airlines change their business model, this scenario is most likely to become reality. Scenario 5 was linked to three CONOPS of which CONOPS Franklin, located at a regional airport, scores best. It is interesting to see that CONOPS Volta, located at the current runways of Schiphol Airport, is a good competitor as it scores just slightly lower.

In addition, a sensitivity analysis is performed in order to check how various sources of uncertainty in a model contribute to the model's overall uncertainty. In the sensitivity analysis, the influence of the independent variables, qualitative variables and the weights of the KPIs are checked. Adjusting the weights per KPI and the uncertainty of independent variables do not have a major influence on the outcome. It can however be concluded that the qualitative KPIs influence the outcome to a large extent.

Phase IV of this research consists of scorecard II. Now that this second scorecard has been completed in this chapter, it can be concluded that phase IV is finished. The purpose of this chapter is to determine the CONOPS potential for each scenario. The outcome of this assessment shows the answer on this research question.

9 CONCLUSION AND DISCUSSION

This research was an attempt to explore potential CONOPS to integrate HEA in the ATM-system. The results obtained from this study can be used in order to do further research into more detailed CONOPS and the (positive) effects on feasibility, sustainability and efficiency. This research consists of four parts. Every part is completed and the scorecard in chapter 8 shows which CONOPS is potential per scenario from the ANSP's point of view. In section 9.1 an answer to the main research question is given. This is based on the answers of the sub research questions. In section 9.3 the recommendations are given for the data, further research and other ANSPs.

9.1 CONCLUSIONS

This section presents the conclusions of this research. In order to answer the main research question, several sub research questions were determined. These sub research questions and finally the main question are answered in subsection 9.1.1. In subsection 9.2, the general conclusion of this research is given.

9.1.1 Answers (sub) research questions

This subsection answers the sub- and main research questions. The main research question of this study is:

What are potential concepts of operations for the integration of HEA in the air traffic management system in 2035?

Four sub research questions are defined in order to answer the main research question. These can be found below along with the answers per question.

SQ1. What are the deviating performances and effects of HEA (compared to conventional aircraft) and the associated consequences for the ATM-system?
The main difference between a conventional aircraft and HEA is the replacement of fuel with a battery. The batteries have a low power-to-weight ratio and are therefore heavier than fuel. This leads to three deviating technical performances: range, passenger capacity and the increased approach and landing speed. Due to the batteries weight, the design of the aircraft has to cut back on the range and the passenger capacity. It can be concluded that the maximum range of HEA is approximately 1000km. The maximum passenger capacity is 100 passengers. That means that with this maximum range and passenger capacity, HEA can only be used for regional or short-haul flights. Lastly, since the weight of the battery does not decrease over the flight (different from fuel), the landing weight of HEA is much higher.

There are also six deviating effects of HEA. CO_2-emissions decreases with 80 gram/passenger/km for HEA in the ATM-system. For NO_x a value of 1222.14 gram/aircraft applies. HEA have a reduced aircraft noise up to 85 percent which equals -10 dBa for commercial aircraft and -19 EPNdB for private jets. Indirect effects of HEA are the shift in the aviation network from hub-and-spoke to more point-to-point flights. Furthermore, the operational costs for airlines decrease up to

20 percent since airlines do not have to pay for fuel. Lastly, an increased landing weight leads subsequently leads to a decreased maximum runway capacity.

SQ2. What is the objective and what are the requirements, constraints and KPIs of the design space?

The objective of the design space is that the CONOPS should be able to handle conventional, hybrid and electric aircraft. This means that the CONOPS should handle the take-off and landing of the three types of aircraft, which forms the functional requirements. The non-functional requirements are that take-off and landing can only be located at current runways. In addition, the CONOPS should be efficient in passenger capacity. Lastly, the CONOPS should be environmentally friendly in terms of CO_2, NO_x and noise. This can lead to growth in air traffic movements per year in the Netherlands, without increasing the nuisance for residents.

The constraints say something about the capacity, safety, regulations or technical performances that the CONOPS must meet. Next to the objective, requirements and constraints the KPIs are determined. These KPIs are used to assess the CONOPS per scenario. The KPIs are as following: runway capacity, complexity of implementation, noise-, CO_2-reduction and NO_x-reduction, possibility to grow, operation cost reduction and total travel time.

SQ3. What are possible future scenarios to take into account?
It can be concluded that the scenario space exists of two driving forces, namely the technology breakthrough and the decisions of regulations regarding HEA. In this scenario space, five scenarios are defined. For each scenario, consisting of a specific combination between the two driving forces, absolute values are given to the dependent variables.

The outcome of this analysis are five scenarios. Scenario 5 is the most positive scenario with 25 percent HEA in the ATM-system. This gradually decreases with scenario 1 as the most negative scenario. This latter one represents the base case. Each scenario consists of six characteristics. These characteristics are the percentage of HEA in the ATM-system, the range and passengers per HEA, the type of aircraft and electrification and the expected approach and landing speed. Each characteristic is assigned an absolute value. This has been done with the minimum and maximum performances of HEA, which are the result of the data analysis. The specifications can be found in figure 9.1.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Positive regulations regarding HEA	None	Positive	None	Medium	Positive
	Technology breakthrough	Low	Low	High	Medium	High
	Percentage HEA in ATM-system [%]	0	5	10	20	25
	Range [km]	0	500	1000	500	1000
	Passenger capacity [pax/HEA]	0	19	100	50	100
	Type of aircraft	N.A.	Private jets	Private jets, airlines	Private jets, airlines	Private jets, airlines
	Type of electrificiation	N.A.	Hybrid and electric aircraft	Electric aircraft	Hybrid and electric aircraft	Electric aircraft
Hybrid aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1	1 (compared to conventional, 100-passengers)	1
Electric aircraft	Approach and landing speed (compared to conventional, similar size unless indicated otherwise)	N.A.	1	1,15	1,1 (compared to conventional, 100-passengers)	1,15

Figure 9.1: Characteristics per scenario

SQ4. What are the feasible CONOPS per scenario that have the highest pressure on the ATM-system?
There are nine CONOPS determined that are each linked to a scenario. They consist of a feasible combination between three variables: time, airport and runway. These nine CONOPS are determined based on the pressure on the ATM-system when a

certain percentage of HEA is integrated into the ATM-system with certain performances.

Scenario 1 and 2 are both connected to only one CONOPS. Scenario 3 is combined with CONOPS Ferraris and Tesla that are both located at Schiphol Airport during peak hours. These combinations study whether it is better to make use of the current runways or make use of an extra runway, in case of ten percent HEA. The same applies for CONOPS Siemens and Thompson, related to scenario 4 where only off-peak hours are considered. In addition, 20 percent HEA with a shorter range and smaller passenger capacity have to be integrated in this scenario. Lastly, scenario 5 is combined with CONOPS Volta, Franklin and Kelvin. These three combinations make it possible to study whether it is better to accommodate 25 percent of HEA at Schiphol airport on the current runways, at Schiphol airport with one extra runway or at the regional airports. The details per CONOPS can be found in figure 9.2.

CONOPS	Linked to CONOPS	Percentage HEA	Range	Passengers capacity per HEA	Airport	Time	Runway
Bell	1	0	N.A.	N.A.	N.A.	N.A.	N.A.
Edison	2	5	500	19	Schiphol	All day	Oostbaan
Ferraris	3	10	1000	100	Schiphol	Peak-hours	Current runways
Tesla	3	10	1000	100	Schiphol	Peak-hours	Current runways + 1
Siemens	4	20	500	50	Schiphol	Off-peak hours	Current runways
Thompson	4	20	500	50	Schiphol	Off-peak hours	Current runways + 1
Volta	5	25	1000	100	Schiphol	All day	Current runways
Franklin	5	25	1000	100	Regional airport	All day	Current runways
Kelvin	5	25	1000	100	Schiphol	All day	Current runways + 1

Figure 9.2: Variables per CONOPS

Main research question:
What are the potential concepts of operations for the integration of HEA in the air traffic management system in 2035?
Since the future is unknown, potential CONOPS are determined per scenario. The feasible CONOPS with the highest pressure on the ATM-system per scenario are assessed on the KPIs. Potential CONOPS per scenario are:

- Scenario 1 - CONOPS Bell: Scenario 1 presents the base case where no HEA are integrated in the ATM-system. CONOPS Bell is therefore not compared to another CONOPS for this scenario. The emissions and noise nuisance do not decrease as a result of HEA. This means that the minister of Infrastructure and Water Management does not authorize the Dutch aviation sector to increase the number of movements per year.

- Scenario 2 - CONOPS Edison: CONOPS Edison locates hybrid and electric private jets on the *Oostbaan*. Since the noise reduction of hybrid and electric private jets is twice the noise reduction of commercial HEA, the total noise reduction is significantly large for five percent of HEA. The private jets have a passenger capacity up to 19 passengers which means that the runway occupancy time does not increase. Subsequently, the runway capacity is equal to the runway capacity where only conventional aircraft are integrated.

- Scenario 3 - CONOPS Ferraris: In case scenario 3 becomes reality, it is recommended to let 10 percent of HEA integrate on the current runways during peak hours. Integrating 10 percent of HEA causes a decrease in noise, CO_2- and NO_x-emissions. This decrease in nuisance for residents makes it possible for Schiphol Airport to grow to 540,000 movements. However, using only the current runways leads to a capacity of 532,444 movements per year. CONOPS Tesla can handle 540.000 movements since there is more space on four runways but the complexity of a fourth runway during peak-hours does not outweigh these extra movements. That is why CONOPS Ferraris with a lower maximum capacity received a higher final score.

- Scenario 4 - CONOPS Siemens: For scenario 4 it is recommended to implement CONOPS Siemens. This CONOPS is located at Schiphol Airport and let smaller commercial HEA take-off and land at the current runways during off-peak hours. This CONOPS does not meet the non-functional requirement that it should be efficient in passenger capacity. But from the point of view of the ANSP, this is still a potential CONOPS to implement. Since the noise nuisance, CO_2- and NO_x-emissions decreases, it is possible to grow to 540,000 movements. However, since HEA have a longer ROT the airport can only handle 536,788 movements per year.

- Scenario 5 - CONOPS Franklin: This scenario consists of a demand of airlines to let 25 percent HEA take-off and land at a Dutch airport. It is recommended to let these aircraft take-off and land at a regional airport at the current runways. The noise nuisance, CO_2- and NO_x-emissions decreases significantly since one-fourth of the aircraft cause much less nuisance. This makes it possible to locate HEA at regional airports. CONOPS Franklin shows that with the currently stated capacities, it is possible to move up to 25 percent HEA to regional airports. A CONOPS with a higher percentage HEA (not part of this research) will exceed the maximum capacity of regional airports. 25 percent of HEA equals 74,460 movement. 45,000 movements can be located at Lelystad airport (after the *Luchtruimherziening* [40]). The other flight movements can be located at RTHA. In this conclusion it is important to mention that CONOPS Volta is good competitor since the final scores of the assessment differs by 0.5 on a score around 100.

9.2 GENERAL CONCLUSION

Overall, it can be concluded that HEA can be treated as a conventional aircraft. Even with deviating performances, the integration of HEA entails a limited implementation complexity. When HEA are integrated on the runways already in use, the runway capacity decreases minimally. Using an extra runway influences the complexity of the CONOPS and does not outweigh the loss of runway capacity. The advantage is that HEA make the TWR and APP operations more sustainable. The noise-nuisance, CO_2- and NO_x-emissions decrease significantly. Since residents experience less nuisance of air traffic, airports can grow in air traffic movements and total passengers per year [60]. This is an advantage for airlines and airports. However, the total passenger capacity of airports and airlines is related to the definitive passenger capacity of HEA. When this passenger capacity is relatively small, this will effect the airlines operations significantly. Since airports and airlines want to maintain their passenger capacity, HEA with a smaller passenger capacity can only be integrated when the business model of airlines are adjusted.

There is also the possibility to move a percentage of HEA to regional airports. For the regional airports Lelystad and RTHA, a maximum of 25 percent applies. This is the maximum percentage of HEA that can be moved to regional airports without resulting in more complexity of the new CONOPS. HEA can be integrated like a conventional aircraft at these airports. However, the sensitivity analysis shows that the outcome of the assessment is mainly based on the qualitative KPIs. It is therefore recommended to do further research on these KPIs. Further recommendations are given in the next section.

This study is a preliminary research for ANSPs to integrate HEA in the ATM-system. When ANSPs at other airports want to integrate HEA, the structure of this case study can be used. The independent performance variables of HEA are independent of the ANSP and airport of implementation. These can therefore be used for all ANSPs. The other independent variables are location-dependent.

9.3 RECOMMENDATIONS

In this section, the limitations and recommendations are given that are part of the results of this study. First, the limitations and recommendations for the data is given in subsection 9.3.1. After that, a recommendation is given for further research in subsection 9.3.2. Lastly, a recommendation for ANSPs abroad is given in subsection 9.3.3

9.3.1 Recommendations for data

Since aircraft manufacturers are still exploring the maximum power-to-weight ratio, there is a lack of exact data of the performances of HEA. This has led to several assumptions being made for independent variables. Attempts have been made to make the assumptions as robust as possible by means of the data analysis. The input of the data analysis consists of data from aircraft manufacturers who make statements about the expected performances. This data has been analyzed and deviating data has been removed. From here, the averages are calculated per RECAT-category. Since the expected performances are all related to one another (see figure 4.3 in chapter 4), the power-to-weight ratio has a great influence on all performances at once. However, the future must show whether these expected performances can be achieved. The following list shows the assumptions that have been made based on the data analysis. In addition, the effects are described when the maximum power-to-weight ratio is not reached.

- MTOW: Based on the expected MTOW of aircraft manufacturers, the RECAT-categories are assigned to HEA. It is concluded that the RECAT-categories of HEA are equal to the RECAT-categories of conventional aircraft, even with an increased MTOW. Since the categories do not differ, the impact of HEA in the ATM-system is minimal. However, the MTOW of HEA is a direct effect on the maximum power-to-weight-ratio. When the ratio is greater than expected, the MTOW increases. This effects the assignment of the RECAT-categories and the impact on the ATM-system.

- passenger capacity of HEA: the assumption is made that the maximum passenger capacity is 100 passengers. But when the maximum power-to-weight ratio is not reached, the maximum passenger capacity decreases. This makes it less interesting for airlines to purchase HEA. When there is a smaller percentage of HEA in the ATM-system, it influences the maximum runway capacity positively.

- Increased ROT of HEA: an assumption is made that the ROT of HEA increases with 5, 10 and 15 percent, dependent on the MTOW and the passenger capacity of HEA. This increase in percentage is applied on a rough estimation of the ROT of conventional aircraft. The ROT of conventional aircraft is calculated roughly by dividing one hour by the number of conventional aircraft. It is not assumed that the aircraft that take-off and land at the runway consist of a mix of different types of aircraft. It is recommended to analyze the current aircraft type mix per runway per hour. This shows exactly which conventional aircraft can be replaced by HEA. It also shows what the exact decrease of runway capacity will be.

- Noise-reduction: Noise increases with intensity. That means that when noise doubles, noise increases from 60dB to 63dB. This intensity is not part of the calculations which makes the outcome of noise-reduction less reliable. In addition, the perception of noise is very complex and subjective. Residents experience more nuisance if more aircraft are flying with less noise, than less aircraft with more noise in total.

- Other assumptions that are made are the range and operational cost of HEA. The impact on the ATM-system of these assumption is however lower. When the assumptions of the range and operational cost are disappointing, it influences the purchase of HEA by airlines. The impact on the ATM-system is therefore less.

In addition, other assumptions, independent of the data analysis, have been made that influence the outcome of the scorecard.

- Pilots choose for the noise- and emission-mode during take-off and landing. This influences the outcome of the decrease of noise-nuisance, CO_2- and NO_x-emissions. This can be solved by adding percentages of electric aircraft, hybrid aircraft in noise- and emissions-mode and hybrid aircraft in economical-mode.

- The CONOPS per scenario are compared to the current situation. The base case does not take future changes into account that are unrelated to HEA. Examples of future changes are the advent of other sustainable aviation fuels, more sustainable conventional aircraft designs and the revised airspace. It is recommended that these future changes be included in further research in due course.

- The assumption is made based on literature research that HEA are expected in 2035. This assumption was partly based on the expected growth of aviation. However, during this study the COVID-19 crisis started. The aviation sector has been seriously affected by this. It is expected that the number of movements at Schiphol will be back at its old level in 2023. In addition, aircraft manufacturers suffer from this and therefore freeze the HEA-projects. It may therefore be that 2035 is no longer a correct time estimate.

In general, an attempt has been made to make the assumptions as robust as possible. However, due to the lack of data the assumptions are still a rough estimation. That is why an explorative research was chosen. In the next subsection a recommendation is given how to perform further research when the independent variables are more reliable.

9.3.2 Recommendations for further research

Since this is an exploratory research, no recommendation of implementation will be given in this discussion. HEA are not expected in the next 15 years which means that there is time left for further research. In subsection 9.3.1, it is mentioned that the independent variables are based on assumptions. For all the assumptions above it is recommended to study the performances and effects of HEA repeatedly when the advent of HEA is closer in time. When the power-to-weight ratio becomes more reliable, all performances and effects become more reliable as well. Subsequently, the dependent variables become more reliable and the outcome of this research becomes more robust. When aircraft manufacturers and aviation organizations publish more reliable data, they can form the input of the same research. The structure of the research can be preserved. It ensures that possibilities are sought in a divergent way and future scenarios keep options open until a scenario becomes reality.

When the data from aircraft manufacturers are more reliable, it is recommended to design the CONOPS more in detail. For example, take into account the specific times that HEA will arrive and take-off (related to charging/battery swap), preference order and runway combinations. In addition, stakeholders used in this study will have a stronger view of HEA as the data of performances are known. For instance, when airlines know what the decrease in operational costs will be, they can give a more accurate number of HEA that they want to purchase.

All of the above ensures that the input for the assessment becomes more reliable. To carry out the assessment, it is important to do more detailed research per KPI. The sensitivity analysis shows that the outcome of the assessment is mainly based on the quantitative KPIs. By starting detailed studies per quantitative study, these can be scores more reliable. Other KPIs that are studied roughly, are the noise-decrease and maximum runway capacity. These detailed studies also ensure that the results per KPI do not only depend on the number of HEA per CONOPS to a great extent. In this research, the number of HEA in the ATM-system has too much influence on the outcome of the scorecard. With a separate detailed study per KPI, it can be said with more certainty whether the CONOPS meet the constraints. It is up to ANSPs, to further elaborate the CONOPS at a much more detailed level.

In addition, for further research is it interesting to look at the effects of combinations between CONOPS. This applies to CONOPS that are located at different runways and/or airports. For example, CONOPS Bell and CONOPS Ferraris can be combined in order to accommodate 15 percent of HEA. In a really successful scenario, 25 percent of HEA can be located at regional airports (CONOPS Franklin) in combination with 25 percent of HEA at Schiphol Airport (CONOPS Volta). In case of a successful scenario (over a longer period of time) is it interesting to research when deviating performances of HEA become the set-up of the network and ATM-system. In that case, it may be possible that conventional aircraft are the exception.

Lastly, a multi-criteria analysis has now been carried out in this study as assessment, since there are still a lot of uncertainties for the independent and subsequently dependent variables. That is why it did not make sense to assess the CONOPS based on the cost and benefits. When all the recommendation mentioned above are applied in further research, it is recommended to apply a cost-benefit analysis for the assessment.

9.3.3 Recommendations for other ANSPs

This research was carried out by means of a case study at Dutch airports. When looking at integrating HEA in the ATM-system at a different location, it is recommended to keep the same structure of this study. However, minor adjustments have to be made. In addition, the recommendations described in subsections 9.3.1 and 9.3.2 also apply to ANSPs. The adjustments are:

- In the Netherlands there is almost no regional air traffic. This means that no flights are offered with both departure and arrival within the Netherlands. When HEA are integrated in a country where regional air traffic is involved, the advent of HEA influences the ATM-system more. The distances of regional air traffic, the maximum range and passenger capacity of HEA are a better match. That means that the percentage of HEA in the ATM-system can increase significantly. The role of regional airports is therefore becoming much more interesting.

- In the Netherlands, there are relatively many runways in use. It is known that this is not always the case at other airports. When only one runway is in use at a bigger airport, this can influence the impact of deviating performances. It is recommended to take this into account.

- It is recommended to keep in close contact of the operations of other ANSPs. When HEA are integrated in the ATM-system, it is important to share experiences of operations with ANSPs abroad.

BIBLIOGRAPHY

[1] AHEV (2019). Ontwerp actieprogramma hybride elektrisch vliegen (ahev).

[2] Airbus (2020). Airbus electric flight - e-fan x. https://www.airbus.com/innovation/future-technology/electric-flight/e-fan-x.html. Accessed: 2019-12-8

[3] Anton, F., Olaf, O., Hetz, J., and Olbrechts, T. (2018). Siemens eaircraft - disrupting the way you will fly!

[4] Bar-Yohay, O. (2019). Eviation alice.

[5] Benegas Jayme, D. (2019). Evaluation of the hybrid-electric aircraft project airbuse-fan x. doi: 10.15488/9353.

[6] Blockley, R. (2016).Green Aviation. John Wiley Sons Inc.

[7] BOEING (2019). Boeing sugar volt: Boeing's hybrid electric aircraft. https://www.boeing.com/features/2012/05/sugar-volt-boeing-hybrid-electric-aircraft-05-2-12.page. Accessed: 2019-12-09.

[8] CBS (2019). Hoeveel uitstoot veroorzaakt de nederlandse luchtvaart?. https://www.cbs.nl/nl-nl/faq/luchtvaart/hoeveel-uitstoot-veroorzaakt-de-nederlandse-luchtvaart-. Accessed: 2019-11-12.

[9] Cinar, G., Mavris, D., Emeneth, M., Schneegans, A., Riediger, C., Fefermann, Y.,and Isikveren, A. (2017). Sizing, integration and performance evaluation of hybrid electric propulsion subsystem architectures. *55th AIAA Aerospace Sciences-Meeting, Grapevine*, TX, USA.

[10] Costello, L. A. (2011). State of the art of piloted electric airplanes, NASA's centennial challenge data and fundamental design implications.

[11] Darecki, M., Edelstenne, C., Enders, T., Fernandez, E., Hartman, P., Herteman, J.,Kerkloh, M., King, I., Ky, P., Mathieu, M., Orsi, G., Schotman, G., Smith, C.,and Worner, J. (2011). Flight path 2050 europe's vision for aviation.

[12] de Vries, R., Brown, M., and Vos, R. (2018). A preliminary sizing method for hybrid-electric aircraft including aero-propulsive interaction effects. *2018 Aviation Technology, Integration, and Operations Conference.* Doi: 10.2514/6.2018-4228

[13] Donners, B. and Heufke Kantelaar, M. (2019). Emissies van korte afstandsvluchten op nederlandse luchthavens.

[14] Dym, C., Little, P., Orwin, E., and Spjut, E. (2009). Engineering design: A project-based introduction. John Wiley and sons.

[15] EASA (2017). Aircraft engine emissions databank. https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissionsdatabank. Accessed: 2020-04-08.

[16] Easyjet (2020). Leading the industry on sustainable travel. https://www.easyjet.com/en/sustainability. Accessed: 2019-12-08.

[17] Enserink, B., Kwakkel, J., Bots, P., Hermans, L., Thissen, W., and Koppenjan, J. (2010). Policy analysis of multi-actor systems. LEMMA.

[18] Fleckenstein, D. and Platts, T. (2019). Electric aircraft working group report.

[19] Galletta, A. (2013). Mastering the Semi-Structured interview and beyond. New York University Press.

[20] Graham, R., Adamson, T., Merlo, P., Joe, S., and Brenner, F. (2015). European wake turbulence categorisation and separation minima on approach and departure.

[21] Heathrow-Airport (2018). Electric aircraft landing fees - the first electric aircraft at Heathrow won't pay landing fees for a year. https://www.heathrow.com/latest-news/first-electric-aircraft-at-heathrow-airport-wont-pay-landing-fees-for-a-year. Accessed: 2020-05-06.

[22] Hermetz, J., Ridel, M., and Doll, C. (2016). Distributed electric propulsion for small business aircraft: A concept-plane for key-technologies investigations. *30th ICAS Congress, Daejeon*, South Korea.

[23] Heufke Kantelaar, M. (2019). Night-time train travel - a stated-preference study in to the willingness to use night trains for european long-distance travel.

[24] Hoogreef, M., Vos, R., de Vries, R., and Veldhuis, L. (2019). Conceptual assessment of hybrid electric aircraft with distributed propulsion and boosted turbofans. *AIAA Scitech 2019 Forum.* Doi: 10.2514/6.2019-1807

[25] IATA (2018). Iata forecast predicts 8.2 billion air travelers in 2037. https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx. Accessed: 2019-11-12

[26] IATA (2019). Fuel for thought - overcoming the challenges of jet fuel use will be vital for aviation growth.

[27] ICAO (2019). Electric and hybrid aircraft platform for innovation (e-hapi). https://www.icao.int/environmental-protection/Pages/electric-aircraft.aspx. Accessed: 2019-12-09.

[28] Kipp, D. and Nessi, D. (2017). Guidance for planning, design and operations of airport communications centers. *ACRP Research report*, 182(3):40–53. Doi: https://doi.org/10.17226/24980

[29] KLM (2019a). Air france-klm takes care: Sustainability report 2018.

[30] KLM (2019b). Fly responsibly. https://flyresponsibly.klm.com/gb_en#home. Accessed: 2020-05-06.

[31] Kolos-Lakatos, T. and Hansman, R. (2013). The influence of runway occupancy time and wake vortex separation requirements on runway throughput.

[32] LVNL (2018a). 'altijd, veilig, duurzaam en kostenbewust'. https://www.lvnl.nl/over-lvnl/corporate-visie-strategie/altijd-veilig-duurzaam-en-kostenbewust. Accessed: 2020-04-28.

[33] LVNL (2018b). Feiten. https://www.lvnl.nl/nieuws/nieuwsberichten/zes-interessante-feiten-over-luchtverkeersleiding. Accessed: 2019-12-16.

[34] LVNL (2019). Schiphol tower en approach. https://www.lvnl.nl/over-lvnl/taken-lvnl/luchtverkeersdiensten/schiphol-tower-en-approach. Accessed: 2019-11-27.

[35] LVNL (2020). Veiligheidsmanagement en -onderzoek. https://www.lvnl.nl/veiligheid/veiligheidsmanagement-en-onderzoek. Accessed: 2019-12-16.

[36] Lyles, L., Smith, P., and Aldrich, A. E. a. (2016). Commercial Aircraft Propulsion and Energy Systems Research. The national academies press, Washington DC.

[37] Min, S., Mavris, D., and Lim, D. (2016). Aircraft noise reduction technology and airport noise analysis for general aviation revitalization. *15th AIAA Aviation Technology, Integration, and Operations Conference.* Doi: 10.2514/6.2015-2389

[38] Ministerie van Infrastructuur en Waterstaat (2012). Luchtruimvisie bijlage rapport3: Opgaven en knelpunten nederlands luchtruim.

[39] Ministerie van Infrastructuur en Waterstaat (2019a). Ontwikkeling lelystad airport. https://www.rijksoverheid.nl/onderwerpen/luchtvaart/ontwikkeling-lelystad-airport. Accessed: 2020-01-13.

[40] Ministerie van Infrastructuur en Waterstaat (2019b). Samenwerken aan het luchtruim - startbeslissing programmaluchtruimherziening.

[41] Ministerie van Infrastructuur en Waterstaat (2020). Verantwoord vliegen naar 2050; ontwerp-luchtvaartnota 2020-2050.

[42] Osborn, A. (1949).Your creative power. Read Books.

[43] Ostertagovaa, E., Kovac, E., Ostertagb, O., and Malegab, P. (2012). Application of morphological analysis in the design of production systems. *Procedia Engineering*, 48(3): 507–512. Doi: 10.1016/j.proeng.2012.09.546

[44] Overheid (1992). Wet luchtvaart. https://wetten.overheid.nl/BWBR0005555/2020-04-01. Accessed: 2020-04-01.

[45] Plotner, K., Schmidt, M., Baranowski, M., Askin, I., and Hornung, M. (2013). Operating cost estimation for electric-powered transport aircraft. *Aviation Technology, Integration, and Operations Conference.*

[46] Pornet, C. and Isikveren, A. (2015). Conceptual design of hybrid-electric transportaircraft. *Progress in Aerospace Sciences*,79:114–135.

[47] Rijksoverheid (2020). Kabinet zet financiele steun klaar voor klm. https://www.rijksoverheid.nl/actueel/nieuws/2020/04/24/kabinet-zet-financiele-steun-klaar-voor-klm. Accessed: 2020-05-20.

[48] Sachs, G. (2012). Flight performance issues of electric aircraft. *AIAA Atmospheric-Flight Mechanics Conference*. Doi: 10.2514/6.2012-4727

[49] Schaar, D. and Sherry, L. (2010). Analysis of airport stakeholders. *Integrated Communic tions Navigation and Surveillance Conference (ICNS)*, pages J4–1.

[50] Schiltgen, B., Freeman, J., and Hall, D. (2016). Aeropropulsive interaction and ther-mal system integration within the eco-150: A turboelectric distributed propul-sion airliner with conventional electric machines. *16th AIAA Aviation TechnologyIntegration and Operations Conference.*

[51] Schiphol Group (2018). Destination: flying greener. https://www.schiphol.nl/en/schiphol-group/page/promoting-more-sustainable-aviation/. Accessed: 2020-04-28.

[52] Schiphol Group (2019). Flight paths and runway use. https://www.schiphol.nl/en/schiphol-as-a-neighbour/page/flight-paths-and-runway-use/. Accessed: 2019-11-18.

[53] Schiphol (2020). Jaarverslag 2019.

[54] Schiphol-Airport (2018). Schiphol tarieven en voorwaarden.

[55] Stoll, A. and Mikic, G. (2016). The analysis of “more electric engine” technology to improve the environmental performance of aircraft jet engine. *16th AIAAAviation Technology Integration and Operations Conference.*

[56] Swan, W. and Adler, N. (2006). Aircraft trip cost parameters: a function of stage length and seat capacity.*Transportation Research Part E*, 42:105–115. Doi: 10.1016/j. tre2005.09.0046.2012-4727

[57] Thompson R., Sachdeva N., B. M. (2018). Aircraft electrical propulsion – onwards and upwards.

[58] Trawick, D. (2018). A methodology for the determination of optimal operational schedules of hybrid electric architectures.

[59] van der Kleij, S. (2017). Ambitie Rotterdam The Hague Airport.

[60] van Nieuwenhuizen Wijbenga, C. (2019). Ontwikkeling schiphol en hoofdlijnen luchtvaartnota.

[61] Werij, H. (2019). Concept ahev v.0.54.

[62] Zart, N. (2019). New electric aircraft motor lab aims for1mw electric airplane motor. https://cleantechnica.com/2019/08/27/new-electric-aircraft-motor-lab-aims-for-1mw-electric-airplane-motor/ Accessed: 2019-12-16.

[63] Zuidberg, J. and Vinkx, K. (2018). Capacity demand at schiphol airport in 2023.

B | DATA ANALYSIS

At this moment there are many companies or start-ups who are designing HEA which can be applied to regional-, general or even large commercial aviation. 36 of these concept HEA aircraft are listed in an overview that can be found in figure B.5 and figure B.6. This overview consists of the performances like range, MTOW, number of passengers per aircraft. The overview is created based on the data from Roland Berger [57], ICAO [27] and complemented with information online from aircraft manufacturers and from interviews.

After collecting the data, a data analysis is performed to substantiate chapter 4. Since not all companies and start-ups publish the data of all performances, there are some gaps in the overview which makes the analysis a supportive tool. The overview can be found in figure B.5 and figure B.6 show the overview of the data that is collected in order to analyse the performances of HEA.

It is determined that several characteristics and performances of HEA are connected (see chapter 4 for explanation). The figures below substantiate this conclusion. Figure B.1 shows that there are multiple concept HEA that can transfer up to 4 passengers. Starting from 8 to 135 passengers, only one concept per passenger capacity is being worked on.

Capacity [pax/aircraft]	Number of concepts
1	10
2	13
4	4
8	1
9	1
11	1
18	1
40	1
90	1
100	1
120	1
135	1

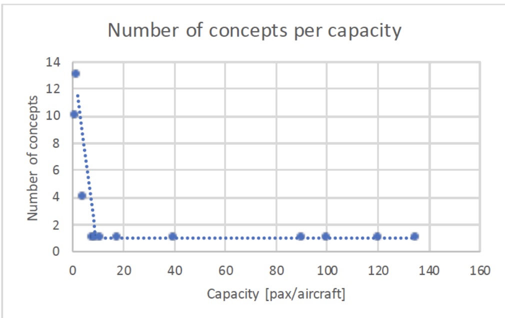

Figure B.1: Number of concepts - pax

When making a distinction between hybrid aircraft and electric aircraft, it can be seen in figure B.2 that the electric aircraft can transfer 1 to 11 passengers. For a medium passenger capacity (18-100 passengers) the concepts are all hybrid. Lastly, there is one electric aircraft with 120 passengers and one hybrid aircraft with a capacity of 135 passengers.

There are five HEA that have a valid capacity for airlines to deploy.

- Project 804: 40 passengers - Regional - Hybrid
- Airbus/Rolls Royce E-thrust: 90 passengers - Large commercial - Hybrid
- Airbus E-fan X: 100 passengers - Large commercial - Hybrid
- Wright Electric/Easyjet: 120 passengers - Large commercial - Electric
- Boeing Sugar Volt: 135 passengers - Large commercial - Hybrid

Passenger capacity [pax/aircraft]	Electric aircraft concepts	Hybrid arcraft concepts
1	9	1
2	11	2
4	1	3
8	1	0
9	1	0
11	1	0
18	0	1
40	0	1
90	0	1
100	0	1
120	1	0
135	0	1
Total:	25	11

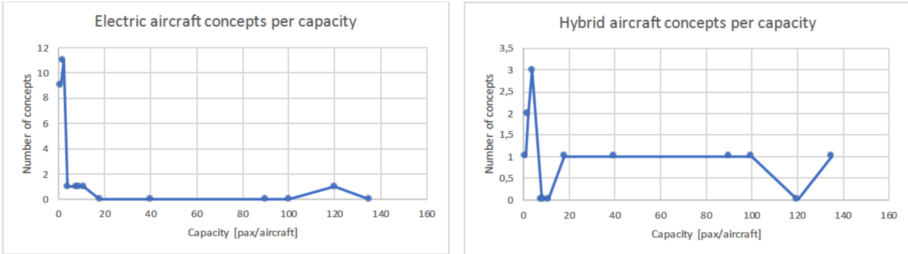

Figure B.2: Number of concepts - pax for HEA

Figure B.3 shows the relation between the range and the capacity. It can be seen that the five HEA mentioned above are outliers. Two of them, namely the Airbus E-fan X and the Airbus E-thrust are not assigned a range. The aircraft manufacturer did not publish this data.

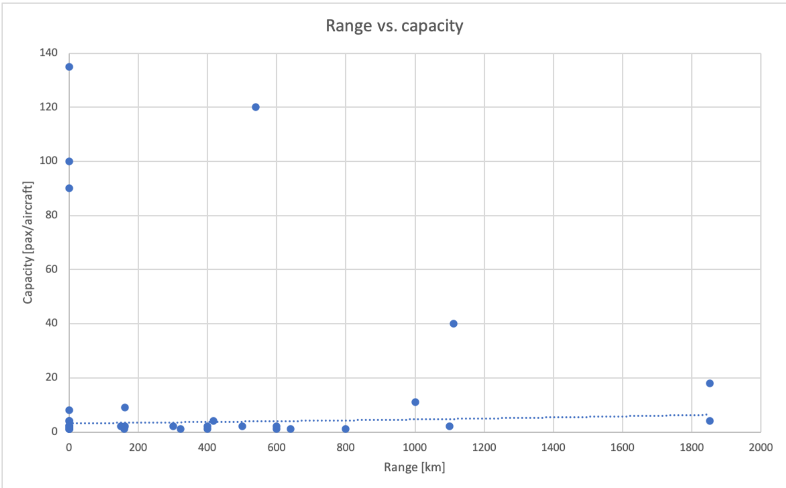

Figure B.3: Range [km] - capacity [pax/aircraft]

The RECAT-Category depends on the MTOW of the aircraft. In figure B.4 it can be seen that HEA are mostly assigned a category D, E and F. HEA with a category F can transfer up to 11 passengers according to the data. Three out of five HEA with 40 or more passengers are assigned a category D or E, dependent on the span of the aircraft (that are unknown). Comparing the RECAT categories with the categories of conventional aircraft, the RECAT category per capacity does not differ.

	Number of concepts	Data MTOW known	CAT-F	CAT-E or D
Electric	25	11	11	0
Hybrid	11	8	5	3

Figure B.4: RECAT Categories overview

	Name company	Propulsion	Type	Pax	Motor Power	Number of engines	Thrust	Type of thrust	First flight	Range [km]	Range [h]
1	Volta Volare Da Vinci	Hybrid	General aviation/business jets	4	450	1	1	propeller	2012	1852	
2	Ampaire TailWind	Electric	Business aircraft	9			1	ducted fans	N.A.	161	
3	Bye Aerospace Sun Flyer 2	Electric	General aviation/recreational aircraft	2	90				N.A.		
4	Bye Aerospace Sun Flyer 4	Electric	general aviation	4	105		1	propeller	2018	417	
5	Sonex Aircraft (modified Waiex)	Electric	general aviation	1	54		1	propeller	2010	640	
6	NASA X-57 Maxwell	Electric	general aviation	2	340		14	propeller	2020-2021	161	
7	Project 804	Hybrid	regional	40	2000	2	2	propeller	2022	1111	
8	ACS Aviation SORA-e	Electric	general aviation	2	70		1	propeller	2015	300	1,5
9	Air Race E	Electric	General aviation	1			1	propeller	2020		
10	Cranfield Aerospace/Britten Norman Islander	Electric	regional	8			9	propeller	2021		1+0,5
11	Accelerating the Electrification of Flight (ACCEL)	Electric	General aviation	1	750		1	propeller	2020	322	
12	Faradair (Bio Electric Hybrid Aircraft) BEHA	Hybrid	Regional	18	450	1	1	ducted fans	2020	1852	
13	Siemens/Extra 330LE	Electric	General aviation	2	260		1	propeller	2016		0,333333
14	Airbus (former EADS) Cri-cri	Electric	General aviation	1			4	propeller	2010		0,5
15	LSA MC30E	Electric	General aviation	1	19		1	propeller	2011	800	
16	Airbus E-fan 4.0	Hybrid	General aviation	4			2	ducted fans			3,5
17	Airbus E-fan 1.0	Electric	General aviation	2	60		2	ducted fans	2014		1
18	Airbus/Rolls-Royce E-thrust	Hybrid	Large commercial	90		1	6	ducted fans			
19	Dufour aEro1	Electric	General aviation	1			1	propeller	2016		1
20	PC Aero Elektra One	Electric	General aviation	1	16		1	propeller	2011	400	3
21	PC Aero Elektra One solar	Electric	General aviation/recreational aircraft	1	32				N.A.	600	
22	PC Aero Elektra two solar	Electric	General aviation/recreational aircraft	2	23				N.A.		
23	PC Aero Elektra solar trainer	Electric	General aviation/recreational aircraft	2	32				N.A.	400	
24	Airbus/Siemens/Rolls-Royce E-fan X	Hybrid	Large commercial	100	2000	3 turbofans + 1 hybrid generator			2030		
25	Rapid-200-FC	Hybrid	General aviation	1	40	1	1	propeller	2010		0,75
26	Pipistrel/Siemand WATTsUP	Electric	General aviation	2	85		1	propeller	2014	150	
27	Alpha Electro	Electric	General aviation	2	60		1	propeller	2018	600	1-1,5
28	Diamond DA40 NG	Hybrid	General aviation	4	150	2	2	propeller	2018		5
29	Diamond DA36 E-star 2	Hybrid	General aviation	2	80	1	1	propeller	2013		
30	Magnus aircraft/Siemens eFusion	Hybrid	General aviation	2	60	2	1	propeller	2018	1100	
31	Eviation Alice	Electric	Business aircraft	11	900		3	propeller	2021	1000	
32	Wright electric/Easyjet	Electric	Large commercial	120	780				2027	539	
33	Boeing Sugar Volt	Hybrid	Large commercial	135					2030-2050	6482	
34	DigiSky SkySpark	Electric	General aviation/recreational aircraft	2	65				N.A.	500	
35	Hamilton aEro	Electric	General aviation/recreational aircraft	1	80				2017	160	
36	Yuneec International E430	Electric	General aviation/recreational aircraft	2							

Figure B.5: Overview data-analysis performances - part I

	Name company	RECAT-Categorie	Cruise altitude [FT]	Cruise speed [kt]	Payload [KG]	Take-off distance [ft]	Rate of climb [ft/min]	Stall speed [KIAS]	Minimum speed [kts]	Maximum speed (sea level) [kts]	Landing speed [kts]	Landing distance	Weight [kg]	Weight empty [kg]
1	Volta Volare Da Vinci	CAT-F	24000	160	600	1400	1800		65	310	75	1500	408	1179
2	Ampaire TailWind													
3	Bye Aerospace Sun Flyer 2	CAT-F		55-135	363								25.8	
4	Bye Aerospace Sun Flyer 4			125			1250							
5	Sonex Aircraft (modified Waiex)			150										
6	NASA X-57 Maxwell		14000	149,464				58 knots/67mph					390	1361
7	Project 804	CAT-E of D												
8	ACS Aviation SORA-e			102,6			1500							
9	Air Race E													
10	Cranfield Aerospace/Britten Norman Islander													
11	Accelerating the Electrification of Flight (ACCEL)			260										
12	Faradair (Bio Electric Hybrid Aircraft) BEHA			200		985						985		
13	Siemens/Extra 330LE	CAT-F	9843	184 (top)			2300			182,24			1000	
14	Airbus (former EADS) Cri-cri	CAT-F		59,4			1040	45mph		117				
15	LSA MC30E													
16	Airbus E-fan 4.0													
17	Airbus E-fan 1.0													
18	Airbus/Rolls-Royce E-thrust									35,6m/s				
19	Dufour aEro1													
20	PC Aero Elektra One													
21	PC Aero Elektra One solar	CAT-F	19600	76	100									
22	PC Aero Elektra two solar	CAT-F	65616	37,8	200									
23	PC Aero Elektra solar trainer	CAT-F		76,6	260									
24	Airbus/Siemens/Rolls-Royce E-fan X	CAT-E of D			6650									
25	Rapid-200-FC	CAT-F												
26	Pipistrel/Siemand WATTsUP	CAT-F		85		Short take-off	1200	69km/h		105			14	
27	Alpha Electro	CAT-F		85 KIAS	200		1220	38 KCAS with flaps, 45 without		70 kias		459		
28	Diamond DA40 NG	CAT-F		231KM/H		370m	3,5m/s	107 KM/H		285 KM/H		270m		
29	Diamond DA36 E-star 2	CAT-F												
30	Magnus aircraft/Siemens eFusion	CAT-F		130		130m		35kt		144		200m		
31	Eviation Alice	CAT-F	32808	240	1250	914								
32	Wright electric/Easyjet													
33	Boeing Sugar Volt	CAT-E of D												
34	DigiSky SkySpark		N.A.	162 (top)										
35	Hamilton aEro	CAT-F	N.A.	92										
36	Yuneec International E430	CAT-F	9840	52										

Figure B.6: Overview data-analysis performances - part II

C STAKEHOLDER ANALYSIS

The stakeholder analysis is a supporting tool to define the design space. The stakeholder analysis is performed based on the objective of this research and [49]. A step-by-step plan of Enserink [17] is followed.

C.1 PROBLEM FORMULATION PER STAKEHOLDER

Figure C.1, C.2 and C.3 list all the stakeholders with their corresponding interests, objectives, their current situation and solutions. It can be seen that the general objective of all stakeholders is to make aviation more sustainable.

C.2 INTERACTION BETWEEN STAKEHOLDERS

The reason why the stakeholders want to make aviation more sustainable differs per stakeholder. It is therefore important to know what the interactions between the stakeholders are. Figure C.4 presents the formal relationships between the different stakeholders that are involved. Single-sided arrows indicate hierarchical relationships, two-sided arrows indicate formal representation relationships.

Explanation formal relations

Royal Schiphol Group and LVNL are both facilitators for airlines. These two parties want to improve the sustainability of the aviation sector and joined The *Nationaal Actieprogramma Hybride Elektrische Vliegtuigen* [51][32]. Residents affected by airport operations and NGOs share the goal to decrease the nuisance as they want to increase the quality of life and preserve the environment [49]. These two parties exert pressure on the executive parties.

Governments and regulators are the legislative parties. The goal of governments is the economic development of the country (federal government) and the region (local). The Netherlands is a democratic constitutional state which means that votes of citizens are important for political parties. This may play a role in the choices that parties make about the stimulation of sustainable aviation, in particular HEA. As can be seen in the interview with the CEO of Twente and Teuge Airport (see interview A.3), two parties were against the purchase of a Cessna 337 Skymaster for the use of test aircraft. At the same time, the Ministry of Finance is a shareholder of Royal Schiphol Group which makes it a complicated situation. Regulators like EASA and ICAO aim to keep aviation as safe and efficient possible.

The six parties with high interest and high power are all part of the The *Nationaal Actieprogramma Hybride Elektrische Vliegtuigen*. This makes that the conflicts between stakeholders is limited and the problem less complicated. As is said before airports, airlines and ATM service providers are executive aviation parties that have high power and interests. They are the parties that have to respond to the regulations of the government in case they want to grow. The growth in air traffic movements is a respond to the growing demand of passengers. This can also be seen in figure 5.2 in chapter 5.

Actors	Interests	Desired situation/objectives	Existing or expected situation and gap	Causes	Possible solutions
ATM Service Provider	Decrease of nuisance, provide growth of airlines, safety and efficiency	When the demand comes from airlines to land/take off in the Netherlands with a hybrid/electric aircraft, the ATM service provider needs to able to accommodate this.	The current CONOPS is not suitable to let hybrid or electric aircraft land and take-off at an airport.	The performances of hybrid and electric aircraft differ from conventional aircraft.	Design a new CONOPS that integrates hybrid and electric aircraft into the ATM-system.
Employees	Stable income, safety of employees	The objective of employees is that their manpower does not increase and that they have a stable job. Their safety should not decrease.	Fear that the workload becomes too high, fear of decrease safety.	A different work method	CONOPS must be designed in such a way that the pressure on employees does not become too high.
Schiphol Airport	Provide demand of passengers, growth, profit, keep highest status as hub airport	As hybrid and electric aircraft emit less nuisance, the desired situation is that Schiphol airport can increase its air traffic movements per year. This leads to a better provision of the passengers' demand and Schiphol Airport can keep the high status as hub airport with the supplement that its sustainable.	Not possible to provide the demand of passengers. As the airport is not able to grow the airport can lose its high status as hub airport.	The nuisance of conventional aircraft is too high. This leads to a restriction of increasing the movements per year. The minister emphasizes that there can no longer be any question of unconditional growth when the advantages and disadvantages of aviation are not balanced for residents.	Prove that the nuisance has decreased due to the use of hybrid and electric aircraft, more sustainable ground operations etc.
Regional airports	Provide demand of passengers, growth, profit	As hybrid and electric aircraft emit less nuisance, it is possible for regional airports to grow and provide demand of passengers and grow.	Not possible to grow.	Residents protest due to nuisance increase.	Stimulate airlines to buy more quiet and cleaner/sustainable aircraft.

Figure C.1: Stakeholders' problem formulations

Airlines	Provide demand of passengers, profit, provide service to passengers, competition	The airline owns a fleet which is used to provide air transport. Hybrid and electric aircraft have a reduced maintenance cost. Besides that, airlines can provide better service to their passengers by letting them travel in a sustainable way.	Not possible to provide the demand of passengers. The maintenance costs are high.	Current aircraft in the fleet are ‘less-sustainable’, there is a restriction on increasing the movements per year.	Purchase sustainable aircraft, e.g. hybrid and electric aircraft.
Passengers	Use of services, travel with decreased emissions, comfortable flying experience	Hybrid and electric aircraft make it possible for passengers to travel in a sustainable way.	Passengers realize that air traffic is not sustainable which makes their travel experience less comfortable.	Airlines only offer flights with a ‘less-sustainable’-aircraft.	Airlines decide to purchase hybrid or electric aircraft.
Residents	Decrease of nuisance	Less nuisance of aircraft.	The number of flight movements per year is stable, but the aircraft cause too much nuisance.	Airlines own a fleet of aircraft that emit a relatively large amount of CO_2, NO_x and noise	Airlines decide to purchase hybrid or electric aircraft.
Investors and shareholders	Economic profit	In case of hybrid and electric aircraft, investors and shareholders can make more profit when there is a high-capacity airport with a sustainable status	Airports have difficulties handling the demand.	There is a restriction on increasing the movements per year.	More investments to accommodate the arrival of hybrid and electric aircraft.
Federal government	Economic development of the country.	High capacity airport that is leading in sustainable aviation.	Airport has difficulties handling the demand and there is no flexibility to integrate a vast percentage of aircraft with different performances	There is a restriction on increasing the flight movements per year	Reduce number of traffic movements, stimulate aviation sector to purchase more sustainable aircraft.
Local government	Regional economic development, welfare of citizens, environmental protection.	Continue a smoothly running airport but with limited negative impact of nuisance.	Airports cannot grow.	Due to the growth of aviation, increase of CO_2-, NO_x- and noise pollution.	Reduce number of traffic movements, stimulate aviation sector to

Figure C.2: Stakeholders’ problem formulations

					purchase more sustainable aircraft.
NGOs	Welfare of environment, sustainable development	Decrease of noise, $CO2$- and NOx-pollution due to aviation	High emission and noise hindrance to residents.	High number of flight movement with 'less-sustainable' aircraft.	Lobby for stricter regulations and restriction of flight movements.
Regulators	Safety, efficiency	The desire is to preserve safety and efficiency and in the ideal situation these will increase.	Regulation concerning hybrid and electric aircraft is still lacking	Hybrid and electric aircraft are not active yet	Regulators start now with positive regulation for hybrid and electric aircraft where safety and efficiency are still preserved.

Figure C.3: Stakeholders' problem formulations

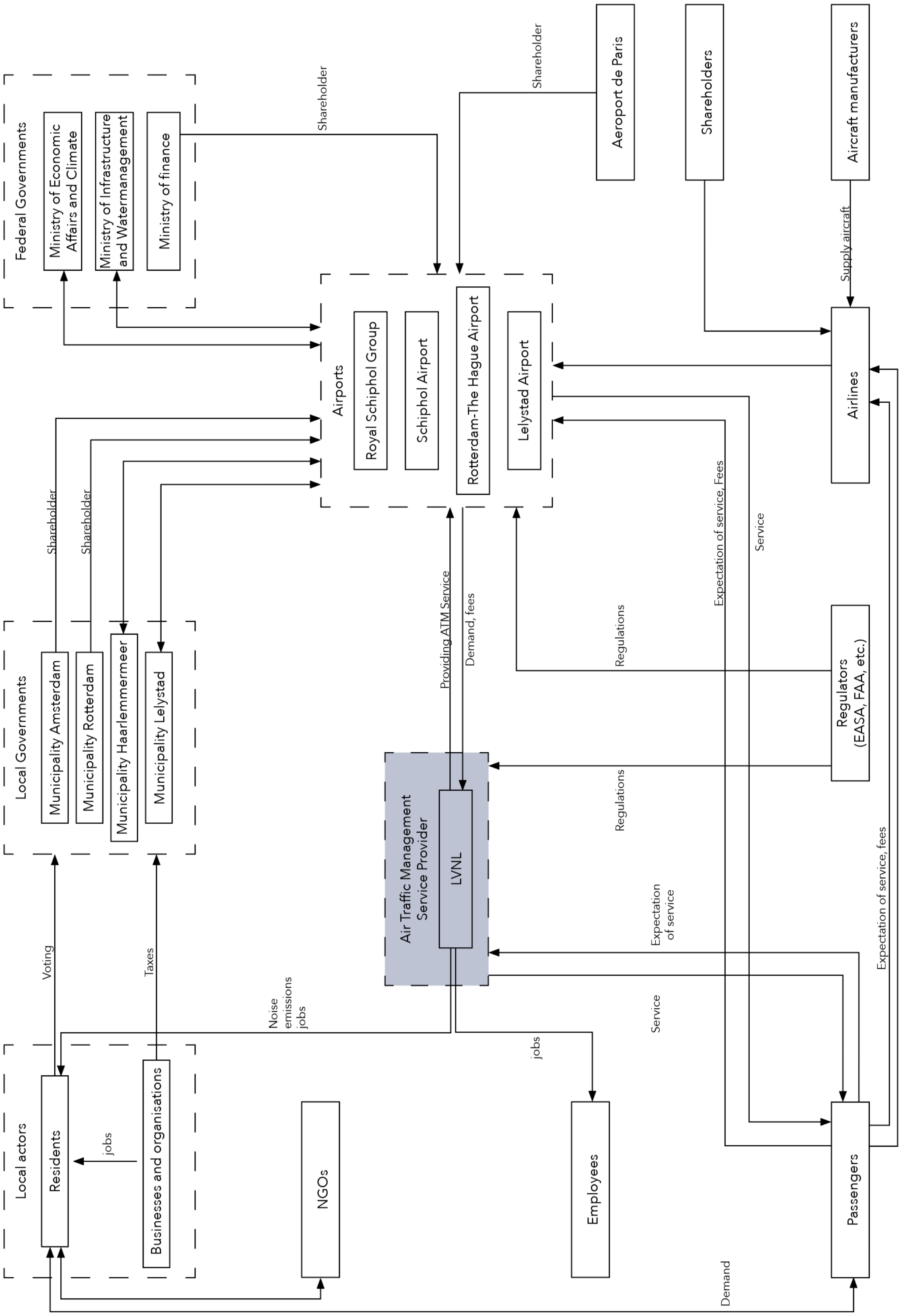

Figure C.4: Formal relationships between stakeholders

D SCENARIO ANALYSIS - PROCESS

A scenario analysis is used to look at various future states of an uncertain environment in which the CONOPS must be operating. The process of scenario planning that is used in this research is based on Enserink et al. [17] and can be found in this appendix. The outcome of the scenario analysis are five different scenarios that are described in detail in chapter 6.

External factors
The causal diagram in figure 6.5 shows the contextual factors and the relationship between these contextual factors. Each contextual factor has a number that refers to a stakeholder from the stakeholder analysis. Number 14 refers to a actor outside the stakeholder analysis or is too complex to assign an actor. The numbers indicate that all factors are exogenous as none of these factors can be influenced by the ANSP.

Explanation causal diagram
Aircraft manufacturers are working hard to make HEA technically work. However, financial motivation and positive regulations from the government, EU and FAA are needed to make this happen (see interview A.3). This motivation can lead to a better development of batteries and better performances of HEA. A better power-to-weight ratio leads to better performances. This makes it more attractive for airlines to purchase HEA instead of conventional aircraft [58]. The more HEA are purchased, the higher the percentage of HEA becomes of the total number of aircraft. Governments and regulators can influence the decision of airlines between hybrid, electric or conventional aircraft by means of subsidies for HEA and taxes for take-off and landing based on emissions (government, EU). This can also be applicable for parking charges (airport) or slot regulations (IATA). These parties are all members of *Ontwerpakkoord duurzame luchtvaarttafel*, which means that they will be open to this type of regulation [61].

Another factor that influences the purchase of HEA are the developments of international trains [23]. When HEA are smaller in capacity [travellers/aircraft], it is known that HEA are mainly used for regional or point-to-point flights (see interview A.7, A.3, A.8). The flights from regional airports shorten door-to-door trips in hours, which is in line with the four hours door-to-door-concept of the European Union [11]. When many efficient connections are created by an international train, a competitor arises for HEA. This can have a negative influence on the purchase of HEA by airlines as they choose to focus on their hub-and-spoke model. This latter indirect influence is also applicable to HEA with a similar capacity to e.g. the embraer190. In this case, the aircraft that will bring you from the hub to your destination can be replaced by an international train [13][23].

However, when the development of international trains does not push through, it can increase the point-to-point percentage. This can even exceed the capacity of 540.000 aircraft per year as airlines can decide to fly from regional airports. As the HEA make less noise and emit less CO_2 and NO_x, it can be experienced as less nuisance to residents (see interview A.3 and chapter 4).

Driving forces and their importance
These external factors that are depicted in the causal diagram are classified into sev-

eral driving forces. These driving forces are ranked according to their importance and uncertainty. This can be found in figure D.1 and figure D.2.

Social pressure	**Governmental decisions**
"Vliegschaamte"	Presence taxes non-electric aircraft
	Presence of landing/take-off charges for hybrid/electric aircraft
Breakthrough of technologies	Presence of parking charges non-electric aircraft
Development batteries	Motivation technical innovation
Performances non-electric aircraft	Ceiling 500.000 flight government
Performances hybrid/electric aircraft	**(International) economic developments**
Maintenance cost hybrid/electric aircraft	Economic growth
Health of global civil aviation	**Airspace management**
Willingness to purchase hybrid/electric aircraft airlines	Percentage point-to-point
Profitability of the aviation industry	Percentage hyb-and-spoke
Ticket price	Number of total aircraft in airspace
Demand passengers hybrid/electric aircraft	**High speed trains**
Airport possibilities	Development international trains
Airport capacity	**Fuel market**
Growth regional airports	Oil price

Figure D.1: Driving forces

		Uncertainty	
		Low	High
Impact	Low	"Vliegschaamte" High speed train	Social pressure
	High	Airport possibilities (International) economic development Fuel market Health of global civil aviation Airspace management	Breakthrough of technologies Regulation decisions

Figure D.2: Importance and uncertainty of driving forces

The breakthrough of technologies and the decisions in regulations are the driving forces with the highest uncertainty and impact. This means that these driving forces will be taken into account in the scenarios. These two driving forces form the axes of the scenarios.

Scenario axes

In figure D.3, the scenario space is determined. It is difficult to predict what will happen with these driving factors but the decisions that will be made within these driving forces also have a huge impact on the problem of HEA in the ATM-system. There are five scenarios included in this research which are used as the design space of several CONOPS where HEA are integrated into the ATM-system.

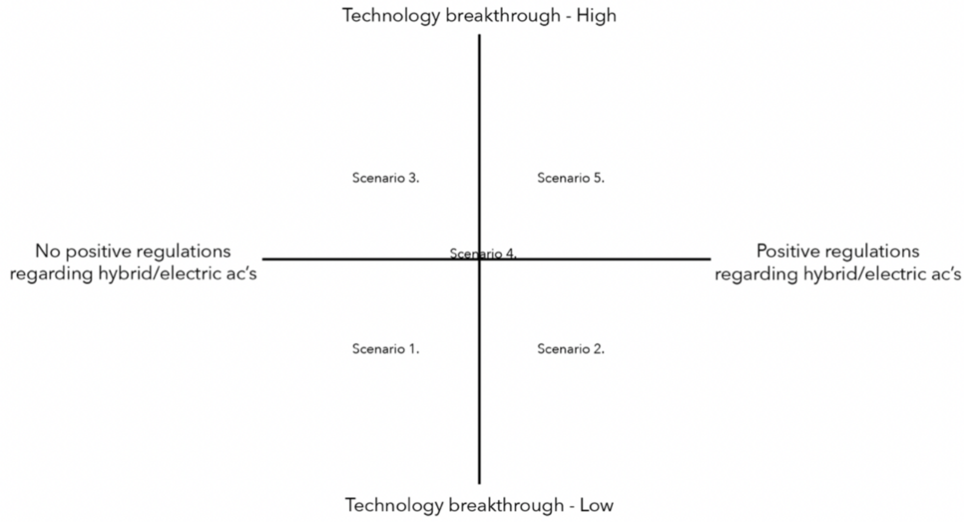

Figure D.3: Scenario space

When only looking at one axis, the description below holds. The assumptions regarding regulations decisions are based on the stakeholder analysis (see C). The assumptions regarding technology breakthrough are based on the data analysis of HEA (see appendix 4).

Regulations decisions:

- Positive: the government fully supports the development and purchase of HEA. This is done with the use of regulations. Examples of these regulations are the cost of taxes. These costs are determined based on emissions and noise. In that case, airlines pay more take-off and landing charges for a conventional aircraft. These charges for a hybrid aircraft are average where an electric aircraft can land and take-off for (almost) free. This can also be applicable for parking charges that have to to be paid to airports. In addition, there are special slots for HEA that airlines can purchase on top of the 'normal' slots for conventional aircraft.
- Neutral: the regulators have adopted a neutral stance on the motivation of HEA landing at Dutch airports. This means that there is a relatively small advantage for HEA to take-off and land. This regulation only plays a role when an airline has doubts about purchasing an HEA. In general it is not decisive for airlines to purchase HEA. The same holders for parking and landing fees of the airports. No special slots are designated for HEA.
- Negative: The regulators take an inactive stance in the development of HEA. No distinction is made between conventional, HEA.

Technology breakthrough:

- Low: aircraft manufacturers have concluded that it is not possible to produce HEA that meets the requirements of airlines and/or can be certified. This means that HEA are mainly used as private jets, given the number of passengers that the aircraft can transfer.
  - Range = 500km
  - Number of passengers per aircraft = 19 (based on the regulations regulations that distinguish between fewer or more than 19 passengers)
  - Type of aircraft: private jets
  - Type of electrification: HEA

- Medium: HEA are certified. The performances of the aircraft are not yet ideal for airlines, but manageable. In case of a medium technological breakthrough, the following performances hold:
  - Range = 500km
  - Number of passengers per aircraft = 50
  - Type of aircraft: private jets, airlines
  - Type of electrification: HEA
- High: aircraft manufacturers have reached their goal. The range and passenger capacity of HEA is suitable for airlines. This means that a HEA can easily replace a conventional aircraft that has the same capacity (e.g. Embraer190) and a destination within the range.
  - Range = 1000km
  - Number of passengers per aircraft = 100
  - Type of aircraft: private jets, airlines
  - Type of electrification: electric aircraft

There is one more characteristic per scenario that is related to both decisions regulations and technology breakthrough, namely the percentage of HEA in the ATM-system. The performances of HEA that are the effect of the technology breakthrough, are important for airlines to purchase a HEA. An extra motivation to purchase HEA is when the regulations regarding HEA are based on the sustainability of the aircraft. That means that airlines have to pay less for e.g. landing fees, parking fees and taxes in case of HEA. The exact percentage is based on the literature research and interviews. 38 percent of the movements at Schiphol is shorter than 750km [13]. This is the maximum range that a HEA can fly, in order to keep reserves for unexpected events. Based on this percentage, the percentage of HEA in the ATM-system are set to 0, 5, 10, 20 and 25 percent. Here is included that Easyjet want to have an all-electric fleet in 2030 [16] and KLM is exploring the possibilities of purchasing HEA (see interview A.2). The share of Easyjet flights at Schiphol Airport in 2019 is 39.163 flights, which is 7.4 percent of 540,000 movements. KLM has a share of 46 percent but this also includes long-distance flights [53].

The conclusion of the the scenario analysis contains five scenarios that are described in chapter 6.

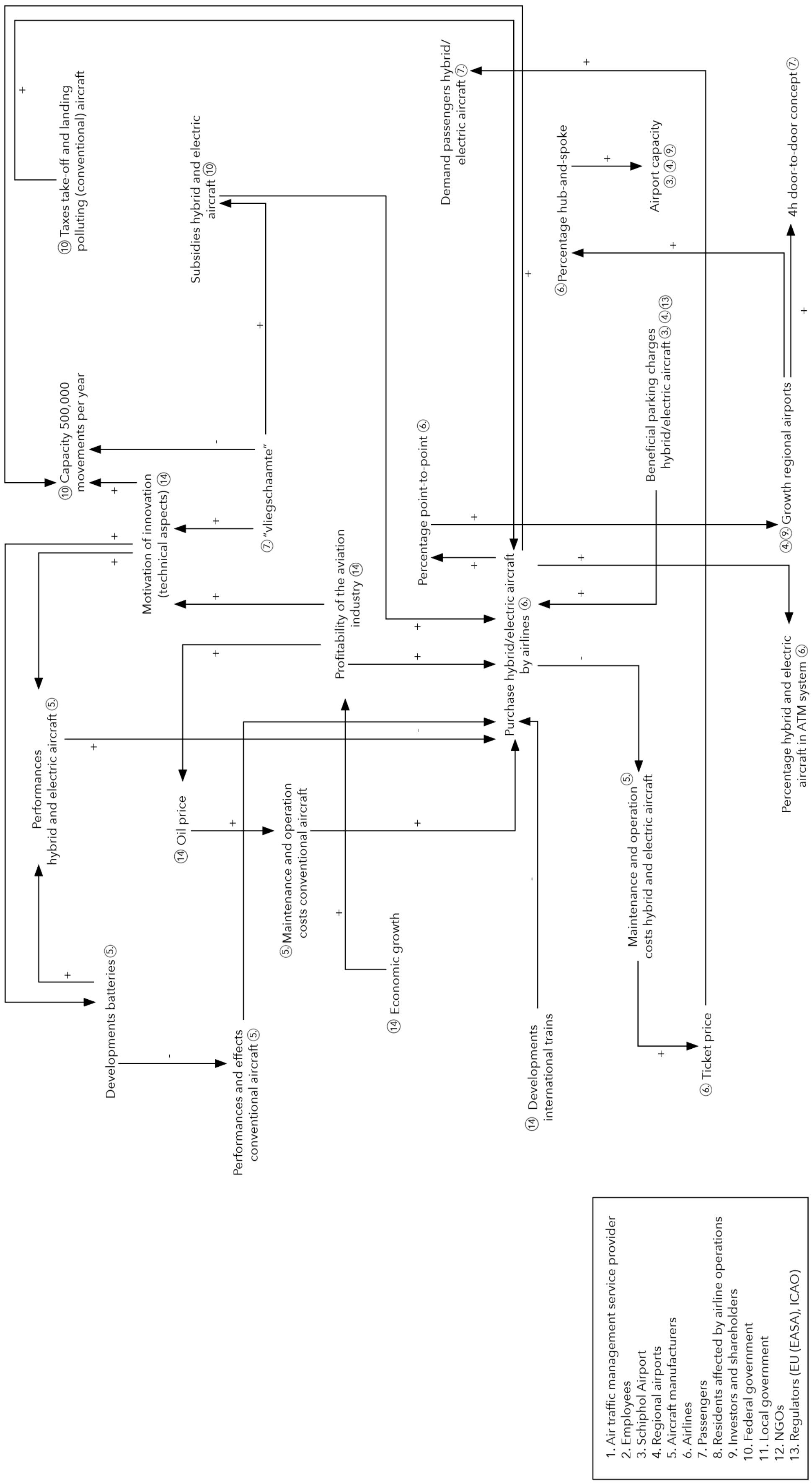

Figure D.4: Causal Diagram

E EFFECTS OF SCENARIOS ON KPIS

This appendix describes the effects of the five scenarios on the KPIs. It contributes to get a sense of the possible outcomes of this research.

Scenario 1. No positive regulations regarding HEA – low technological breakthrough

- Runway capacity: The capacity of set on 0 percent. Since conventional aircraft have a shorter ROT compared to the ROT of HEA. This means that the runway capacity is higher compared to scenarios where HEA are integrated.
- Complexity of implementation: The complexity of implementation is about opening an extra runway. This entails additional difficulties, for example the effect on air routes. However, the number of runways are not a characteristic of the scenario but of the CONOPS. Therefore, no effect can be described in this appendix of the scenario on the KPI
- Passenger capacity HEA: Conventional aircraft do not have to take into account an optimal power-to-weight ratio of batteries. That means they have no limited capacity on the same scale as HEA and conventional aircraft can easily transfer more than 100 passengers per aircraft. The passenger capacity is high.
- Noise-reduction: conventional aircraft produce more noise than HEA. This leads to a KPI that is labeled high.
- CO_2-reduction: The CO_2 emissions is high as there are no HEA integrated in this scenario.
- NO_x-reduction: The NO_x emissions is high as there are no HEA integrated in this scenario.
- Possibility to grow: the aviation sector can only earn growth through demonstrable reduction of nuisance [60]. It is mentioned above that the noise nuisance, CO_2- and NO_x-emissions are labeled high. That means that there is no possibility to grow.
- Operational costs: The operational cost of conventional aircraft is high, mainly because of the fuel cost.
- Total travel time: The total travel time is based on the airport where aircraft land. This is a characteristic of the CONOPS instead of the scenario. Therefore no description of this KPI in this appendix.

Scenario 2. Positive regulations regarding HEA – low technological breakthrough

- Runway capacity: The capacity of HEA is low since there has been a low technological breakthrough. This means that the number of HEA is set on 5 percent and therefore limited even though the regulators have a positive approach on the integration of HEA in the ATM-system. Since five percent of the total aircraft capacity has an increased ROT of five percent, the runway capacity that includes HEA decreases to 39 movements per hour per runway.

- Complexity of implementation: N.A.
- Passenger capacity HEA: Only conventional private jet aircraft are replaced by HEA. These conventional private jets can transfer up to 19 passengers which means that the passenger capacity in HEA is low.
- Noise-reduction: the noise nuisance decreases with 19 EPNdB per private jet. This is almost twice as much as commercial aircraft. This means that the noise reduction is relatively high for the number of HEA in this scenario, compared to other scenarios.
- CO_2-reduction: CO_2-emissions are expressed in gram/passenger/km. The total CO_2-emissions depend on the number of HEA in the ATM-system. Since this scenario integrates five percent HEA, the reduction of CO_2-reduction is relatively low.
- NO_x-reduction: The NO_x-emissions are expressed in gram as well and relates to the number of HEA in the system. That means that the NO_x-reduction is also low.
- Possibility to grow:
- Operational costs per passenger: The operational cost for the airline or private owner are up to 20 percent lower [45]. The private jets also have to pay less for e.g. landing- and parking fees. This decreases the operational costs even more.
- Total travel time for passengers: N.A.

Scenario 3. No positive regulations regarding HEA – high technological breakthrough

- Runway capacity: As the government and regulators do not take an active role in motivating airlines to purchase HEA, 10 percent of the total aircraft is HEA. The influence on the runway capacity is a decrease of 1 movement per hour per runway.
- Complexity of implementation: N.A.
- Passenger capacity HEA: HEA can transfer up to 100 passengers. That means that a conventional aircraft like an Embraer 190 can be replaced with a HEA of the same capacity. Compared to the other scenarios, the passenger capacity of scenario three is medium.
- Noise-reduction: The noise reduces in this scenario since 10 percent of the total aircraft is HEA. Compared to the other scenarios, the noise nuisance is set to medium.
- CO_2-reduction: The CO_2-reduction is set to medium. The CO_2-reduction depends on the number of HEA which is 10 percent of the total aircraft. Compared to the other scenarios, this is medium.
- NO_x-reduction: The same holds for NO_x.
- Possibility to grow:
- Operational costs: The operational cost for airlines are lower. When an airline purchases HEA, the operational cost decreases by 20 percent. Compared to scenarios where there are positive regulations regarding HEA, the operational cost are a higher. [45]. The aircraft has the same capacity of passengers per aircraft compared to conventional aircraft. The operational cost per passenger decreases since the airline does not have to pay for fuel anymore. The airlines do not profit from regulations such as landing- and parking fees.

- Total travel time for passengers: N.A.

Scenario 4. Medium regulations regarding hybrid/electric aircraft – medium technological breakthrough

- Runway capacity: 20 percent of the total aircraft is HEA. That means that eight HEA have a higher ROT. This results in a decrease in runway capacity of two aircraft.
- Complexity of implementation: N.A.
- Passenger capacity HEA: The capacity of passengers per year decreases compared to the base case. The capacity of passengers per aircraft is divided into halve which means that one conventional aircraft that transfers 100 passengers has to be replaced with two HEA of 50 passengers. To transfer 100 passengers to their destination, two air traffic movements are used instead of one. To meet airline restrictions, this scenario can only become a reality if airlines decide to adjust their business model (see interview A.9).
- Noise-reduction: Noise nuisance reduces in this scenario since 20 percent of the total aircraft is HEA. Compared to the other scenarios, the reduction of noise is medium-high.
- CO_2-emissions: The CO_2 emissions decrease as 20 percent of the total aircraft is HEA.
- NO_x-emissions: The NO_x decreases as 20 percent of the total aircraft is HEA.
- Possibility to grow:
- Operational costs: The operational cost for airlines are higher. The airlines do profit from the deduction in fuel cost but as the capacity per aircraft decreases as well, their income from airline tickets decreases as well. Besides that, the airline has to purchase, maintain and operate two hybrid or electric aircraft to transfer the same amount of passengers of one conventional aircraft. As the regulations regarding HEA are set to medium in this scenario, the cost of landing, take-off and parking charges decreases a bit. This makes that the operational cost per passenger is higher.
- Total travel time for passengers: N.A.

Scenario 5. Positive regulations regarding hybrid/electric aircraft – high technological breakthrough

- Runway capacity: 25 percent of the total aircraft is HEA. These 10 HEA have a higher ROT which results in a runway capacity of two aircraft less. This is a decrease compared to the base case.
- Complexity of implementation: N.A.
- Passenger capacity HEA: HEA can transfer up to 100 passengers. That means that a conventional aircraft like an Embraer 190 can be replaced with a HEA of the same capacity. The capacity of passengers stays equal compared to the base case and is therefore set to high. Since 25 percent is HEA, this scenario consists of the highest passenger capacity transfer with HEA.
- Noise-reduction: Since the capacity of HEA is high, the noise-reduction is high as well.
- CO_2-reduction: The CO_2 emissions are low as 25 percent of the total aircraft is HEA. That means that the reduction is high.

- NO_x-reduction: The NO_x emissions are low as 25 percent of the total aircraft is HEA. That means that the reduction is high.
- Possibility to grow:
- Operational costs: The operational cost for airlines are really low in this scenario. Assuming that all airlines have replaced 25 percent of the fleet with HEA, the operational cost decreases significantly. Since the regulations are positive regarding HEA, the airlines can save on e.g. landing- and parking fees. Airlines save the most amount of money in this scenario, compared to other scenarios.
- Total travel time for passengers: N.A.

F DESIGN PROCESS

F.1 BRAINSTORM AND MORPHOLOGICAL CHART

The participants of the brainstorm were asked to perform an individual brainstorm before the meeting. To lead this brainstorm remotely, participants received a presentation that included all findings of this research so far. In addition, they received four forms that they could fill in. The goal was that participants came up with CONOPS for scenario three, four and five, as those three are the most complex. This was not necessary for scenario one as it is equal to the base case and in scenario two, hybrid and electric private jets can be integrated like conventional private jets. This way, limited time of aviation experts could be used efficiently.

A case study was used to make this subject tangible. The first part of this case study consists of an airline that starts a trial. This trial involves one aircraft that flies between The Netherlands and London. The aircraft takes off and lands once a week. The question was asked in what way this aircraft would land and take-off from a Dutch airport in case of HEA. The intention of this trial is to help participants get a grip on the performances of HEA into the ATM-system.

The second part of the case study focused on the three different scenarios. For each scenario, the participants had to brainstorm about different CONOPS. Each scenario differs in the performances of the HEA (like the range and capacity of the aircraft) and the percentage of these aircraft in the ATM-system. The specifics can be found in 6. After the individual brainstorm, the individual conclusions were discussed during a three-hours meeting. After each round, the participants were asked if they came up with a new CONOPS. An advantage was that for every scenario a problem-definition and recommendations per scenario were mentioned as can be seen in figure F.1.

The outcome of the brainstorm can be divided into three parameters: time, airport and runway. The first six CONOPS are labeled undesirable, based on the experiences of ATCOs in '*werkwijze 3*' (see interview A.10), which contains segregation of aircraft with outstanding performances. The last three CONOPS are labeled impossible as there is no extra runway present at regional airports.

	Scenario 3.	Scenario 4.	Scenario 5.
CONOPS 1	**Hybrid aircraft**: Performances similar to A320: Adjustment CONOPS not needed.	**Hybrid and electric aircraft:** Electric aircraft can only take-off and land from regional airports. Another idea is to relocate heavier or more polluting aircraft to regional airports.	Electric aircraft cannot be treated differently. They must be taken into account in the 3D separation of routes. - Battery packages can be swapped/reload quickly: electric aircraft land at the beginning of the inbound, take-off at the end of the peak hour. Electric aircraft should get their own RECAT category when needed.
CONOPS 2	**Electric aircraft**: Electric aircraft should not be treated differently. Similar to conventional aircraft. The chosen airport is Schiphol. Partly because it is good press for the airport. Holiday flights are relocated at regional airports which creates space for electric aircraft. Electric aircraft can also operate during peak hours, but this can lead to a decrease of capacity. This can be solved with tactical planning.	Integration: a fourth runway must be made available at Schiphol during peak-hours.	Battery packages cannot be swapped/reload quickly: Outside in- and outbound. Spread over the day for times when there is relatively less supply.
CONOPS 3	Especially electric aircraft take-off and land at regional airports (Lelystad airport or Rotterdam-The Hague Airport) for point-to-point traffic.	Electric aircraft have to take-off and land from a separate runway. This leads to integration.	Wake turbulence: in case of light category (large separation) segregation outside peak hours.
CONOPS 4	Electric aircraft have to take-off and land from a separate runway. This leads to integration.	Hub-related aircraft take-off from and land at Schiphol. Point-to-point aviation from Lelystad.	
Further research:	- When starting/landing on electric motors only, it is important what the environment demands. - Turnaround time is still important, maybe more aircraft stands needed.	- 20 percent at one runway is a lot (especially when hub-and-spoke and point-to-point are both located at Schiphol). Is this achievable/plannable? - Possibly Eelde, Beek and Lelystad but research if this is possible in terms of environment	- When will the network be set up on/adjusted to electric planes? At what percentage? In that case conventional aircraft must adapt. This can cause a negative sound output: noise, CO_2 - Battery packages load time
Problem:	- Segregation leads to problems and complexity	- More capacity pressure since the separation is bigger. Performances of hybrid aircraft are similar to conventional aircraft. CONOPS should not be adjusted due to the performances but should be adjusted because of the capacity	Battery-capacity bigger, loading time is longer in case in the event that batteries cannot be changed. With a range of 1000km electric aircraft are part of the hub-and-spoke. However, the differences with scenario three is the 25 percent. This leads to several problems: - Segregation of electric aircraft is not possible. - Tactical planning is not relevant for such a large percentage

Figure F.1: Brainstorm

CONOPS	Time			Airport		Runway			Impossible or undesirable
	Peak hour	Off-peak hour	Both	Schiphol	Regional airport	Segregation	Integration	Integration extra runway	
1	Peak hour			Schiphol Airport		Segregation			undesirable
2		off-peak hours		Schiphol Airport		Segregation			undesirable
3			all day	Schiphol Airport		Segregation			undesirable
4	Peak hour				Regional airport	Segregation			undesirable
5		off-peak hours			Regional airport	Segregation			undesirable
6			all day		Regional airport	Segregation			undesirable
7	Peak hour			Schiphol Airport			Integration		
8		off-peak hours		Schiphol Airport			Integration		
9			all day	Schiphol Airport			Integration		
10	Peak hour				Regional airport		Integration		
11		off-peak hours			Regional airport		Integration		
12			all day		Regional airport		Integration		
13	Peak hour			Schiphol Airport				Integration extra runway	
14		off-peak hours		Schiphol Airport				Integration extra runway	
15			all day	Schiphol Airport				Integration extra runway	
16	Peak hour				Regional airport			Integration extra runway	Impossible
17		off-peak hours			Regional airport			Integration extra runway	Impossible
18			all day		Regional airport			Integration extra runway	Impossible

Figure F.2: Morphological chart

G SCORECARD - PROCESS

G.1 DESCRIPTION AND FORMULAS KPIS

- **Runway capacity:** The runway capacity indicates the total number of aircraft (conventional and HEA). LVNL is aiming to retrieve a runway capacity of 120 aircraft during peak-hours (2+1-runways) and 80 aircraft during off-peak hours (1+1-runways) [38]. Since the ROT per aircraft increases for HEA, the capacity of one runway decreases (see interview A.4 and A.8). It is assumed that the separation and ROT are equal for every type of aircraft; aircraft type is therefore not taken into account. The runway capacity is one of the main pillars for the ANSP and is therefore assigned the highest weight. The formula that is used in order to calculate the exact runway capacity is:

  $$C_{\text{runway, total}} = O_{\text{runway, HEA}} + (60 - O_{\text{runway, HEA}} * ROT_{\text{HEA}}) / ROT_{\text{Conv.}}$$

  Since it is much more interesting to see what the maximum capacity is per year, the runway capacity is expressed in movements per year. A rough estimation is made that shows that 324,000 movements (60 percent) are performed during peak-hours and 216,000 movements (40 percent) during off-peak hours when only conventional aircraft make use of the ATM-system.

- **Complexity of implementation**: The complexity of implementation plays in the short term and can be seen as an investment. When only the current runways are used, the integration of HEA in-between the conventional aircraft is an easier implementation than when one extra runway has to be opened. This has to do with the airways. A simple approach has been chosen for this KPI; if only the current runways are used, a score of 1 is assigned to this KPI. If an extra runway is opened, a score of 0 is given. This can also be seen in the formula below. Since the complexity of the CONOPS implementation is very important for the ANSP, a high weight is assigned to this KPI.

  $$Complexity = If current runways = 1, if current runways + 1 = 0$$

- **passenger capacity HEA**: The number of passengers that make use of HEA is important for the airlines and airports, as is concluded in the stakeholder analysis (see C). The number of passengers per HEA and the number of HEA differ per CONOPS. The passenger capacity is not really important for the ASNP since the number of aircraft is much more important to them. The weight of the passenger capacity HEA is therefore assigned a low weight.

  $$C_{\text{passengers, total HEA}} = C_{\text{total HEA}} * C_{\text{passengers, singleHEA}}$$

- **Noise:** Hybrid and electric general aircraft make 10dBa less noise compared to conventional aircraft, as can be seen in chapter 4. For private jets, a value of 19 EPNdB applies. For this KPI, an assumption is made that the total reduction of noise happens within TWR and APP. This assumption can be made due to the fact that noise nuisance is the worst when an aircraft flies at a lower level. As noise is a complex variable with a logarithmic scale, a separate study must be done to calculate the total noise around the airport.

$$Noisedecrease = 0 - (C_{\text{HEA, total}} * Noise_{\text{single HEA}})$$

- **CO_2-reduction:** In chapter 4 the CO_2-emissions are given in gram/passenger/km. In 2018 the CO_2-emission was 80 gram/passengers/km [29]. Since this study focuses on TWR and APP, a distance of 50 km is used. The number of HEA is also input to calculate the CO_2-reduction. This can be seen in the following formula:

$$CO_2reduction = CO_{2,\text{ passenger/km}} * C_{\text{HEA, total}} * D_{\text{TWR/APP}}$$

- **NO_x:** The NO_x mass is often determined for landing- and take-off only (LTO). The total NO_x mass is set to 1222,14 gram [5]. The NO_x-reduction can be calculated by multiplying the NO_x-mass times the number of HEA.

$$NO_X - reduction = NO_{x,\text{ LTO}} * C_{\text{HEA, total}}$$

- **Possibility to grow:** The possibility to grow is related the percentage of HEA in the ATM-system and the maximum runway capacity. When an additional runway is put into service, the maximum capacity of the aircraft will increase. The possibility is scored in a qualitative way, which means that no formula is used.

- **Operational cost for airlines:** The current operational cost for airlines consists of many variables from crew to fuel costs. Operational and maintenance cost for HEA are reduced by up to 20 percent [62]. Since the operational costs per aircraft are not disclosed by airlines, it is not possible to calculate the exact numbers. However, this does not mean that the scores cannot be determined for this KPI. The operational costs are based on the capacity passengers per aircraft, the capacity of HEA and the decision about regulations regarding HEA (negative, medium or positive)

$$OC_{\text{HEA, total}} = C_{\text{HEA, total}} / C_{\text{passengers, singleHEA}} + decisionaboutregulations$$

- **Total travel time:** A rough indication is made for the total travel time since there are many variables (specific destinations, speed of the HEA etc) that are unknown. This KPI says something about the effect of location (Schiphol airport/regional airport) on the 4hours door-to-door concept of the European Union [11]. The scores of this KPI are only based on the location of take-off and landing of the HEA. If a HEA takes-off or lands at Schiphol, a score of 0 is assigned. If a HEA takes-off or lands at a regional airport, a score of 1 is given.

$$TT_{\text{total, HEA}} = IfSchiphol = 0, ifRegionalairport = 1$$

G.2 VARIABLES KPIS

In order to calculate the hard KPIs per CONOPS, variables are used. The variables to calculate the KPIs per CONOPS are as followed:

- $C_{\text{runway, total}}$ [aircraft/runway/hour] = total runway capacity per hour
- C_{HEA} [%] = Percentage of HEA of all aircraft at Schiphol.
- C_{R} [aircraft/hour] = Runway capacity
- $C_{\text{total HEA}}$ [HEA/hour] = Capacity of HEA per hour.
- $C_{\text{passengers, single HEA}}$ [passengers/single HEA] = Capacity of passengers per HEA.

- $C_{\text{passengers, total HEA}}$ [passengers/allHEA] = Total passengers in HEA
- $CO_{2,\text{ passenger/km}}$ = CO_2 per passenger per km
- $D_{TWR/APP}$ [km] = Total distance of TWR and APP = 50 km
- $Noise_{\text{single HEA}}$ [dBA] and [EPNdB]= Noise reduction single HEA
- $O_{\text{runway, HEA}}$ = Runway occupancy [HEA/runway]
- $OC_{\text{HEA, total}}$ = total operational cost for airlines
- $R_{reduced}$ = Range [km]
- ROT_{HEA} [min/HEA] = Runway Occupancy Time per HEA
- $ROT_{Conv.}$ [min/aircraft] = Runway Occupancy Time per conventional aircraft
- $TT_{\text{total, HEA}}$ = total travel time per HEA passenger

G.3 SCORECARD

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
		CONOPS	CONOPS 3A		CONOPS 3G	
			Ferraris		Tesla	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Peak-hours		Peak-hours	
		Number of runways	3		4	
		Percentage of total aircraft [%]	10		10	
		Range [km]	1000		1000	
		Aircraft capacity [passengers]	100		100	
	Capacity HEA	Movements/hour	12	N.A.	12	N.A.
		Movements/day	138		138	
		Movements/year	50370		50370	
25	Runway capacity	Movements/hour	39,40	24,650	40,00	25
		Movements/year	532.444,50		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passengers capacity HEA	Passengers/hour	1.200	2,706	1.200	2,706
		Passeners/day	13.800		13.800	
		Passengers/year	5.037.000		5.037.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
15	Noise reduction	dB/hour	120	11,250	120	11,250
		dB/day	1.380		1.380	
		dB/year	503.700		503.700	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-201.480.000	10,147	-201.480.000	10,147
		Percentage of base case	-0,1171395%		-0,1171395%	
15	NO_x-reduction	gram/year	-61.559.191,80	10,147	-61.559.191,80	10,147
10	Possibility to grow		N.A.	3	N.A.	4
4	Operational cost reduction	euro/hour	0,120	0,429	0,120	0,429
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			72,329		63,679

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
		CONOPS	CONOPS 4B		CONOPS 4H	
			Siemens		Thompson	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Off-peak-hours		Off-peak-hours	
		Number of runways	2		3	
		Percentage of total aircraft [%]	20		20	
		Range [km]	500		500	
		Aircraft capacity [passengers]	50		50	
	Capacity HEA	Movements/hour	16	N.A.	16	N.A.
		Movements/day	182		182	
		Movements/year	66430		66430	
25	Runway capacity	Movements/hour	39,20	24,851	40,00	25
		Movements/year	536.788		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	800	1,784	800	1,784
		Passeners/day	9.100		9.100	
		Passengers/year	3.321.500		3.321.500	
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
15	Noise reduction	dB/hour	160	15,000	160	15,000
		dB/day	1.820		1.820	
		dB/year	664.300		664.300	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-265.720.000	13,382	-265.720.000	13,382
		Percentage of base case	-0,1544884%		-0,1544884%	
15	NO_x-reduction	gram/year	-81.186.760,20	13,382	-81.186.760,20	13,382
10	Possibility to grow		N.A.	6	N.A.	7
4	Operational cost reduction	euro/hour	0,820	2,929	0,820	2,929
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			87,329		78,478

Weight	KPI		CONOPS 5C	Scores	CONOPS 5F	Scores	CONOPS 5I	Scores
		CONOPS	CONOPS 5C		CONOPS 5F		CONOPS 5I	
			Volta		Franklin		Kelvin	
		Airport	Schiphol Airport		Regional airport		Schiphol Airport	
		Runway	Current runways		Current runway		Current runway + 1	
		Time	All day		All day		All day	
		Number of runways	3 2		1		4 3	
		Percentage of total aircraft [%]	25		25		25	
		Range [km]	1000		1000		1000	
		Aircraft capacity [passengers]	100		100		100	
	Capacity HEA	Movements/hour	12 12	N.A.	12	N.A.	12 12	N.A.
		Movements/day	138 66		204		138 66	
		Movements/year	50370 24090		74460		50370 24090	
25	Runway capacity	Movements/hour	39,40 39,10	24,483	40,00	25	39,55 39,40	25
		Movements/year	528.831		540.000		540.000	
10	Complexity of implementation		N.A.	10	N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	1.200	4,000	1.200	4,000	1.200	4,000
		Passeners/day	20.400		20.400		20.400	
		Passengers/year	7.446.000		7.446.000		7.446.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00 6,00	N.A.	12,00	N.A.	3,00 4,00	N.A.
15	Noise reduction	dB/hour	120	11,250	120	11,250	120	11,250
		dB/day	2.040		2.040		2.040	
		dB/year	744.600		744.600		744.600	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-297.840.000	15	-297.840.000	15	-297.840.000	15
		Percentage of base case	-0,1731628%		-0,1731628%		-0,1731628%	
15	NO_x-reduction	gram/year	-91.000.544,40	15	-91.000.544,40	15	-91.000.544,40	15
10	Possibility to grow		N.A.	8	N.A.	7	N.A.	10
4	Operational cost reduction	euro/hour	1,120	4	1,120	4	1,120	4
2	Total travel time	hours	N.A.	0	N.A.	1	N.A.	0
100	Total:			91,733		92,250		84,250

Figure G.1: Scorecard

H | SENSITIVITY ANALYSIS

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
	CONOPS		Ferraris		Tesla	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Peak-hours		Peak-hours	
	Number of runways		3		4	
	Percentage of total aircraft [%]		10		10	
	Range [km]		1000		1000	
	Aircraft capacity [passengers]		100		100	
	Capacity HEA	Movements/hour	12	N.A.	12	N.A.
		Movements/day	138		138	
		Movements/year	50370		50370	
25	Runway capacity	Movements/hour	39,20	24,534	40,00	25
		Movements/year	529.926,00		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	1.200	2,706	1.200	2,706
		Passeners/day	13.800		13.800	
		Passengers/year	5.037.000		5.037.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
15	Noise reduction	dB/hour	150	11,250	150	11,250
		dB/day	1.725		1.725	
		dB/year	629.625		629.625	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-251.850.000	10,147	-251.850.000	10,147
		Percentage of base case	-0,1464244%		-0,1464244%	
15	NO_x-reduction	gram/year	-75.555.000,00	10,147	-75.555.000,00	10,147
10	Possibility to grow		N.A.	3	N.A.	4
4	Operational cost reduction	euro/hour	0,120	0,429	0,120	0,429
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			72,212		63,679

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
	CONOPS		Siemens		Thompson	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Off-peak-hours		Off-peak-hours	
	Number of runways		2		3	
	Percentage of total aircraft [%]		20		20	
	Range [km]		500		500	
	Aircraft capacity [passengers]		50		50	
	Capacity HEA	Movements/hour	16	N.A.	16	N.A.
		Movements/day	182		182	
		Movements/year	66430		66430	
25	Runway capacity	Movements/hour	38,80	24,777	40,00	25
		Movements/year	535.182		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	800	1,784	800	1,784
		Passeners/day	9.100		9.100	
		Passengers/year	3.321.500		3.321.500	
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
15	Noise reduction	dB/hour	200	15,000	200	15,000
		dB/day	2.275		2.275	
		dB/year	830.375		830.375	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-332.150.000	13,382	-332.150.000	13,382
		Percentage of base case	-0,1931105%		-0,1931105%	
15	NO_x-reduction	gram/year	-99.645.000,00	13,382	-99.645.000,00	13,382
10	Possibility to grow		N.A.	6	N.A.	7
4	Operational cost reduction	euro/hour	0,820	2,929	0,820	2,929
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			87,255		78,478

Weight	KPI		CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
	CONOPS		Volta			Franklin		Kelvin		
	Airport		Schiphol Airport			Regional airport		Schiphol airport		
	Runway		Current runway			Current runway		Current runways + 1		
	Time		All day			All day		All day		
	Number of runways		3	2		1		4	3	
	Percentage of total aircraft [%]		25			25		25		
	Range [km]		1000			1000		1000		
	Aircraft capacity [passengers]		100			100		100		
	Capacity HEA	Movements/hour	12	12	N.A.	12	N.A.	12	12	N.A.
		Movements/day	138	66		204		138	66	
		Movements/year	50370	24090		74460		50370	24090	
25	Runway capacity	Movements/hour	39,20	38,80	24,311	40,00	25	39,40	39,20	25
		Movements/year	525.108			540.000		540.000		
10	Complexity of implementation		N.A.		10	N.A.	10	N.A.		0
4	Passenger capacity HEA	Passengers/hour	1.200		4,000	1.200	4,000	1.200		4,000
		Passeners/day	20.400			20.400		20.400		
		Passengers/year	7.446.000			7.446.000		7.446.000		
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
15	Noise reduction	dB/hour	150		11,250	150	11,250	150		11,250
		dB/day	2.550			2.550		2.550		
		dB/year	930.750			930.750		930.750		
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-372.300.000		15	-372.300.000	15	-372.300.000		15
		Percentage of base case	-0,2164535%			-0,2164535%		-0,2164535%		
15	NO_x-reduction	gram/year	-111.690.000,00		15	-111.690.000,00	15	-111.690.000,00		15
10	Possibility to grow		N.A.		8	N.A.	7	N.A.		10
4	Operational cost reduction	euro/hour	1,120		4	1,120	4	1,120		4
2	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				91,561		92,250			84,250

Figure H.1: Sensitivity analysis - independent variables (s)

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
		CONOPS	Ferraris		Tesla	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Peak-hours		Peak-hours	
		Number of runways	3		4	
		Percentage of total aircraft [%]	10		10	
		Range [km]	1000		1000	
		Aircraft capacity [passengers]	100		100	
	Capacity HEA	Movements/hour	12	N.A.	12	N.A.
		Movements/day	138		138	
		Movements/year	50370		50370	
25	Runway capacity	Movements/hour	39,00	24,417	40,00	25
		Movements/year	527.407,50		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	1.200	2,706	1.200	2,706
		Passeners/day	13.800		13.800	
		Passengers/year	5.037.000		5.037.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
15	Noise reduction	dB/hour	180	11,250	180	11,250
		dB/day	2.070		2.070	
		dB/year	755.550		755.550	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-302.220.000	10,147	-302.220.000	10,147
		Percentage of base case	-0,1757093%		-0,1757093%	
15	NO_x-reduction	gram/year	-88.147.500,00	10,147	-88.147.500,00	10,147
10	Possibility to grow		N.A.	3	N.A.	4
4	Operational cost reduction	euro/hour	0,120	0,429	0,120	0,429
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			72,096		63,679

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
		CONOPS	Siemens		Thompson	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Off-peak-hours		Off-peak-hours	
		Number of runways	2		3	
		Percentage of total aircraft [%]	20		20	
		Range [km]	500		500	
		Aircraft capacity [passengers]	50		50	
	Capacity HEA	Movements/hour	16	N.A.	16	N.A.
		Movements/day	182		182	
		Movements/year	66430		66430	
25	Runway capacity	Movements/hour	38,40	24,703	40,00	25
		Movements/year	533.576		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	800	1,784	800	1,784
		Passeners/day	9.100		9.100	
		Passengers/year	3.321.500		3.321.500	
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
15	Noise reduction	dB/hour	240	15,000	240	15,000
		dB/day	2.730		2.730	
		dB/year	996.450		996.450	
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-398.580.000	13,382	-398.580.000	13,382
		Percentage of base case	-0,2317326%		-0,2317326%	
15	NO_x-reduction	gram/year	-116.252.500,00	13,382	-116.252.500,00	13,382
10	Possibility to grow		N.A.	6	N.A.	7
4	Operational cost reduction	euro/hour	0,820	2,929	0,820	2,929
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			87,180		78,478

Weight	KPI		CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
		CONOPS	Volta			Franklin		Kelvin		
		Airport	Schiphol Airport			Regional airport		Schiphol Airport		
		Runway	Current runways			Current runway		Current runways + 1		
		Time	All day			All day		All day		
		Number of runways	3	2		1		4	3	
		Percentage of total aircraft [%]	25			25		25		
		Range [km]	1000			1000		1000		
		Aircraft capacity [passengers]	100			100		100		
	Capacity HEA	Movements/hour	12	12	N.A.	12	N.A.	12	12	N.A.
		Movements/day	138	66		204		138	66	
		Movements/year	50370	24090		74460		50370	24090	
25	Runway capacity	Movements/hour	39,00	38,50	24,138	40,00	25	39,25	39,00	25
		Movements/year	521.385			540.000		540.000		
10	Complexity of implementation		N.A.		10	N.A.	10	N.A.		0
4	Passenger capacity HEA	Passengers/hour	1.200		4,000	1.200	4,000	1.200		4,000
		Passeners/day	20.400			20.400		20.400		
		Passengers/year	7.446.000			7.446.000		7.446.000		
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
15	Noise reduction	dB/hour	180		11,250	180	11,250	180		11,250
		dB/day	3.060			3.060		3.060		
		dB/year	1.116.900			1.116.900		1.116.900		
15	CO_2-emissions-reduction (million)	Gram/passenger/year	-446.760.000		15	-446.760.000	15	-446.760.000		15
		Percentage of base case	-0,2597442%			-0,2597442%		-0,2597442%		
15	NO_x-reduction	gram/year	-130.305.000,00		15	-130.305.000,00	15	-130.305.000,00		15
10	Possibility to grow		N.A.		8	N.A.	7	N.A.		10
4	Operational cost reduction	euro/hour	1,120		4	1,120	4	1,120		4
2	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				91,388		92,250			84,250

Figure H.2: Sensitivity analysis - independent variables (m)

		CONOPS	CONOPS 3A	Scores	CONOPS 3G	Scores
			Ferraris		Tesla	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Peak-hours		Peak-hours	
		Number of runways	3		4	
		Percentage of total aircraft [%]	10		10	
		Range [km]	1000		1000	
		Aircraft capacity [passengers]	100		100	
Weight	KPI					
	Capacity HEA	Movements/hour Movements/day Movements/year	12 138 50370	N.A.	12 138 50370	N.A.
25	Runway capacity	Movements/hour Movements/year	38,60 522.370,50	24,184	40,00 540.000	25
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 13.800 5.037.000	2,706	1.200 13.800 5.037.000	2,706
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
15	Noise reduction	dB/hour dB/day dB/year	240 2.760 1.007.400	11,250	240 2.760 1.007.400	11,250
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-352.590.000 -0,2049942%	10,147	-352.590.000 -0,2049942%	10,147
15	NO_x-reduction	gram/year	-100.740.000,00	10,147	-100.740.000,00	10,147
10	Possibility to grow		N.A.	3	N.A.	4
4	Operational cost reduction	euro/hour	0,120	0,429	0,120	0,429
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			71,862		63,679

		CONOPS	CONOPS 4B	Scores	CONOPS 4H	Scores
			Siemens		Thompson	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Off-peak-hours		Off-peak-hours	
		Number of runways	2		3	
		Percentage of total aircraft [%]	20		20	
		Range [km]	500		500	
		Aircraft capacity [passengers]	50		50	
Weight	KPI					
	Capacity HEA	Movements/hour Movements/day Movements/year	16 182 66430	N.A.	16 182 66430	N.A.
25	Runway capacity	Movements/hour Movements/year	38,00 531.970	24,628	40,00 540.000	25
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	800 9.100 3.321.500	1,784	800 9.100 3.321.500	1,784
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
15	Noise reduction	dB/hour dB/day dB/year	320 3.640 1.328.600	15,000	320 3.640 1.328.600	15,000
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-465.010.000 -0,2703547%	13,382	-465.010.000 -0,2703547%	13,382
15	NO_x-reduction	gram/year	-132.860.000,00	13,382	-132.860.000,00	13,382
10	Possibility to grow		N.A.	6	N.A.	7
4	Operational cost reduction	euro/hour	0,820	2,929	0,820	2,929
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			87,106		78,478

		CONOPS	CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
			Volta			Franklin		Kelvin		
		Airport	Schiphol Airport			Regional airport		Schiphol Airport		
		Runway	Current runways			Current runway		Current runways + 1		
		Time	All day			All day		All day		
		Number of runways	3	2		1		4	3	
		Percentage of total aircraft [%]	25			25		25		
		Range [km]	1000			1000		1000		
		Aircraft capacity [passengers]	100			100		100		
Weight	KPI									
	Capacity HEA	Movements/hour Movements/day Movements/year	12 138 50370	12 66 24090	N.A.	12 204 74460	N.A.	12 138 50370	12 66 24090	N.A.
25	Runway capacity	Movements/hour Movements/year	38,60 513.939	37,90	23,793	40,00 540.000	25	38,95 540.000	38,60	25
10	Complexity of implementation		N.A.		10	N.A.	10	N.A.		0
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 20.400 7.446.000		4,000	1.200 20.400 7.446.000	4,000	1.200 20.400 7.446.000		4,000
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
15	Noise reduction	dB/hour dB/day dB/year	240 4.080 1.489.200		11,250	240 4.080 1.489.200	11,250	240 4.080 1.489.200		11,250
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-521.220.000 -0,3030349%		15	-521.220.000 -0,3030349%	15	-521.220.000 -0,3030349%		15
15	NO_x-reduction	gram/year	-148.920.000,00		15	-148.920.000,00	15	-148.920.000,00		15
10	Possibility to grow		N.A.		8	N.A.	7	N.A.		10
4	Operational cost reduction	euro/hour	1,120		4	1,120	4	1,120		4
2	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				91,043		92,250			84,250

Figure H.3: Sensitivity analysis - independent variables (l)

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
	CONOPS		Ferraris		Tesla	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Peak-hours		Peak-hours	
	Number of runways		3		4	
	Percentage of total aircraft [%]		10		10	
	Range [km]		1000		1000	
	Aircraft capacity [passengers]		100		100	
	Capacity HEA	Movements/hour Movements/day Movements/year	12 138 50370	N.A.	12 138 50370	N.A.
25	Runway capacity	Movements/hour Movements/year	39,40 532.444,50	24,650	40,00 540.000	25
10	Complexity of implementation		N.A.	2	N.A.	8
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 13.800 5.037.000	2,706	1.200 13.800 5.037.000	2,706
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	N.A.
15	Noise reduction	dB/hour dB/day dB/year	120 1.380 503.700	11,250	120 1.380 503.700	11,250
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-201.480.000 -0,1171395%	10,147	-201.480.000 -0,1171395%	10,147
15	NO_x-reduction	gram/year	-61.559.191,80	10,147	-61.559.191,80	10,147
10	Possibility to grow		N.A.	4	N.A.	4
4	Operational cost reduction	euro/hour	0,120	0,429	0,120	0,429
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			65,329		71,679

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
	CONOPS		Siemens		Thompson	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Off-peak-hours		Off-peak-hours	
	Number of runways		2		3	
	Percentage of total aircraft [%]		20		20	
	Range [km]		500		500	
	Aircraft capacity [passengers]		50		50	
	Capacity HEA	Movements/hour Movements/day Movements/year	16 182 66430	N.A.	16 182 66430	N.A.
25	Runway capacity	Movements/hour Movements/year	39,20 536.788	24,851	40,00 540.000	25
10	Complexity of implementation		N.A.	5	N.A.	6
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	800 9.100 3.321.500	1,784	800 9.100 3.321.500	1,784
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
15	Noise reduction	dB/hour dB/day dB/year	160 1.820 664.300	15,000	160 1.820 664.300	15,000
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-265.720.000 -0,1544884%	13,382	-265.720.000 -0,1544884%	13,382
15	NO_x-reduction	gram/year	-81.186.760,20	13,382	-81.186.760,20	13,382
10	Possibility to grow		N.A.	6	N.A.	6
4	Operational cost reduction	euro/hour	0,820	2,929	0,820	2,929
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			82,329		83,478

Weight	KPI		CONOPS 5C	Scores	CONOPS 5F	Scores	CONOPS 5I	Scores
	CONOPS		Volta		Franklin		Kelvin	
	Airport		Schiphol Airport		Regional airport		Schiphol Airport	
	Runway		Current runways		Current runway		Current runways + 1	
	Time		All day		All day		All day	
	Number of runways		3 2		1		4 3	
	Percentage of total aircraft [%]		25		25		25	
	Range [km]		1000		1000		1000	
	Aircraft capacity [passengers]		100		100		100	
	Capacity HEA	Movements/hour Movements/day Movements/year	12 12 138 66 50370 24090	N.A.	12 204 74460	N.A.	12 12 138 66 50370 24090	N.A.
25	Runway capacity	Movements/hour Movements/year	39,40 39,10 528.831	24,483	40,00 540.000	25	39,55 39,40 540.000	25
10	Complexity of implementation		N.A.	10	N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 20.400 7.446.000	4,000	1.200 20.400 7.446.000	4,000	1.200 20.400 7.446.000	4,000
N.A.	Runway occupancy	HEA/Runway/hour	4,00 6,00	N.A.	12,00	N.A.	3,00 4,00	N.A.
15	Noise reduction	dB/hour dB/day dB/year	120 2.040 744.600	11,250	120 2.040 744.600	11,250	120 2.040 744.600	11,250
15	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-297.840.000 -0,1731628%	15	-297.840.000 -0,1731628%	15	-297.840.000 -0,1731628%	15
15	NO_x-reduction	gram/year	-91.000.544,40	15	-91.000.544,40	15	-91.000.544,40	15
10	Possibility to grow		N.A.	9	N.A.	5	N.A.	10
4	Operational cost reduction	euro/hour	1,120	4	1,120	4	1,120	4
2	Total travel time	hours	N.A.	1	N.A.	0	N.A.	1
100	Total:			93,733		89,250		85,250

Figure H.4: Sensitivity analysis - qualitative KPIs

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
			Ferraris		Tesla	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Peak-hours		Peak-hours	
	Number of runways		3		4	
	Percentage of total aircraft [%]		10		10	
	Range [km]		1000		1000	
	Aircraft capacity [passengers]		100		100	
	Capacity HEA	Movements/hour Movements/day Movements/year	12 138 50370	N.A.	12 138 50370	N.A.
16	Runway capacity	Movements/hour Movements/year	39,40 532.444,50	15,776	40,00 540.000	16
8	Complexity of implementation		N.A.	8	N.A.	0
20	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 13.800 5.037.000	13,529	1.200 13.800 5.037.000	13,529
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	N.A.
10	Noise reduction	dB/hour dB/day dB/year	120 1.380 503.700	7,500	120 1.380 503.700	7,500
10	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-201.480.000 -0,1171395%	6,765	-201.480.000 -0,1171395%	6,765
10	NO_x-reduction	gram/year	-61.559.191,80	6,765	-61.559.191,80	6,765
20	Possibility to grow		N.A.	6	N.A.	8
2	Operational cost reduction	euro/hour	0,120	0,214	0,120	0,214
4	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			64,549		58,773

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
			Siemens		Thompson	
	Airport		Schiphol Airport		Schiphol Airport	
	Runway		Current runways		Current runways + 1	
	Time		Off-peak-hours		Off-peak-hours	
	Number of runways		2		3	
	Percentage of total aircraft [%]		20		20	
	Range [km]		500		500	
	Aircraft capacity [passengers]		50		50	
	Capacity HEA	Movements/hour Movements/day Movements/year	16 182 66430	N.A.	16 182 66430	N.A.
16	Runway capacity	Movements/hour Movements/year	39,20 536.788	15,905	40,00 540.000	16
8	Complexity of implementation		N.A.	8	N.A.	0
20	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	800 9.100 3.321.500	8,922	800 9.100 3.321.500	8,922
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
10	Noise reduction	dB/hour dB/day dB/year	160 1.820 664.300	10,000	160 1.820 664.300	10,000
10	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-265.720.000 -0,1544884%	8,922	-265.720.000 -0,1544884%	8,922
10	NO_x-reduction	gram/year	-81.186.760,20	8,922	-81.186.760,20	8,922
20	Possibility to grow		N.A.	12	N.A.	14
2	Operational cost reduction	euro/hour	0,820	1,464	0,820	1,464
4	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			74,134		68,229

Weight	KPI		CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
			Volta			Franklin		Kelvin		
	Airport		Schiphol Airport			Regional airport		Schiphol Airport		
	Runway		Current runways			Current runway		Current runways + 1		
	Time		All day			All day		All day		
	Number of runways		3	2		1		4	3	
	Percentage of total aircraft [%]		25			25		25		
	Range [km]		1000			1000		1000		
	Aircraft capacity [passengers]		100			100		100		
	Capacity HEA	Movements/hour Movements/day Movements/year	12 138 50370	12 66 24090	N.A.	12 204 74460	N.A.	12 138 50370	12 66 24090	N.A.
16	Runway capacity	Movements/hour Movements/year	39,40 528.831	39,10	15,669	40,00 540.000	16	39,55 540.000	39,40	16
8	Complexity of implementation		N.A.		8	N.A.	8	N.A.		0
20	Passenger capacity HEA	Passengers/hour Passeners/day Passengers/year	1.200 20.400 7.446.000		20,000	1.200 20.400 7.446.000	20,000	1.200 20.400 7.446.000		20,000
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
10	Noise reduction	dB/hour dB/day dB/year	120 2.040 744.600		7,500	120 2.040 744.600	7,500	120 2.040 744.600		7,500
10	CO_2-emissions-reduction (million)	Gram/passenger/year Percentage of base case	-297.840.000 -0,1731628%		10	-297.840.000 -0,1731628%	10	-297.840.000 -0,1731628%		10
10	NO_x-reduction	gram/year	-91.000.544,40		10	-91.000.544,40	10	-91.000.544,40		10
20	Possibility to grow		N.A.		16	N.A.	14	N.A.		20
2	Operational cost reduction	euro/hour	1,120		2	1,120	2	1,120		2
4	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				89,169		88,500			85,500

Figure H.5: Sensitivity analysis - weights airport

Weight	KPI		CONOPS 3A	Scores	CONOPS 3G	Scores
		CONOPS	CONOPS 3A	Scores	CONOPS 3G	Scores
			Ferraris		Tesla	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Peak-hours		Peak-hours	
		Number of runways	3		4	
		Percentage of total aircraft [%]	10		10	
		Range [km]	1000		1000	
		Aircraft capacity [passengers]	100		100	
Weight	KPI					
	Capacity HEA	Movements/hour	12	N.A.	12	N.A.
		Movements/day	138		138	
		Movements/year	50370		50370	
15	Runway capacity	Movements/hour	39,40	14,790	40,00	15
		Movements/year	532.444,50		540.000	
5	Complexity of implementation		N.A.	5	N.A.	0
20	Passengers capacity HEA	Passengers/hour	1.200	13,529	1.200	13,529
		Passeners/day	13.800		13.800	
		Passengers/year	5.037.000		5.037.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
10	Noise reduction	dB/hour	120	7,500	120	7,500
		dB/day	1.380		1.380	
		dB/year	503.700		503.700	
10	CO_2-emissions-reduction (million)	Gram/passenger/year	-201.480.000	6,765	-201.480.000	6,765
		Percentage of base case	-0,1171395%		-0,1171395%	
10	NO_x-reduction	gram/year	-61.559.191,80	6,765	-61.559.191,80	6,765
20	Possibility to grow		N.A.	6	N.A.	8
8	Operational cost reduction	euro/hour	0,120	0,857	0,120	0,857
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			61,206		58,416

Weight	KPI		CONOPS 4B	Scores	CONOPS 4H	Scores
		CONOPS	CONOPS 4B	Scores	CONOPS 4H	Scores
			Siemens		Thompson	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Off-peak-hours		Off-peak-hours	
		Number of runways	2		3	
		Percentage of total aircraft [%]	20		20	
		Range [km]	500		500	
		Aircraft capacity [passengers]	50		50	
Weight	KPI					
	Capacity HEA	Movements/hour	16	N.A.	16	N.A.
		Movements/day	182		182	
		Movements/year	66430		66430	
15	Runway capacity	Movements/hour	39,20	14,911	40,00	15
		Movements/year	536.788		540.000	
5	Complexity of implementation		N.A.	5	N.A.	0
20	Passengers capacity HEA	Passengers/hour	800	8,922	800	8,922
		Passeners/day	9.100		9.100	
		Passengers/year	3.321.500		3.321.500	
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
10	Noise reduction	dB/hour	160	10,000	160	10,000
		dB/day	1.820		1.820	
		dB/year	664.300		664.300	
10	CO_2-emissions-reduction (million)	Gram/passenger/year	-265.720.000	8,922	-265.720.000	8,922
		Percentage of base case	-0,1544884%		-0,1544884%	
10	NO_x-reduction	gram/year	-81.186.760,20	8,922	-81.186.760,20	8,922
20	Possibility to grow		N.A.	12	N.A.	14
8	Operational cost reduction	euro/hour	0,820	5,857	0,820	5,857
2	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			74,533		71,622

Weight	KPI		CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
		CONOPS	CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
			Volta			Franklin		Kelvin		
		Airport	Schiphol Airport			Regional airport		Schiphol Airport		
		Runway	Current runways			Current runway		Current runways + 1		
		Time	All day			All day		All day		
		Number of runways	3	2		1		4	3	
		Percentage of total aircraft [%]	25			25		25		
		Range [km]	1000			1000		1000		
		Aircraft capacity [passengers]	100			100		100		
Weight	KPI									
	Capacity HEA	Movements/hour	12	12	N.A.	12	N.A.	12	12	N.A.
		Movements/day	138	66		204		138	66	
		Movements/year	50370	24090		74460		50370	24090	
15	Runway capacity	Movements/hour	39,40	39,10	14,690	40,00	15	39,55	39,40	15
		Movements/year	528.831			540.000		540.000		
5	Complexity of implementation		N.A.		5	N.A.	5	N.A.		0
20	Passengers capacity HEA	Passengers/hour	1.200		20,000	1.200	20,000	1.200		20,000
		Passeners/day	20.400			20.400		20.400		
		Passengers/year	7.446.000			7.446.000		7.446.000		
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
10	Noise reduction	dB/hour	120		7,500	120	7,500	120		7,500
		dB/day	2.040			2.040		2.040		
		dB/year	744.600			744.600		744.600		
10	CO_2-emissions-reduction (million)	Gram/passenger/year	-297.840.000		10	-297.840.000	10	-297.840.000		10
		Percentage of base case	-0,1731628%			-0,1731628%		-0,1731628%		
10	NO_x-reduction	gram/year	-91.000.544,40		10	-91.000.544,40	10	-91.000.544,40		10
20	Possibility to grow		N.A.		16	N.A.	14	N.A.		20
8	Operational cost reduction	euro/hour	1,120		8	1,120	8	1,120		8
2	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				91,190		90,500			90,500

Figure H.6: Sensitivity analysis - weights airlines

		CONOPS	CONOPS 3A	Scores	CONOPS 3G	Scores
			Ferraris		Tesla	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Peak-hours		Peak-hours	
		Number of runways	3		4	
		Percentage of total aircraft [%]	10		10	
		Range [km]	1000		1000	
		Aircraft capacity [passengers]	100		100	
Weight	KPI					
	Capacity HEA	Movements/hour	12	N.A.	12	N.A.
		Movements/day	138		138	
		Movements/year	50370		50370	
15	Runway capacity	Movements/hour	39,40	14,790	40,00	15
		Movements/year	532.444,50		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	1.200	2,706	1.200	2,706
		Passeners/day	13.800		13.800	
		Passengers/year	5.037.000		5.037.000	
N.A.	Runway occupancy	HEA/Runway/hour	4,00	N.A.	3,00	
20	Noise reduction	dB/hour	120	15,000	120	15,000
		dB/day	1.380		1.380	
		dB/year	503.700		503.700	
20	CO_2-emissions-reduction (million)	Gram/passenger/year	-201.480.000	13,529	-201.480.000	13,529
		Percentage of base case	-0,1171395%		-0,1171395%	
20	NO_x-reduction	gram/year	-61.559.191,80	13,529	-61.559.191,80	13,529
5	Possibility to grow		N.A.	2	N.A.	2
2	Operational cost reduction	euro/hour	0,120	0,214	0,120	0,214
4	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			71,269		61,979

		CONOPS	CONOPS 4B	Scores	CONOPS 4H	Scores
			Siemens		Thompson	
		Airport	Schiphol Airport		Schiphol Airport	
		Runway	Current runways		Current runways + 1	
		Time	Off-peak-hours		Off-peak-hours	
		Number of runways	2		3	
		Percentage of total aircraft [%]	20		20	
		Range [km]	500		500	
		Aircraft capacity [passengers]	50		50	
Weight	KPI					
	Capacity HEA	Movements/hour	16	N.A.	16	N.A.
		Movements/day	182		182	
		Movements/year	66430		66430	
15	Runway capacity	Movements/hour	39,20	14,911	40,00	15
		Movements/year	536.788		540.000	
10	Complexity of implementation		N.A.	10	N.A.	0
4	Passenger capacity HEA	Passengers/hour	800	1,784	800	1,784
		Passeners/day	9.100		9.100	
		Passengers/year	3.321.500		3.321.500	
N.A.	Runway occupancy	HEA/Runway/hour	8,00	N.A.	5,33	N.A.
20	Noise reduction	dB/hour	160	20,000	160	20,000
		dB/day	1.820		1.820	
		dB/year	664.300		664.300	
20	CO_2-emissions-reduction (million)	Gram/passenger/year	-265.720.000	17,843	-265.720.000	17,843
		Percentage of base case	-0,1544884%		-0,1544884%	
20	NO_x-reduction	gram/year	-81.186.760,20	17,843	-81.186.760,20	17,843
5	Possibility to grow		N.A.	3	N.A.	4
2	Operational cost reduction	euro/hour	0,820	1,464	0,820	1,464
4	Total travel time	hours	N.A.	0	N.A.	0
100	Total:			86,846		77,435

		CONOPS	CONOPS 5C		Scores	CONOPS 5F	Scores	CONOPS 5I		Scores
			Volta			Franklin		Kelvin		
		Airport	Schiphol Airport			Regional airport		Schiphol Airport		
		Runway	Current runways			Current runway		Current runways + 1		
		Time	All day			All day		All day		
		Number of runways	3	2		1		4	3	
		Percentage of total aircraft [%]	25			25		25		
		Range [km]	1000			1000		1000		
		Aircraft capacity [passengers]	100			100		100		
Weight	KPI									
	Capacity HEA	Movements/hour	12	12	N.A.	12	N.A.	12	12	N.A.
		Movements/day	138	66		204		138	66	
		Movements/year	50370	24090		74460		50370	24090	
15	Runway capacity	Movements/hour	39,40	39,10	14,690	40,00	15	39,55	39,40	15
		Movements/year	528.831			540.000		540.000		
10	Complexity of implementation		N.A.		10	N.A.	10	N.A.		0
4	Passenger capacity HEA	Passengers/hour	1.200		4,000	1.200	4,000	1.200		4,000
		Passeners/day	20.400			20.400		20.400		
		Passengers/year	7.446.000			7.446.000		7.446.000		
N.A.	Runway occupancy	HEA/Runway/hour	4,00	6,00	N.A.	12,00	N.A.	3,00	4,00	N.A.
20	Noise reduction	dB/hour	120		15,000	120	15,000	120		15,000
		dB/day	2.040			2.040		2.040		
		dB/year	744.600			744.600		744.600		
20	CO_2-emissions-reduction (million)	Gram/passenger/year	-297.840.000		20	-297.840.000	20	-297.840.000		20
		Percentage of base case	-0,1731628%			-0,1731628%		-0,1731628%		
20	NO_x-reduction	gram/year	-91.000.544,40		20	-91.000.544,40	20	-91.000.544,40		20
5	Possibility to grow		N.A.		4	N.A.	4	N.A.		5
2	Operational cost reduction	euro/hour	1,120		2	1,120	2	1,120		2
4	Total travel time	hours	N.A.		0	N.A.	1	N.A.		0
100	Total:				89,690		90,500			81,000

Figure H.7: Sensitivity analysis - weights Government

I | SCIENTIFIC PAPER

The integration of hybrid and electric aircraft in the air traffic management system

M.N.A. (Nanette) Lim
2020-06-24

Abstract— **The demand for sustainable air traffic is growing. That is why aircraft manufacturers are researching the possibilities of hybrid and electric aircraft (HEA). HEA contains a powertrain that (partly) consist of a battery. The benefits are that aircraft ensure less noise nuisance, CO_2- and NO_x-emissions. However, due to a heavier powertrain, the performances of HEA are deviating compared to conventional aircraft. This paper is the first study into the integration of HEA in the air traffic management (ATM) system. The advent of HEA is related to many stakeholders. In addition, there is a lot of uncertainty in the specific performances and effects of HEA. This study aims to structure the context of HEA, explore different scenarios for 2035 and define potential concepts of operations (CONOPS) where HEA are integrated in the ATM-system. This is done based on a case study for Dutch airports.**

Keywords: **Air traffic management, TWR, APP, hybrid aircraft, electric aircraft, concept of operations**

I. INTRODUCTION

This paper is about the integration of hybrid and electric aircraft (HEA) in the air traffic management (ATM) system. This has been done through a case study for Dutch airports. Dutch airlines are responsible for 13 billion kilos of CO_2 and 57 billion kilos of NO_x [1]. These emissions contribute heavily to climate change. In addition, aviation creates a lot of noise pollution. These disadvantages have meant that Dutch aviation can only grow through demonstrable reduction of nuisance. This has subsequently led to the continuation of the *Nieuwe normen en Handhavenstelsel* until 2021 [2]. It states that Schiphol Airport is restricted to 500,000 air traffic movements per year [3]. In addition to restriction of air traffic movements, the *Koninklijke Luchtvaart Maatschappij* (KLM) received state aid due to the COVID-19-crisis, in return for more sustainable aviation [4]. In order to become more sustainable, KLM and and the Dutch Air Navigation Service Provider (ANSP) *Luchtverkeersleiding Nederland* (LVNL) have therefore joint *Nationaal actieprogramma Hybride Elektrische Vliegen* (AHEV) with 24 other aviation parties. This program aims to reduce the CO_2-emissions in 2030 to the level of emissions in 2005 with the implementation of HEA. [5][6].

The disadvantages of the (growing) aviation sector has resulted in pressure from various stakeholders to make aviation more sustainable. The advent of HEA can decrease the emissions and noise nuisance of aircraft. However, there is little to no knowledge about the integration of HEA on (crowded) airports. To the best of the authors' knowledge, no research has been conducted to this issue. This means there is a knowledge gap. In contrast, the architecture and design of HEA is studied widely. But in order to implement HEA on a large scale, it is necessary to study the integration of these aircraft as well. For ANSPs it is important to know what adjustments need to be made to the operation to allow HEA to land at and take-off from (crowded) airports.

The pressure for more sustainable aviation has led to aircraft manufacturers and start-ups to develop HEA. Boeing started the Boeing SUGAR VOLT program with the aim to design a hybrid aircraft that can transport 135 passengers [7]. Airbus is working on the E-fan X, which is a large commercial aircraft for 100 passengers. It is planned to take its first commercial flight within the 2030's timeframe [8]. Since Easyjet wants to own a fully electric short-distance fleet in 2030, they have partnered up with Wright Electric to design the first electric, large commercial aircraft [9]. In a shorter period of time, Eviation aims to have their aircraft Alice certified in one year. Alice is a nine-seater fully-electric aircraft that can fly up to 1000 kilometers [10].

In addition to these sustainable projects being developed, replacing conventional aircraft requires the knowledge on how to integrate HEA in the ATM-system. A proposal for new ATM operations is described in a concept of operations (CONOPS). The problem is that a CONOPS that integrates HEA in the ATM-system does not exist. Therefore, the objective is defined as "Find the potential concepts of operations that integrate HEA in the air traffic management system", to close the gap. These CONOPS have to be safe, efficient and more environmental friendly. The first step to find these CONOPS is to obtain a clear and structured overview of the context of HEA. Since the performances of HEA are uncertain, it is needed to variate them in different scenarios. In addition, the design space has to be determined in order to define CONOPS that are feasible.

This study only focuses on Tower (TWR) and Approach (APP) air traffic control operations at Schiphol Airport, Lelsystad Airport and Rotterdam-The Hague Airport (RTHA). APP accompanies aircraft from the air route to the airport and vice versa for around 50 kilometers around the airport. The APP air traffic controllers (ATCOs) hand the aircraft over to TWR ATCOs, who are responsible for aircraft within 15 kilometer around the airport [11] [12]. Both hybrid and electric passenger aircraft are included and have to fly under instrument flight rules. Vertical take-off and landing aircraft, hydrogen-powered aircraft and cargo aircraft are excluded. Lastly, the integration of HEA in the ATM-system are suitable for both peak- and off-peak hours.

This papers starts with an explanation of the methodology in section II. Since there are only studies available about the performances and effects of HEA, it is important to understand the context of HEA. The context analysis is described in section III. Next, the process and results of finding the design space, scenarios and CONOPS is described in section IV. This will be followed by section V with the preparations for the assessment. Finally, the CONOPS is assessed in section VI. This paper ends with the conclusion that can be drawn in section VII and the discussion for further research in section VIII.

II. Methodology

This study aims to explore potential concepts of operations (CONOPS) to integrate HEA in TWR and APP operations. This will be done with applying an assessment. In order to find these potential CONOPS, this study is divided into four phases. The first phase towards closing the knowledge gap is to obtain a clear overview of the context. The objectives and desires of important stakeholders related to HEA are collected from interviews. These stakeholders play a major role in the advent and implementation of this innovation. These are structured in a stakeholder analysis. Additionally, the deviating performances of HEA have to be clear in order to know what the effect is on TWR and APP operations.

Phase II relates to exploring the three types of input for the assessment, namely the scenarios, design space and CONOPS. Since the performances of HEA are still uncertain, a scenario analysis is applied in order to cover all possibilities for these performances. Based on external factors, different absolute values are assigned to each independent HEA performance variable per scenario. The outcome of the stakeholder analysis forms the input for the design space. This design space includes the frameworks in which the CONOPS must comply, consisting of objectives, requirements, constraints and KPIs. The ANSP is the decision maker but relies on important stakeholders as well. When the design space was clear, an exploration was done to potential CONOPS that integrate HEA in the ATM-system. These CONOPS are dependent on the HEA performance variables per scenario and the design space. First, an exploration was done in a brainstorm with HEA- and ATM-experts. In this brainstorm the goal was to diverge and find as many CONOPS as possible, regardless of the design space restrictions. Using a morphological analysis, the variables as outcome of the brainstorm, were structured and CONOPS that did not meet the constraints of the design space were eliminated.

The assessment is done using a scorecard with two axes. This means a combination must be made between the CONOPS and scenarios in phase III. Combinations that did not meet the constraints of the design space were eliminated. Only the vertices, the most interesting combinations, are used

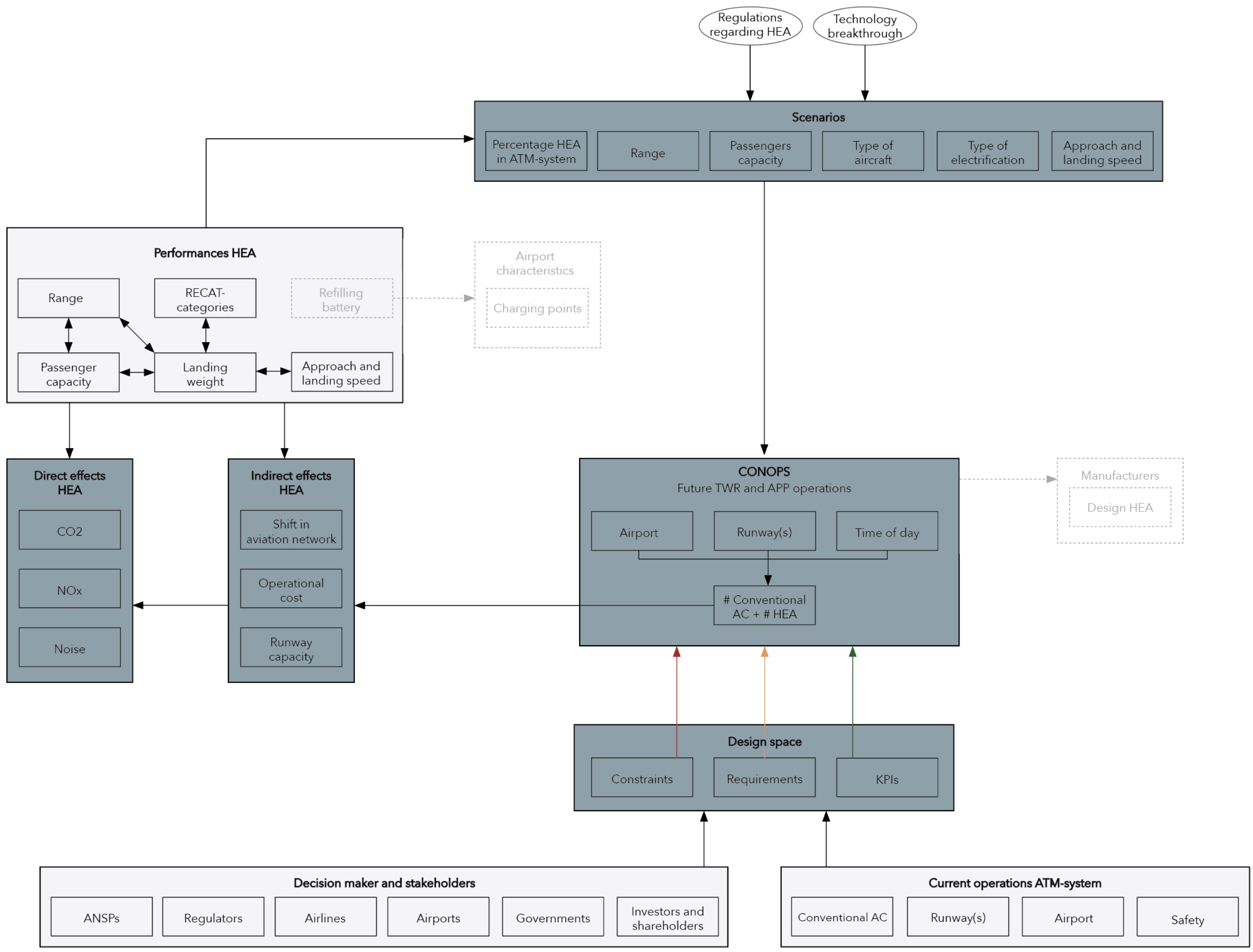

Fig. 1: Theoretical Framework

for further research. The dashed information is important for the advent of HEA but not studied in this research. From this moment on, the combinations are also called CONOPS.

In the last phase, the CONOPS are assessed based on the KPIs from the design space and the performances and effects of HEA. Figure 1 shows the theoretical framework. The independent variables are coloured grey. The dependent variables in blue. The circles refer to exogenous factors.

III. Phase I. Context analysis

The main difference between a conventional aircraft and HEA is the replacement of fuel with a battery. One of the barriers for enabling new propulsion systems is the battery density. Research shows that there is potential to close this technology gap. At the moment, the battery density is beneath the needed performances. For example, a 50 kg electric motor with a power output of 260 kW is developed but the required power for a commercial aircraft is 2-50 MW [13]. The weight of a lithium battery-ion battery pack is expected to decrease by 60 percent before 2030 [14]. However, the powertrain will still be heavier compared to conventional aircraft [15][16][17][18][19]. It can already be stated that the difference in weight of the powertrain leads to deviating (technical) performances [20]. Firstly, the weight of an aircraft can be broken down into the energy (fuel or battery), payload and operating energy weight [21]. This means that when the energy weight increases, the total weight has to be compensated by the passengers capacity [22]. The passengers are part of the payload. It is expected that HEA can transfer up to 100 passengers. This means that the passenger capacity per HEA decreases compared to conventional aircraft. Secondly, a characteristic of battery-energy is that the weight of the powertrain does not decrease over the flight [23]. This affects the approach and landing speed and a longer Runway Occupancy Time (ROT) is needed. This subsequently affects the runway capacity. Lastly, since the power-to-weight ratio is limited [14], it effects the maximum range of the aircraft [22][24]. The maximum range of the aircraft is expected to be around 1000km [25][26]. This can also be seen in figure 2 as outcome of the data-analysis.

The replacement of fuel by batteries leads to differences in effects of HEA. CO_2- and NO_x-emissions are specific emissions for combustion engines. However, electric aircraft do not emit CO_2- and NO_x-emissions. For hybrid aircraft applies that these emissions are reduced up to 40 percent [27]. The CO_2-emissions for conventional aircraft per passenger/km is 80 gram [28]. The NO_x-emissions per conventional aircraft is 1222.14 gram [29][22]. The use of batteries also ensures noise reduction. Commercial hybrid and electric propulsion reduces aircraft noise by up to 85 percent [27]. This equals 10 dBA compared to conventional aircraft of similar size. For private jets the noise decrease is 19 EPNdB [30].

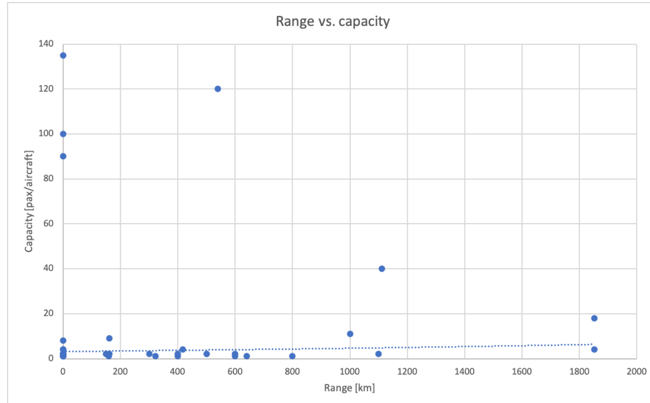

Fig. 2: Range [km] - passenger capacity [pax/aircraft]

Three indirect effects of HEA are the shift in aviation network, operation costs and the runway capacity. This latter one is already discussed above. The shift in aviation network is the effect of the short range and limited passenger capacity. It is expected that with the advent of HEA, more point-to-point flights are offered by airlines. HEA are attractive for airlines to purchase as the operating cost will be reduced by up to 20 percent [31].

The advent of HEA is related to many stakeholders. Their objectives and desires can influence the operations of the ATM-system. That is why it is important to take their objectives, constraints and requirements related to HEA into account as well. A stakeholder analysis is applied in order to define the important stakeholders and their judgement of HEA [32]. Even thought stakeholders have a different underlying reason, it is striking that all stakeholders have the same goal to make aviation more sustainable. The interaction between the important stakeholders to make aviation more sustainable can be seen in figure 3. Now that the context of HEA is clear, phase I of this study is completed.

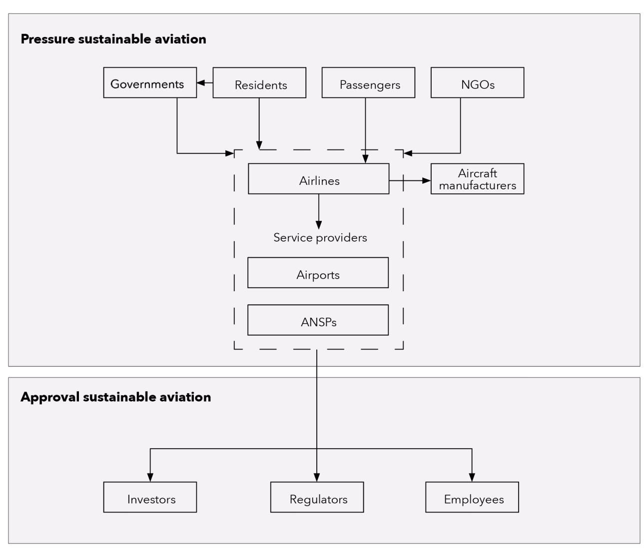

Fig. 3: Pressure sustainable aviation and stakeholders

IV. Phase II. Assessment input

In the second phase of this research the input for the assessment has been explored. The input for the assessment contains the design space, scenarios and CONOPS.

Design space: The design space is based on the objectives, requirements and constraints of the decision maker and also takes the important stakeholders into account. The objective states that the CONOPS should be able to handle conventional, hybrid and electric aircraft. That means that the CONOPS should be able to handle both the take-off and landing of these three types of aircraft. Since the ANSP is a service providing actor, a requirement of the CONOPS is that it should be efficient in passenger capacity. This is important for the airlines. For airports it is important in order to maintain their status. Another requirement is that only existing runways can be used. In the current operations, the 2+1-runway use if applicable for peak-hours. During off-peak hours one runway is used for take-off and one for landing [33]. The design space also states that there is a possibility to make use of extra runways. However, a new runway cannot be build due to the complexity of the CONOPS. The last requirement is that the CONOPS should be environmentally friendly in terms of CO_2, NO_x and noise.

The constraints say something about the capacity, safety, regulations or technical performances that the CONOPS must meet. Next to the objective, requirements and constraints the KPIs are determined. These KPIs are used to assess the CONOPS per scenario. The KPIs are as following: runway capacity, complexity of implementation, noise-, CO_2-reduction and NO_x-reduction, possibility to grow, operation cost reduction and total travel time.

Scenarios: The dependent variables of the performances of HEA are still uncertain. That is why five scenarios are determined in a scenario analysis [34]. It can be concluded that the scenario space exists of the technology breakthrough and the decisions of regulations regarding HEA. In the scenario space, five scenarios are defined. For each scenario, consisting of a specific combination between the two driving forces, absolute values are given to the dependent variables. The five scenarios and their corresponding performances and characteristics can be found in figure 4.

It can be seen that there are six characteristics per scenario, namely the percentage of HEA in the ATM-system, range, passenger capacity, type of aircraft and electrification and the approach and landing speed. Each characteristic is assigned an absolute value. A distinction has been made between the minimum and maximum performances of HEA, which are the result of the data analysis. The percentage of HEA in the ATM-system is based on the number of flights up to 750 km. It is concluded that HEA have a maximum range of 1000km. However, regulations require that there will be enough fuel on board for the flight to be completed safely and for the alternate airport specified in the navigation plan to be reached, in case of unexpected events [2]. That is why HEA can only fly up to 750km in practice. This equals 38 percent of the current flights at Schiphol Airport and 25 percent at RTHA [35]. The range and passenger capacity are assumed based on the data-analysis. Figure 2 shows that the majority of HEA concepts are within a range of 500km with up to 20 passengers. There are also some concept HEA that expect to fly up to 1000 km with 100 passengers. It is concluded in the data analysis that HEA with a longer range and higher passenger capacity are mainly outliers. Therefore it is less likely that HEA with a higher passenger capacity and range become reality.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Positive regulations regarding HEA	None	Positive	None	Medium	Positive
Technology breakthrough	Low	Low	High	Medium	High
Percentage HEA in ATM-system [%]	0	5	10	20	25
Range [km]	0	500	1000	500	1000
Passenger capacity [pax/HEA]	0	19	100	50	100
Type of aircraft	N.A.	Private jets	Private jets, airlines	Private jets, airlines	Private jets, airlines
Type of electrificiation	N.A.	Hybrid and electric	Electric	Hybrid and electric	Electric aircraft
Hybrid aircraft: Approach and landing speed	N.A.	1	N.A.	1	N.A.
Electric aircraft: Approach and landing speed	N.A.	1	1,15	1,1	1,15

Fig. 4: Performances per scenario

The first scenario is presents the base case. The technology breakthrough and lack of positive regulations regarding HEA lead to zero percent HEA. Scenario 2 contains five percent of HEA. Due to the limited technology breakthrough, only HEA with a maximum passenger capacity of 19 passengers are certified. In combination with a limited maximum range of 500km, purchasing HEA is only attractive for private jet owners. In scenario 3 and 5, a technology breakthrough has occurred. Because of this, both scenarios contain HEA that can fly up to 1000km with 100 passengers. However, due to the lack of positive regulations in scenario 3, the percentage of HEA is only ten percent. In scenario 5, the regulations are positive which means it is more attractive for airlines to purchase HEA, due to the economic and sustainable benefits. This leads to 25 percent HEA in the ATM-system.

CONOPS: Many ideas for CONOPS are devised in a brainstorm. The brainstorm, in which ATM and HEA experts participated, was mainly focused on scenario 3, 4 and 5. Scenario 1 represents the base case in which no HEA are integrated. The CONOPS related to scenario 2 is apparent. These two scenarios are temporarily put aside. During the brainstorm both segregation and integration were mentioned. Other ideas have been suggested as locating HEA at Schiphol Airport or at regional airports, opening up a fourth runway during peak-hours if the capacity does not allow otherwise and discussions were held about integrating HEA during peak- and/or off-peak hours. These ideas can be classified into three variables: time, airport and runway. A morphological analysis was applied in order to make all combinations between these variables. CONOPS that were not feasible or did not meet the constraints were filtered out.

The outcome contains of nine CONOPS (A to I), that can be found in figure 5.

CONOPS	Time	Airport	Runway
A	Peak hours	Schiphol Airport	Integration
B	off-peak hours	Schiphol Airport	Integration
C	all day	Schiphol Airport	Integration
D	Peak hours	Regional airport	Integration
E	off-peak hours	Regional airport	Integration
F	all day	Regional airport	Integration
G	Peak hours	Schiphol Airport	Integration extra runway
H	off-peak hours	Schiphol Airport	Integration extra runway
I	all day	Schiphol Airport	Integration extra runway

Fig. 5: Outcome morphological analysis

The aim of phase II is to determine the design space, scenarios and CONOPS as input for the assessment. Now that these are determined, phase II can be completed.

V. Phase III. Preparation assessment

Since there are three types of input and a scorecard only has two axes, scenarios 3, 4 and 5 are combined with the nine CONOPS. The result consists of 27 combinations. However, only the vertices are chosen to do further research on. The vertices are the most interesting combinations that cause the most friction in the ATM-system. They are chosen in a scorecard, based on the constraints and the characteristics of the scenario-CONOPS-combinations. First, the variables of the scenario-CONOPS-combination are made more exact by defining the number of runways, number of HEA, the specific time of peak- and off-peak hours [min] [36] and the current pressure on the ATM-system of the location. Hereafter, normalized scores between zero and one are added to these defined variables. The scenario-CONOPS-combination with the highest score per CONOPS is chosen as vertex since this is the most interesting to research more in detail. Thereby, it is also examined whether the scenario-CONOPS-combinations meet the constraints that have been established earlier in the design space. Nine combinations are determined as vertices. These combinations are from now on called CONOPS and are given a name, as can be seen in figure 6.

It can be seen that scenario 1 and 2 are both connected to only one CONOPS. Scenario 3 is combined with CONOPS Ferraris and CONOPS Tesla that are both located at Schiphol Airport during peak hours. These combinations study whether it is better to make use of the current runways or make use of an extra runway, in case of ten percent HEA. The same applies for CONOPS Siemens and CONOPS Thompson that are related to scenario 4 where only off-peak hours are considered. In addition, this scenario contains 20 percent HEA with a shorter range and smaller passenger capacity. Since HEA have a smaller passenger capacity compared to conventional aircraft, the CONOPS can only be implemented when the business model of airlines are adjusted. Lastly, scenario 5 is combined with CONOPS Volta, CONOPS Franklin and CONOPS Kelvin. These three combinations make it possible to study whether it is better to accommodate 25 percent of HEA at Schiphol airport on the current runways, at Schiphol airport with one extra runway or at the regional airports. Now that the combinations between scenarios and CONOPS have been made, phase III has been completed.

VI. Phase IV. Assessment

With the CONOPS and the KPIs that are determined before, the assessment is performed. This section first describes the outcome of the assessment. This is followed by the sensitivity analysis in order to determine how various sources of uncertainty in a model contribute to the model's overall uncertainty.

Outcome assessment

The input for the assessments consists of the CONOPS (related to a scenario) and KPIs. Each CONOPS is assessed on the KPIs by first calculating the absolute numbers of the KPIs. The absolute numbers are calculated based on the characteristics of the CONOPS and the performances and effects defined in the data-analysis. Based on the absolute numbers, normalized scores are given to the KPIs per CONOPS. The final score per CONOPS shows which CONOPS is potential per scenario. It was already clear that CONOPS Bell and CONOPS Edison are the best fit in case

CONOPS	Linked to CONOPS	Percentage HEA	Range	Passengers capacity per HEA	Airport	Time	Runway
Bell	1	0	N.A.	N.A.	N.A.	N.A.	N.A.
Edison	2	5	500	19	Schiphol	All day	Oostbaan
Ferraris	3	10	1000	100	Schiphol	Peak-hours	Current runways
Tesla	3	10	1000	100	Schiphol	Peak-hours	Current runways + 1
Siemens	4	20	500	50	Schiphol	Off-peak hours	Current runways
Thompson	4	20	500	50	Schiphol	Off-peak hours	Current runways + 1
Volta	5	25	1000	100	Schiphol	All day	Current runways
Franklin	5	25	1000	100	Regional airport	All day	Current runways
Kelvin	5	25	1000	100	Schiphol	All day	Current runways + 1

Fig. 6: Characteristics per CONOPS

respectively scenario 1 and 2 become reality. For scenario 3, CONOPS Ferraris has the highest final score. This CONOPS integrates 10 percent HEA during peak hours on the current runways. In case scenario 4 becomes reality, it is recommended to implement CONOPS Siemens. It is therefore recommended to integrate 20 percent of HEA during off-peak hours on the current runways. For scenario 5, it was also researched what the effect is of implementing HEA at regional airports. This CONOPS Franklin scores best of the three. The absolute numbers in the scorecard also show that a CONOPS with a higher percentage HEA (not part of this research) will exceed the maximum capacity of the two regional airports. 25 percent of HEA equals 74,460 movement. 45,000 movements can be located at Lelystad airport (after the *Luchtruimherziening* [37]). The other flight movements can be located at RTHA [38]. Furthermore, it was striking that CONOPS Volta scores second best. The difference in final scores between CONOPS Franklin and Volta is around 0.5 on a total score around 100. This means that both CONOPS can be implemented.

Sensitivity analysis

As is said before, the independent variables are based on an assumption. This means that this affects the dependent variables as well. With this sensitivity analysis, it is studied how various sources of uncertainty in a model contribute to the model's overall uncertainty. The independent variables that are of great influence of the outcome of the assessment are the landing weight, noise nuisance, CO_2- and NO_x-emissions. The landing weight subsequently affects the RECAT-categories, the approach and landing speed, ROT and runway capacity. The increase of the ROT is assumed to be 5, 10 and 15 percent dependent on the HEA's passenger capacity. If the landing weight becomes much heavier than expected, the runway capacity will decrease significantly. In this case, the final scores decrease of CONOPS that include more HEA which shows that it is less attractive for an ANSP to include HEA to a larger extent, based on the runway capacity.

Based on scientific research, the noise nuisance, CO_2- and NO_x-emissions are assumed as well [30][28][29]. These three variables are of great importance for the Dutch minister of Infrastructure and Water Management since the aviation sector can only grow through demonstrable reduction of nuisance [3]. By varying these variables, the greatest possible growth can be created. Different values for these four independent variables are applied in the sensitivity analysis. The outcome shows that the final scores change minimally. The adjustments of the variables and the effects on the final scores can be found in table 7.

The reason why the final scores do not change that much is because the outcome of the assessment is to a great extent based on the qualitative KPIs. These KPIs are the complexity of implementation and possibility to grow for CONOPS related to scenario 3 and 4. For CONOPS related to scenario 5, the qualitative KPIs that influence the outcome are the possibility to grow and the total travel time. A sensitivity analysis is applied for these CONOPS. The results show that when the scores of the qualitative KPIs are adjusted, the final scores differ significantly. In case of scenario 3, CONOPS Tesla scores higher than CONOPS Ferraris which means that it is recommended to make use of an extra runway. The same holds for CONOPS related to scenario 4. This can be seen in figure 8.

			Assessment base case	Sensitivity analysis	
			Scores	Scores	Δ
Complexity of implementation	Scenario 3	Ferraris	10	2	8
		Tesla	0	8	-8
	Scenario 4	Siemens	10	5	5
		Thompson	0	6	-6
Possibility to grow	Scenario 3	Ferraris	3	4	-1
		Tesla	4	4	0
	Scenario 4	Siemens	6	6	0
		Thompson	7	6	1
Final score	Scenario 3	Ferraris	72,329	65,329	-10,715%
		Tesla	63,679	71,679	11,161%
	Scenario 4	Siemens	87,329	82,329	-6,073%
		Thompson	78,478	83,478	5,990%

Fig. 8: Sensitivity analysis qualitative KPIs - scenario 3 and 4

Scenario 5 is related to three CONOPS. The outcomes of CONOPS Franklin and Franklin are already close together. CONOPS Franklin is assigned the highest score and CONOPS Franklin scores slightly lower. A minimal change in the scores of the qualitative KPIs is needed in order to assign CONOPS Franklin the highest score. One of the qualitative scores is the total travel time. Further research must be done to the total travel time from door-to-door for passengers in order to assign this KPI a quantitative score. It can for example be that Schiphol Airport is better accessible

			Assessment	Sensitivity analysis					
			Base case	Small	Δ	Medium	Δ	Large	Δ
Indepent variables	CO2-decrease	gram/passenger/km	80	100	20	120	40	140	60
	NOX-decrease	gram/aircraft	1222,14	1500	277,86	1750	527,86	2000	777,86
	Noise-decrease	dB	10	12,5	3	15	5	20	10
	ROT 50-70p	%	10	15	5	20	10	25	15
	ROT 70-100p	%	15	20	5	25	10	35	20
Outcome	Scenario 3	Ferraris	72,329	72,212	0,161%	72,096	0,322%	71,862	0,645%
		Tesla	63,679	63,679	0,000%	63,679	0,000%	63,679	0,000%
	Scenario 4	Siemens	87,329	87,255	0,085%	87,180	0,170%	87,106	0,255%
		Thompson	78,478	78,478	0,000%	78,478	0,000%	78,478	0,000%
	Scenario 5	Volta	91,733	91,561	0,188%	91,388	0,376%	91,043	0,752%
		Franklin	92,250	92,250	0,000%	92,250	0,000%	92,250	0,000%
		Kelvin	84,250	84,250	0,000%	84,250	0,000%	84,250	0,000%

Fig. 7: Sensitivity analysis

for more passengers, due to the better infrastructure and higher population density. In that case, CONOPS Volta is assessed a higher score for this KPI and subsequently for the final score. This is shows in figure 9

		Assessment base case	Sensitivity analysis	
		Scores	Scores	Δ
Possibility to grow	Volta	8	9	-1
	Franklin	7	5	2
	Kelvin	10	10	0
Total travel time	Volta	0	1	-1
	Franklin	1	0	1
	Kelvin	0	1	-1
Final score	Volta	91,733	93,733	2,134%
	Franklin	92,250	89,250	-3,361%
	Kelvin	84,250	85,250	1,173%

Fig. 9: Sensitivity analysis qualitative KPIs - scenario 5

A third sensitivity analysis is based on the weight of the KPIs. The weights are applied from the decision makers' point of view. However, many stakeholders are involved as is proved earlier in this research. Some KPIs are only related to only the ANSP, others are related to important stakeholders. Implementing the weights of importance per KPI can be based on the relationships between the ANSP with other stakeholders. A sensitivity analysis is applied on the relationships with airports, airlines and governments. The results can be found in figure 10. The different weights of the KPIs lead to different final scores. For CONOPS related to scenario 3 and 4, the differences in final scores do not influence to the extent that the CONOPS with a lowest score in the base case gets the highest score in the sensitivity analysis. For CONOPS related to scenario 5, CONOPS Volta and Franklin change in highest score. However, it can be concluded that weights do not affect the final outcome of this study significantly.

It can be concluded from the sensitivity analysis that mainly the uncertain qualitative sources in the model contribute to the model's overall uncertainty.

VII. Conclusion

Overall, it can be concluded that HEA can be treated as a conventional aircraft. Even with deviating performances, the integration of HEA entails a limited implementation complexity. When HEA are integrated on the already used runways, the runway capacity decreases minimally. Using an extra runway influences the complexity of the CONOPS and does not outweigh the loss of runway capacity. The advantage is that HEA make the TWR and APP operations more sustainable. The noise-nuisance, CO_2-and NO_x-emissions decrease significantly. Since residents experience less nuisance of air traffic, airports can grow in air traffic movements and total passengers per year [3]. This is an advantage for airlines and airports. However, the total passenger capacity of airports and airlines is related to the definitive passenger capacity of HEA. When this passenger capacity is relatively small, this will effect the airlines operations significantly. Since airports and airlines want to maintain their passenger capacity, HEA with a smaller passenger capacity can only be integrated when the business model of airlines are adjusted [39].

There is also the possibility to move a percentage of HEA to regional airports. For the regional airports Lelystad and RTHA, a maximum of 25 percent applies. This is the maximum percentage of HEA that can be moved to regional airports without resulting in complexity of the new CONOPS . HEA can be integrated like a conventional aircraft. However, the sensitivity analysis shows that the outcome of the assessment is mainly based on the qualitative KPIs. It is therefore recommended to do further research on the following KPIs: complexity of implementation, possibility to grow and total travel time. Further recommendations are given in the next section. This study is a preliminary research for ANSPs to integrate HEA in the ATM-system. When ANSPs at other airports want to integrate HEA, the structure of this case study can be used. As the independent variables of the performances and effects of HEA, that are independent of the ANSP and airport of implementation.

			Assessment	Sensitivity analysis					
			Base case	Airports	Δ	Airlines	Δ	Government	Δ
Weights KPIs	Runway capacity		25	16	-9	15	-10	15	-10
	Complexity of implementation		10	8	-2	5	-5	10	0
	Passengers capacity HEA		4	20	16	20	16	4	0
	Noise reduction		15	10	-5	10	-5	20	5
	CO_2-emissions-reduction		15	10	-5	10	-5	20	5
	NO_x-reduction		15	10	-5	10	-5	20	5
	Possibility to grow		10	20	10	20	10	5	-5
	Operational cost reduction		4	2	-2	8	4	2	-2
	Total travel time		2	4	2	2	0	4	2
Outcome	Scenario 3	Ferraris	72,329	64,549	10,756%	61,206	15,378%	71,269	1,465%
		Tesla	63,679	58,773	7,703%	58,416	8,264%	61,979	2,669%
	Scenario 4	Siemens	87,329	74,134	15,110%	74,533	14,653%	86,846	0,553%
		Thompson	78,478	68,229	13,059%	71,622	8,736%	77,435	1,329%
	Scenario 5	Volta	91,733	89,169	2,795%	91,190	0,592%	89,690	2,227%
		Franklin	92,250	88,500	4,065%	90,500	1,897%	90,500	1,897%
		Kelvin	84,250	85,500	-1,484%	90,500	-7,418%	81,000	3,858%

Fig. 10: Sensitivity analysis weights KPIs

VIII. Discussion

In this section, the recommendations are given that are part of the results of this study. First, the limitations and recommendations for the data is given. This is followed by the recommendations for further research. Next, recommendations for ANSPs abroad are given.

Recommendations for data: In figure 1 it is shows that the performances of HEA are independent variables. Since aircraft manufacturers are still exploring the maximum power-to-weight ratio, there is a lack of (exact) data about the performances of HEA. A data-analysis and the implementation of scenarios in this study attempt to make the values of the independent variables as robust as possible. However, this does not change the fact that assumptions had to be made for the performances of HEA. When independent variables are uncertain, this uncertainty can affect the outcome of the overall model. It is therefore recommended to repeat this research again in the future with more reliable data. Since the performances and effects are linked to the power-to-weight ratio, a certain ratio will effect the certainty of this study significantly.

In addition, other assumptions, independent of the data analysis, have been made that can influence the outcome of the scorecard. Firstly, the CONOPS are compared to the current situation. The base case does not take future changes into account that are unrelated to HEA, for example the advent of other sustainable aviation fuels. It is recommended that these future changes be included in further research in due course. Secondly, based on literature research the assumption is made that HEA are expected in 2035. This assumption was partly based on the expected growth of aviation. However, during this study the COVID-19 crisis started. The aviation sector has been seriously affected by this. It is expected that the number of movements at Schiphol will be back at its old level in 2023. In addition, aircraft manufacturers suffer from this and therefore freeze the HEA-projects. It may therefore be that 2035 is no longer a correct time estimate.

Recommendations for further research: As said above, the independent variables are uncertain. That is why the context has to be analyzed again in the future. The structure of this research can be maintained in the future. It ensures that possibilities are sought in a divergent way and future scenarios keep options open until a scenario becomes reality. Since the independent variables becomes more certain over time, the outcome of this research becomes more robust. When they are more certain, it is important to do more detailed research per KPI. When more detailed studies are performed per KPI, each KPI can be assessed at the same detailed level. This means that the qualitative KPIs can be transformed into quantitative KPIs. Lastly, for further research is it interesting to look at the effects of combinations between CONOPS. This applies to CONOPS that are located at different runways and/or airports can be combined. For example CONOPS Franklin, located at the regional airports, can be combined with CONOPS Volta in order to integrate 50 percent of HEA.

Recommendations for ANSPs elsewhere: This research was carried out by means of a case study at Dutch airports. When looking at integrating HEA in the ATM-system at a different location, it is recommended to keep the same structure of this study. However, minor adjustments have to be made. In addition, the recommendations described above also apply to ANSPs at airports abroad. The adjustments are:

- In the Netherlands there is almost no regional air traffic. This means that no flights are offered with both departure and arrival within the Netherlands. When HEA are integrated in a country where regional air traffic is involved, the advent of HEA influences the ATM-system more. The distances of regional air traffic, the maximum range and passenger capacity of HEA are a better match. That means that the percentage of HEA in the ATM-system can increase significantly. The role of regional airports is therefore becoming much more interesting.
- In the Netherlands, there are relatively many runways in use. It is known that this is not always the case at other airports. When only one runway is in use at a bigger airport, this can influence the impact of deviating performances. It is recommended to take this into account.
- It is recommended to keep in close contact of the operations of other ANSPs. When HEA are integrated in the ATM-system, it is important to share experiences of operations with ANSPs abroad.

References

[1] CBS, "Hoeveel uitstoot veroorzaakt de nederlandse luchtvaart?," 2019.
[2] Rijksoverheid, "Wet luchtvaart," 1992.
[3] C. van Nieuwenhuizen Wijbenga, "Ontwikkeling schiphol en hoofdlijnen luchtvaartnota," 2019.
[4] Rijksoverheid, "Kabinet zet financiële steun klaar voor klm," 2020.
[5] H. Werij, "Concept ahev v.0.54," 2019.
[6] CBS, "Hoeveel uitstoot veroorzaakt de nederlandse luchtvaart?," 2018.
[7] BOEING, "Boeing sugar volt: Boeing's hybrid electric aircraft," 2019.
[8] Airbus, "Airbus electric flight - e-fan x," 2020.
[9] Easyjet, "Leading the industry on sustainable travel," 2020.
[10] O. Bar-Yohay, "Eviation alice," 2019.
[11] LVNL, "Schiphol tower en approach," 2019.
[12] LVNL, "feiten," 2018.
[13] F. Anton, O. Olaf, J. Hetz, and T. Olbrechts, "Siemens eaircraft - disrupting the way you will fly!," 2018.
[14] B. M. Thompson R., Sachdeva N., "Aircraft electrical propulsion – onwards and upwards," 2018.
[15] A. Stoll and G. Mikic, "The analysis of "more electric engine" technology to improve the environmental performance of aircraft jet engine," *16th AIAA Aviation Technology Integration and Operations Conference*, 2016.
[16] B. Schiltgen, J. Freeman, and D. Hall, "Aeropropulsive interaction and thermal system integration within the eco-150: A turboelectric distributed propulsion airliner with conventional electric machines," *16th AIAA Aviation Technology Integration and Operations Conference*, 2016.
[17] J. Hermetz, M. Ridel, and C. Döll, "Distributed electric propulsion for small business aircraft: A concept-plane for key-technologies investigations," *30th ICAS Congress, Daejeon, SouthKorea,*, 2016.

[18] G. Cinar, D. Mavris, M. Emeneth, A. Schneegans, C. Riediger, Y. Fefermann, and A. Isikveren, “Sizing, integration and performance evaluation of hybrid electric propulsion subsystem architectures,” *55th AIAA Aerospace Sciences Meeting, Grapevine, TX, USA*, 2017.

[19] C. Pornet and A. Isikveren, “Conceptual design of hybrid-electric transport aircraft,” *Progress in Aerospace Sciences*, vol. 79, pp. 114–135, 2015.

[20] M. Hoogreef, R. Vos, R. de Vries, and L. Veldhuis, “Conceptual assessment of hybrid electric aircraft with distributed propulsion and boosted turbofans,” *AIAA Scitech 2019 Forum*, 2019.

[21] R. de Vries, M. Brown, and R. Vos, “A preliminary sizing method for hybrid-electric aircraft including aero-propulsive interaction effects,” *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[22] D. Benegas Jayme, “Evaluation of the hybrid-electric aircraft project airbus e-fan x,” 2019.

[23] L. A. Costello, “State of the art of piloted electric airplanes, nasa’s centennial challenge data and fundamental design implications,” 2011.

[24] G. Sachs, “Flight performance issues of electric aircraft,” *AIAA Atmospheric Flight Mechanics Conference*, 2012.

[25] J. Stuhlberger, “Interview boeing regarding hea in the atm-system,” 2020.

[26] M. Bradley, “Interview boeing regarding hea in the atm-system,” 2020.

[27] N. Zart, “New electric aircraft motor lab aims for 1mw electric airplane motor,” 2019.

[28] KLM, “Air france-klm takes care : Sustainability report 2018,” 2019.

[29] EASA, “Aircraft engine emissions databank,” 2017.

[30] S. Min, D. Mavris, and D. Lim, “Aircraft noise reduction technology and airport noise analysis for general aviation revitalization,” 2016.

[31] K. Plötner, M. Schmidt, M. Baranowski, I. Askin, and M. Hornung, “Operating cost estimation for electric-powered transport aircraft,” *Aviation Technology, Integration, and Operations Conference*, 2013.

[32] D. Schaar and L. Sherry, “Analysis of airport stakeholders.,” *Integrated Communications Navigation and Surveillance Conference (ICNS)*, pp. J4–1, 2010.

[33] MinisterieIenW, “Luchtruimvisie bijlagerapport 3: Opgaven en knelpunten nederlands luchtruim,” 2012.

[34] B. Enserink, J. Kwakkel, P. Bots, L. Hermans, W. Thissen, and J. Koppenjan, *Policy analysis of multi-actor systems*. LEMMA, 2010.

[35] B. Donners and M. Heufke Kantelaar, “Emissies van korte afstandsvluchten op nederlandse luchthavens,” 2019.

[36] J. Zuidberg and K. Vinkx, “Capacity demand at schiphol airport in 2023,” 2018.

[37] MinisterieIenW, “Samen werken aan het luchtruim - startbeslissing programma luchtruimherziening,” 2019.

[38] S. van der Kleij, “Ambitie rotterdam the hague airport,” 2017.

[39] J. Bekkers, “Interview atco regarding hea in the atm-system,” 2020.