Schiphol Group

The Design of a 'Water Droplet'- Based UFP Mitigation System at airports

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The Design of a 'Water Droplet'-Based UFP Mitigation System at Airports

A Case Study at Amsterdam Airport Schiphol

By

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Preface

Over the last 25 years, I have been able to travel the world and visit many different countries with family and friends. My parents partly made this possible, but without air travel it would have been very difficult to visit places outside this continent. The fact that aviation has made intercontinental travel this easy has always inspired me, but the negative impact of flying began to interest me more and more when I started my bachelor 'Technische Bestuurskunde' at the TU Delft. The domain 'Transport and Logistics' offered me the possibility to take courses in aviation, which also led to my decision to choose the master 'Transport, Infrastructure and Logistics', as I wanted to take as many Aerospace Engineering courses as possible to expand my knowledge about aviation. I am very grateful that I got the opportunity to write my thesis and graduate at the Innovation Hub of Royal Schiphol Group. Thank you Carolijn Schoofs and Jan Zekveld for making this possible.

I would also like to thank my TU Delft supervisors Jaap Vleugel and Jan Anne Annema. Thank you for your flexibility and quick responses throughout my research. My meeting scheduling was often last minute, but you were always prepared and able to give me the feedback I needed. The regular meetings in the final stages of my research kept me sharp and provided the necessary motivation at the end. I would also like to thank Bert van Wee for applying structure to the first meetings and helping me with the formation of my graduation committee.

My year at Royal Schiphol Group has been amazing, mainly due to all the people at the Innovation Hub. Once working at the office became possible again after 2 long years of working at home, they welcomed me with open arms as a working student. These months were very educational and were a great challenge to gain experience in working at a big company in the aviation industry. After this project, my time as a graduating intern started, which was a challenging switch at first. I would like to thank Jan Zekveld and Yannick Enting for all the brainstorm sessions, feedback moments, and the continuous support over the past year. You guys always got me back on track and gave me all the advice I needed at moments when I lost the overview. In addition to the research-related guidance, you were always in for a laugh and provided the desired distractions in between work. Good luck with all the great innovations that you are working on and enjoy your many future trips to the moon and Mars!

Finally, I would like to thank you, the reader, for your interest in this research. We all want to explore the world, and aviation has made it possible to travel to all the destinations we can think of. In order to be able to keep exploring the world, it is essential to keep exploring sustainable innovations in the aviation industry as well.

Rinke Jebbink
December 6, 2022

Executive summary

Introduction

The aviation industry has seen a significant growth over the last decades, with the COVID-19 pandemic as a brief intermezzo. Now that the peak of the pandemic seems to be behind us, the demand for global aviation is advancing again. This is also the case for Amsterdam Airport Schiphol (AMS), which has been the main contributor to the growth of the Dutch aviation industry. The revival of the aviation industry is associated with various advantages, such as a higher accessibility and the creation of many economic opportunities, but the enormous impact that air travel has on the environment has been overshadowing these benefits. Aircraft are known for producing large amounts of harmful emissions, of which particulate matter PM primarily affects the air quality and is one of the most harmful pollutants to human health. Ultrafine particles (UFP) are the smallest form of PM (<100 nm) and research has indicated that these particles are generated in large amounts on airports by the jet engines used in commercial aircraft. At Amsterdam Airport Schiphol (AMS), high UFP concentration were measured close to the terminals around the piers and platforms, as well as in the open field near the runways and taxiways. Several studies on the impact of exposure to (aircraft-produced) UFP on human health have been conducted over the last decade, which have shown some adverse health effects. With these potential risks on the health of the (platform) employees at AMS in mind, Royal Schiphol Group (RSG) initiated a UFP mitigation task force and started various research projects to investigate the potentials of tackling ultrafine particle concentrations at the airport. An innovative technology that is based on the use of a water droplet cloud that interacts with the aircraft-produced ultrafine particles, is deemed to be a very interesting solution direction by RSG. The UFP is encapsulated and coagulates within these water droplets, which means that they clump together and are captured by the droplets. The water droplets with the clumps of UFP will eventually descent to the ground rather than disperse across the airport grounds. This could be an interesting strategy for airports to mitigate the impact of the aircraft operation on the health of employees and neighboring residents, as well as the air quality of the environment.

Research scope and methodology

Previously conducted research regarding aircraft-produced UFP mostly discusses the performed measurements at airports to analyze the concentration distribution, as well as the adverse health effects that are associated with exposure to ultrafine particles. There is currently little to no academic knowledge on potential mitigation strategies to tackle the concentrations, including the potential of deploying water droplets to prevent airborne distribution of these particles. This research aims to fill this knowledge gap, by exploring the relevant (conceptual) design components and requirements of a potential 'water droplet'-based UFP mitigation system at the airport. The objective of this research is to propose a conceptual system design, including the discussed components and requirements, which will be analyzed on its feasibility, viability and desirability. A qualitative, exploratory research methodology is used to answer the main research question, which is stated as follows:

'*What is the most suitable conceptual system design of a 'water droplet'-based mitigation strategy to combat aircraft-produced ultrafine particles at the airport?*'

This research is carried out within Royal Schiphol Group, which is why the provided insights and the proposed conceptual system design are mainly dedicated for Amsterdam Airport Schiphol. First, a literature review was conducted to gather relevant literature and studies to analyze the current state-of-the-art on UFP mitigation within the aviation sector and all airports in general. A case study was conducted as well for AMS specifically, in which the current UFP problem at Schiphol was discussed and an extensive stakeholder analysis was executed. This stakeholder analysis provided an overview of all involved internal and external organisations/companies, of which representatives could be recruited for potentially contributing to the theoretical and organizational framework of this research. A wide range of stakeholders within the aviation industry and stakeholders from the academic community with expertise in this field, were recruited to contribute to this research. Semi-structured interviews were held with these stakeholders about he aircraft operation in general, engine performance and propulsion, aircraft emissions, the theory and science behind UFP-water droplet interaction, and the potential implementation of a 'water droplet'-based UFP mitigation system at the airport.

System design components and requirements

The conceptual system design could be roughly divided into three components: the moment ('When?'), the location ('Where?'), and the way ('How?') of implementing UFP mitigation strategies at the airport grounds. First, there was determined during which process(es) of the aircraft operation the system should be deployed, as well as during which periods of the day. The cold start of the aircraft seems like the most optimal and best fitting aircraft operation process during which a potential UFP mitigation system could be deployed. Several interviewed stakeholders mentioned the production of large quantities of UFP during this process, as well as the fact that the cold start currently takes place at the aircraft stand where (platform) employees are walking around. These aspects show that tackling the production and dispersion of UFP during this part of the aircraft operation is currently the top priority. Besides the beneficial impact on health, the logistical challenges related to implementing a mitigation strategy during the cold start are limited as well, since the aircraft stays positioned at a dedicated location during the stabilization of the aircraft engines.

The location of the system implementation was subsequently determined, since it could be associated with the aircraft operation processes as the aircraft visits a select number of locations at the airport. As the cold start of the aircraft engines currently takes place at the aircraft stand at the pier, it is fairly obvious that the potential UFP mitigation system should be implemented there. However, several stakeholders from RSG addressed that AMS is looking into starting locations moved further away from the piers in order to better protect the health and safety of the employees that are working there. These potential remote starting positions are probably a better fitting location for the 'water droplet'-based UFP mitigation system as well, since the system will use large quantities of water and will require a significant amount of space. Local mitigation, such as at a few central remote starting locations, will most likely contribute to achieving the most optimal system at Schiphol. Figure 1 shows a few interesting remote starting locations at the airport grounds, which are the P-platform (northeast of airport building) and the remote deicing platform, which includes the J-platform (northwest of the airport building), as they show potential in terms of capacity, space and already available facilities.

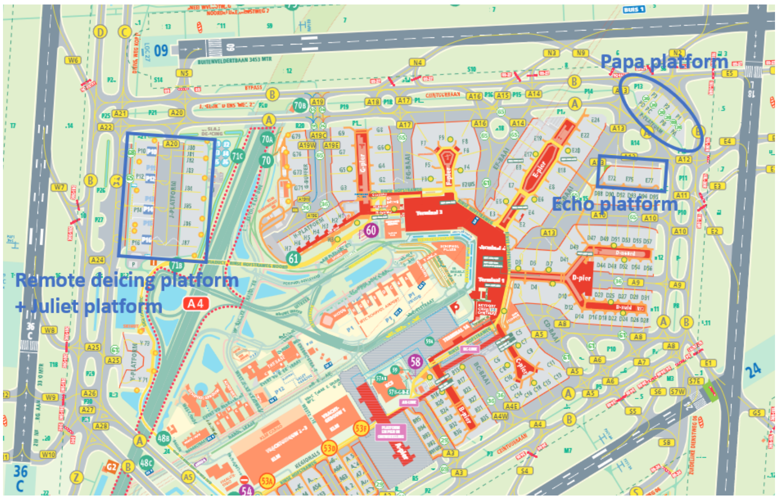

Figure 1: Potential remote starting locations at Amsterdam Airport Schiphol

The final component of the system design integrates potential mitigation strategies to combat the ultrafine particle concentrations at the airport, which currently consists of water spraying equipment from the dust control sector. Most providers in this sector offer several alternatives within two main equipment categories: water spraying cannons and water pipes with spraying nozzles mounted onto them. Spraying cannons can be easily adjusted in spraying the water droplet in a certain direction and angle, while the water pipes with nozzles offer less flexibility and usually produce a water droplet screen. A few stakeholders stated that the water spraying devices should be connected properly to the cores of the aircraft engines in order to spray the water droplets into the area of the engine where the largest amounts of UFP are produced. Water spraying cannons are probably the best alternative when the water droplets need to be sprayed into (the core of) the aircraft engines, as these devices offer more versatility. However, the dissension regarding this issue was clearly evident, as multiple stakeholders indicated that it is probably impractical to spray the water droplets into the core of the engine, as the high temperatures and wind velocities of the thrust negatively impact the effectiveness of the system. The alternative of water pipes with spraying nozzles mounted onto them seem like a good fit for a system that should be placed further away from the aircraft, as it is not able to spray the water droplets into the jet engines. Besides this, the necessary cloud dimensions that cover at least the cross-section of the aircraft vortex are generated more easily and straightforward by these water pipes with spraying nozzles mounted onto them, which results in a more efficient mitigation strategy. A system alternative in which the water droplets are directed into the jet engine outlets by spraying cannons was therefore discussed for a close-up mitigation strategy, while an alternative in which a screen of water droplets is created to absorb the jet blast with emissions was established for the mitigation strategy at a further distance.

Prior to the determination of the discussed system design components, a list of design requirements was established to which the 'water droplet'-based UFP mitigation system at the airport must comply with. The interviews with stakeholders of Royal Schiphol Group, of other parties in the aviation industry, and of research/knowledge institutions consisted largely of discussions regarding the operational and safety aspects of aircraft-produced UFP mitigation strategies at the airport. Operational requirements related to the creation of water droplet-UFP interaction opportunities, the water supply source of the system, the relevant meteorology and weather conditions, and the impact of the system implementation on the aircraft operation. Safety requirements incorporated the use of water on and around the aircraft, the health risks and safety hazards for (platform) employees, and the construction of the mitigation system at the airport grounds. A limited selection of additional requirements, related to investments, logistical challenges and transition into the new system, could be established as well. The economic requirements are taken into account while assessing the viability of the potential conceptual system design, while the logistical challenges and the transition requirements are incorporated into the feasibility assessment. The collection of constraints under which all the requirements are subdivided is presented in table 1.

Table 1: System design constraints

Category	**1**	**Operational Requirements**
Constraint	**1**	The system must create as many opportunities for the UFP to interact with the water droplets as possible.
Constraint	**2**	The water supply source must result in the most optimal system, in terms of filtering, health and investments.
Constraint	**3**	The system must take meteorology and weather conditions into account for the operation.
Constraint	**4**	The system must not negatively affect the aircraft operation.
Category	**2**	**Safety Requirements**
Constraint	**1**	The use of water must not cause damage to the airport, aircraft and environment in any form.
Constraint	**2**	The use of water must not cause health risks and safety hazards for the (platform) employees.
Constraint	**3**	The system implementation must not cause safety risks during the aircraft operation.
Category	**3**	**Economic Requirements**
Constraint	**1**	The system must be as cost efficient as possible.
Category	**4**	**Logistic Requirements**
Constraint	**1**	The logistical challenges associated with the system must be as limited as possible.
Category	**5**	**Transition Requirements**
Constraint	**1**	The impact of the transition from the old situation into the new system must be limited as much as possible.

Conceptual system design assessment

All discussed components were incorporated into a conceptual system design, which should comply with the drawn up list of system requirements. The most suitable conceptual system design is schematically visualized in figure 2, and was assessed on its feasibility, viability and desirability. Overall, the conceptual system design assessment provided promising results, but certain aspects and components of the system need to be analysed more thoroughly before the system could be implemented at Amsterdam Airport Schiphol. The most socio-economically and sustainable water supply source for the mitigation strategy is most likely rainwater, but it is not yet clear whether rainwater as the only water source results in a viable mitigation system at the airport. Besides this, insights regarding the feasibility and viability of water collection and filtering before reuse need to be determined as well. The potential impact of introducing remote starting positions during the aircraft operation on the turnaround time and the starting capacity of AMS also significantly affects the system's feasibility, viability and desirability, and thus requires impact analyses to validate the proposed conceptual system design. The implementation of a 'water droplet'-based ultrafine particle mitigation system at the airport could result in short-term benefits regarding the health of (platform) employees and the air quality of the airport environment, which makes it a desirable solution. However, the financial impact and the impact on the airport processes and infrastructure need to be analyzed further in order to increase the system's viability. Besides this, the use of large amounts of water significantly impacts the feasibility of this mitigation strategy, and thus requires more research prior to implementation.

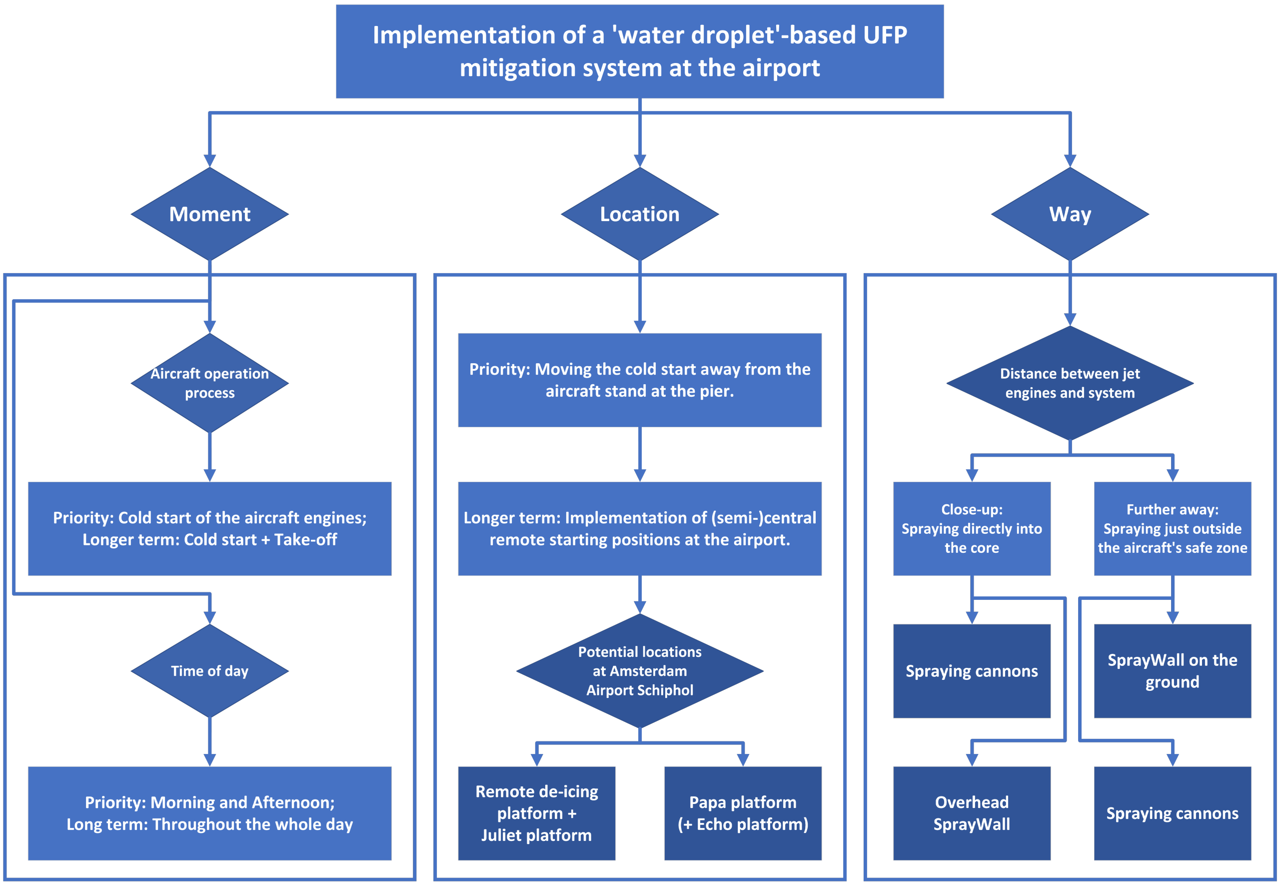

Figure 2: Conceptual system design of a potential UFP mitigation strategy at the airport

Future recommendations

The main recommendations for future research can be divided into two categories: further investigation in the potential of 'water droplet'-based UFP mitigation and exploring other potential UFP mitigation solution directions. A limitation of this research is that there is only focused on the UFP mitigation strategy that is based on the use of water droplets. Other strategies to mitigate the dispersion of aircraft-produced ultrafine particles across Amsterdam Airport Schiphol were briefly mentioned, but were not considered as alternatives in the composition of the conceptual system design. For future research, it is interesting to also investigate potential solutions such as the introduction of sustainable aviation fuels, sustainable taxiing, the realization of a more complete combustion in the jet engines, etc. For follow-up research regarding the potential of water droplets to combat UFP concentrations at the airport grounds, the discussed aspects in the previous section need to be studied more extensively. Finally, as this research was focused on Amsterdam Airport Schiphol, it might be of added value to involve other airports in future research to achieve a more universal overview of the system.

Contents

Acronyms

AMS Amsterdam Airport Schiphol. ii–iv, vi, vii, x, xi, 1–3, 15, 16, 18–33, 35, 37, 39–44, 48, 49, 52, 53, 57, 58, 60–64, 66, 68–74, 95–100, 103–105

APU Auxiliary Power Unit. 103

ASM Asset Management. 23, 96, 99, 100

CIA Ciampino-G. B. Pastine International Airport. 15, 16

CPH Copenhagen Airport. vii, x, 41, 43, 49, 53, 103–105

DG Directorate-General. 96, 99

EASA European Union Aviation Safety Agency. 20, 31, 32, 45, 46, 49, 100

FRA Frankfurt Airport. 15

HSE Health, Safety & Environment. 20, 23, 46, 52, 96, 99, 100

LAX Los Angeles International Airport. 15–17

LHR Heathrow Airport. 15, 16

LTO Landing and Take-Off. vi, 15, 25, 32, 48, 52, 53, 96

LVNL Luchtverkeersleiding Nederland. 21, 24, 58, 63, 97, 99

NLR Netherlands Aerospace Centre. 1, 19, 21, 23, 97–100

OPS Airport Operations. 20, 23, 29–31, 42, 54, 62, 96, 99, 100

PC Procurement and Contracting. 20, 39, 62

PM Particulate Matter. ii, 1, 13, 15

RIVM Rijksinstituut voor Volksgezondheid en Milieu. 14, 16, 21, 23, 97, 99, 100

RSG Royal Schiphol Group. ii, iii, 1–3, 20, 23, 24, 28, 32, 35, 39, 42, 46, 52, 54, 55, 58, 60–62, 64, 71–74, 96–100

RTHA Rotterdam The Hague Airport. 15, 96

S&AP Strategy & Airport Planning. 20, 23, 32, 39, 52, 63, 96, 99, 100

SAF Sustainable Aviation Fuels. 64, 74

SSE Safety, Security & Environment. 20, 31, 32, 35, 96

TUD Delft University of Technology. 35, 36

UFP Ultrafine Particles. ii–vii, x, xi, 1–3, 6, 7, 9, 10, 12–21, 24–33, 35–49, 52–66, 68–74, 94–101, 104, 105

VDGS Visual Docking Guidance System. 58

WUR Wageningen University & Research. 1, 19, 21, 23, 24, 54, 59, 61, 97, 99, 100

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1 Introduction

1.1 Research context

The Dutch aviation industry
The Dutch aviation industry has experienced a substantial growth over the last decades, with Amsterdam Airport Schiphol (AMS) as the main contributor to the increasing number of flight movements. The number of aircraft movements at AMS increased with 40 percent between 1997 and 2019 to a total of 516 thousand movements (CBS, 2022). However, in 2020 the COVID-19 pandemic had an immense impact on the aviation industry, which resulted in plummeting numbers of aircraft movements around the world. Royal Schiphol Group (RSG) documented a decrease of more than 50 percent to a total of 241 thousand flight movements in 2020 (Royal Schiphol Group, 2021). In 2021 the number of aircraft movements experienced a small growth to 286 thousand (Royal Schiphol Group, 2022b) and, now that it seems that the peak of the pandemic is behind us, the airport companies and airlines are preparing to offer their services to returning and new customers at Amsterdam Airport Schiphol.

The impact of air travel
The revival of the aviation industry is accompanied by various advantages, as airports are proven to be a catalyst of regional and national economic growth (ACI Europe, 2015). Not only do airports and air travel function as a way to connect all parts of the world and increase a country's accessibility, they also generate employment and create new economic hubs (Aguirre, Mateu, & Pantoja, 2019). In the last decade, the advantages of the aviation industry have been overshadowed by the negative effects that are caused by traveling by aircraft. This mode of transport is a global contributor to climate change with a current share of 3.5 percent. Besides this, aviation produces 2.5 percent of all CO_2-emissions worldwide (Peeters & Melkert, 2021). In addition to this, arriving and departing aircraft at the airport produce harmful emissions and noise pollution, which have an impact on the health and safety of people working on the airport, but also on people living in neighboring areas. The emissions that are produced while operating aircraft, such as CO_2, NO_x, SO_2 and particulate matter (PM), also have negative effects on the environment and the quality of life (Marcias et al., 2019). The air quality is especially affected by the large quantities of PM that are emitted by airplanes, which is also one of the most harmful pollutants to human health (Lopes, Russo, Monjardino, Gouveia, & Ferreira, 2019).

The rise of ultrafine particles awareness
Within the last couple of years the smallest form of particulate matter, called ultrafine particles (UFP), has received increasing interest from the academic community. UFPs are generally defined as smaller than 100 nm and research has indicated that UFPs are generated in large amounts on airports by the jet engines used in commercial aircraft (Ungeheuer, van Pinxteren, & Vogel, 2021). At AMS, very high UFP concentrations have been measured close to aircraft emissions and were also observable for some distance at airside locations downwind of the aircraft activities (Stacey, 2019). A research conducted recently by TNO (Tromp et al., 2021) performed mobile measurements at the airport side to provide an overview of the UFP concentration accumulations. High UFP concentrations were observed close to the terminals around the piers and platforms, but also close to the open field on runways and taxi infrastructure.

The state-of-the-art regarding UFP research
The number of studies with regard to the contribution of aircraft to UFP concentrations has significantly increased over the last decade, as adverse health effects are associated with both short- and long-term exposure to ultrafine particles (Lammers et al., 2020). Findings showed that short-term exposure to high UFP levels near AMS were associated with prolonged re-polarization of the heart and decreased long function. Prolonged exposure could result in adverse birth outcomes and can induce cell damage and release of pro-inflammatory markers (He et al., 2020). Although there is still relatively limited research conducted about these adverse health effects, the discussed findings were enough reason for RSG to introduce a UFP Taskforce and start various research programs concerning UFP mitigation.

The exploration of potential UFP mitigation strategies at the airport
Amsterdam Airport Schiphol is (one of) the first airport(s) in the world to explore strategies to mitigate the amount of air pollution, in the form of ultrafine particles, to improve the quality of life of the airport communities. A research with regard to an innovative technology to reduce the amount of UFP in the air by using water droplets was recently initiated by RSG, in cooperation with Wageningen University & Research (WUR) and the Netherlands Aerospace Centre (NLR) (Schiphol, 2021). A water droplet screen/cloud is created with which the ultrafine particles can interact. The UFPs coagulate within the water droplets, which means that they clump

together and are captured by the droplet. The water droplets with the clumps of UFP will eventually fall to the ground rather than disperse across the airport grounds, as some sort of "washing" effect. Implementing a UFP mitigation system with water droplet production equipment at AMS is an interesting potential solution for the airport to help improve the safety and health of (platform) workers and neighboring residents and the air quality of the environment.

1.2 Research problem

Prior to this research, a literature review was conducted to assess the state-of-the-art of research regarding ultrafine particle concentrations at airports and the potential mitigation of UFP, for instance by implementing a water droplet screen production system to prevent airborne distribution. The review indicated that there is little to no academic research available about the mitigation of aircraft-produced UFP concentrations at airports. The current knowledge that is available mostly discusses the mobile measurements that were performed at airports to analyze the distribution of UFP, as well as the adverse health effects that are associated with short- and long-term exposure to ultrafine particles. No papers were found that analyze the feasibility, viability and desirability of designing and implementing a UFP mitigation system at the airport, in terms of stakeholder, (non-)functional and transition requirements. This knowledge gap shows that research about the design and implementation of a UFP mitigation system at airports, based on water droplets, can thus be of substantial added value for Amsterdam Airport Schiphol, other airports around the world and the academic community as a whole.

1.3 Research objective

This research aims to explore the relevant (conceptual) design components and requirements of a potential 'water droplet'-based UFP mitigation system at the airport. The objective of this research is to propose a conceptual system design, including the discussed components and requirements, which will be assessed on its feasibility, viability and desirability. A system design sets the theoretical, geographical and operational boundaries in order to combine all relevant components into one framework. In addition to taking the questions 'when?', 'where?' and 'how?' to implement a new UFP mitigation system at the airport into account, the requirements and the potential challenges of the implementation and operation of the 'water droplet'-based system are necessary to include in the design. These requirements are based on, for instance, health and safety regulations of the aviation industry, demands from the involved stakeholders, economic objectives from the problem owners, overcoming the logistical challenges, and enabling transition into the new/desired situation.

The conceptual design integrates certain alternatives of all the necessary components for the implementation of a 'water droplet'-based UFP mitigation system into one overarching system. The assessment of the system's feasibility, viability and desirability is conducted in order to determine whether potential ultrafine particle mitigation system is the most optimal to eventually implement at airports, with Amsterdam Airport Schiphol in particular. This research will thus provide an overview of scientific and theoretical findings, as well as aviation industry stakeholder insights regarding the state-of-the-art of aircraft-produced UFP mitigation at airports, and can assist the aviation industry, with particular focus on Royal Schiphol Group, as some sort of manual.

1.4 Research scope

The scope of this research is bounded by several technical and functional aspects. Firstly, ultrafine particles is the only emission that will be investigated thoroughly in this research, where other emissions (e.g., NO_x, CO_2 and PM) will only be brought up every now and then. Secondly, the research specifically focuses on the mitigation of ultrafine particles that are produced by aircraft. There are other emitters of ultrafine particles at and around the airport grounds, but the UFP produced during the combustion process in the jet engines during the aircraft operation is the only source that is focused on. Besides this, the potential mitigation of the aircraft-produced UFP will be limited to the processes of the aircraft operation that take place at the airport grounds. The vicinity of the airport as a potential location to implement mitigation strategies will not be investigated. There might be several mitigation strategies and potential systems to look into, but the strategy that is based on the use of water droplets to combat the ultrafine particles will be the only solution space to be discussed in this research.

This research is carried out within Royal Schiphol Group, which is why the organisational scope is mainly bounded to involving stakeholders within the organisation and organisations/stakeholder with warm ties with RSG. A wide range of stakeholders within the aviation industry, as well as several experts with knowledge within the topic, have been recruited to contribute to this research. These concern stakeholders from different departments within RSG, airlines (KLM), aircraft manufacturers (Airbus), other airports (Copenhagen Airport), research organisations (TNO), and professors/researchers from different universities (Delft University of Technology, Wageningen University and Research, and University of Twente). The discussion topics were limited to the aircraft operation in general, engine performance and propulsion, aircraft emissions, the theory and science behind UFP-water droplet interaction, and the potential implementation of a 'water droplet'-based UFP mitigation system at the airport.

This research will focus on the use of water droplets for the mitigation of ultrafine particles produced by aircraft at airports in general, but Amsterdam Airport Schiphol (AMS) in the Netherlands will be used as a basis in order to make the analysis and eventual results more tangible. Comparing airports is almost impossible, as their size, layout, vicinity and operations will always be different, and the implementation and operation of a UFP mitigation system depends on too many local factors. Where possible, the conceptual and/or final system design(s), as well as the research insights, will be broadened for other airports, but this will not be done at a data level. The research insights and final product(s) are therefore mainly intended for Amsterdam Airport Schiphol.

1.5 Research questions

The research question, which will serve as the common thread of this study, is stated as follows:

'*What is the most suitable conceptual system design of a 'water droplet'-based mitigation strategy to combat aircraft-produced ultrafine particles at the airport?*'

Several sub-questions, related to the above-mentioned research question, are formulated. These sub-questions address the knowledge gap, research objective and the desired outputs. The sub-questions support the various steps of the research methodology, which will be discussed in chapter 2, with the overall objective to determine the various components of the potential system design(s). They are formulated as follows:

Sub-question 1: '*What are the sources, locations and health effects of ultrafine particle concentrations at airports around the world and which potential mitigation strategies are available?*'

Sub-question 2: '*Who are the stakeholders that should be included in the background research into ultrafine particle mitigation at the airport and throughout the execution of this research?*'

Sub-question 3: '*What are the system design components and the requirements that the 'water droplet'-based ultrafine particle mitigation system at the airport must meet?*'

Sub-question 4: '*What is the feasibility, viability and desirability of the 'water droplet'-based ultrafine particle mitigation system design at the airport?*'

1.6 Research structure

The structure of this research is visualized in figure 3 and can be explained as follows. First, the methodology that will be used for this research is discussed in chapter 2. A general review from the conducted literature research is presented in chapter 3, after which the academic state-of-the-art that can be related to Amsterdam Airport Schiphol is provided in the case study chapter of this research (chapter 4). The design components of a future ultrafine particle mitigation system at the airport can be found in chapter 5, in which the system design requirements are also discussed. The findings from the previous chapter are then used as the building blocks for the conceptual system design, which is presented in chapter 6. The feasibility, viability and desirability assessment of this proposed system design is also discussed in this chapter. The answer to the main research question will finally be discussed in chapter 7, as well as an elaboration on the research contributions. This chapter will also illustrate the limitations of this research and the recommendations for future research.

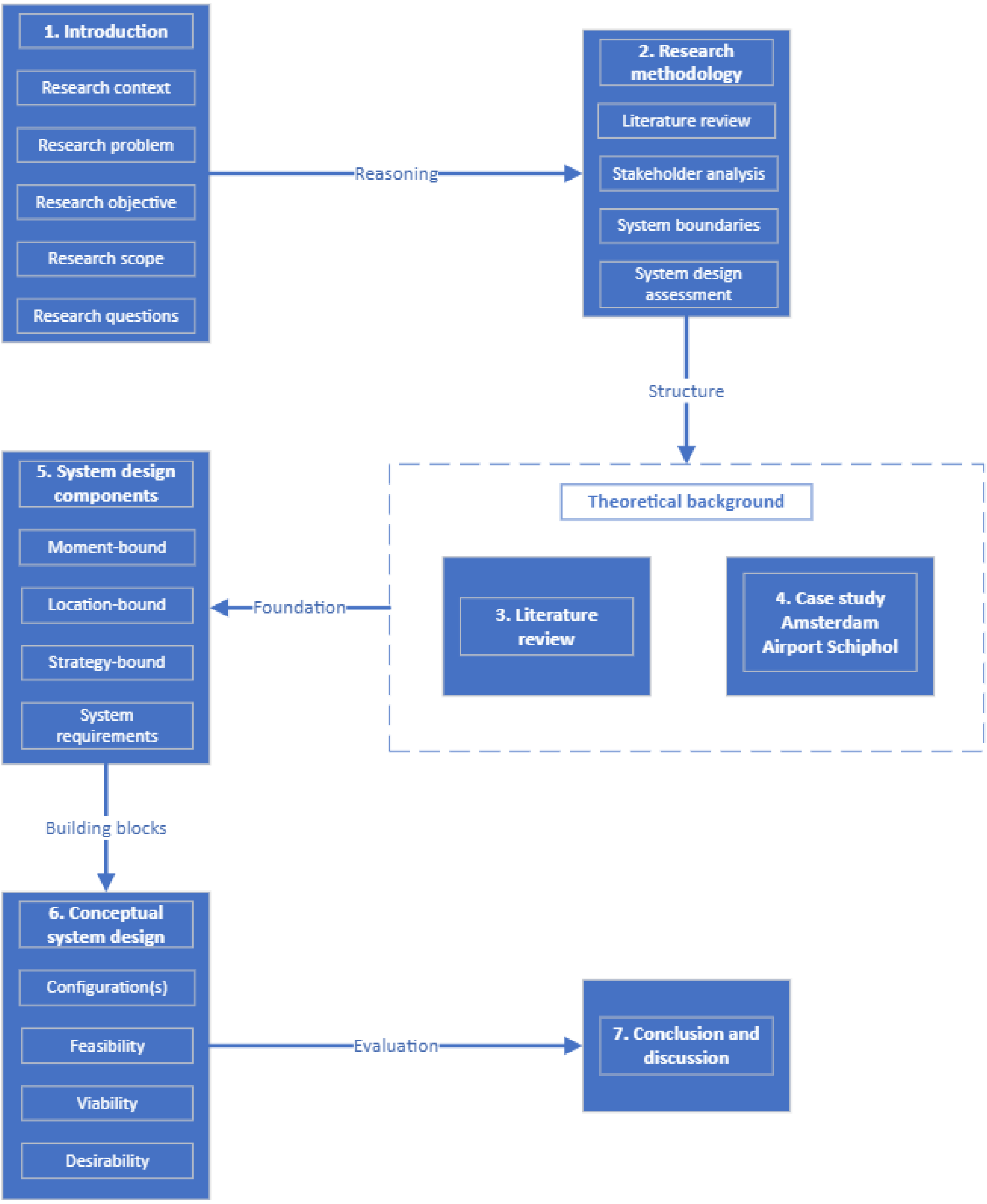

Figure 3: Research structure

2 Research methodology

This chapter provides an overview of the research methodology that is used within this research to gather and analyze data, with which the components for the potential system design can be determined. These components, as well as the system design boundaries integrated within the requirements, are used to compose the potential system design themselves. The methodologies are all deployed to help answer the sub-questions and eventually provide an answer to the main research question. The research methodology structure is visualised in figure 4, in which the relevant research questions for each part of the methodology are indicated in red.

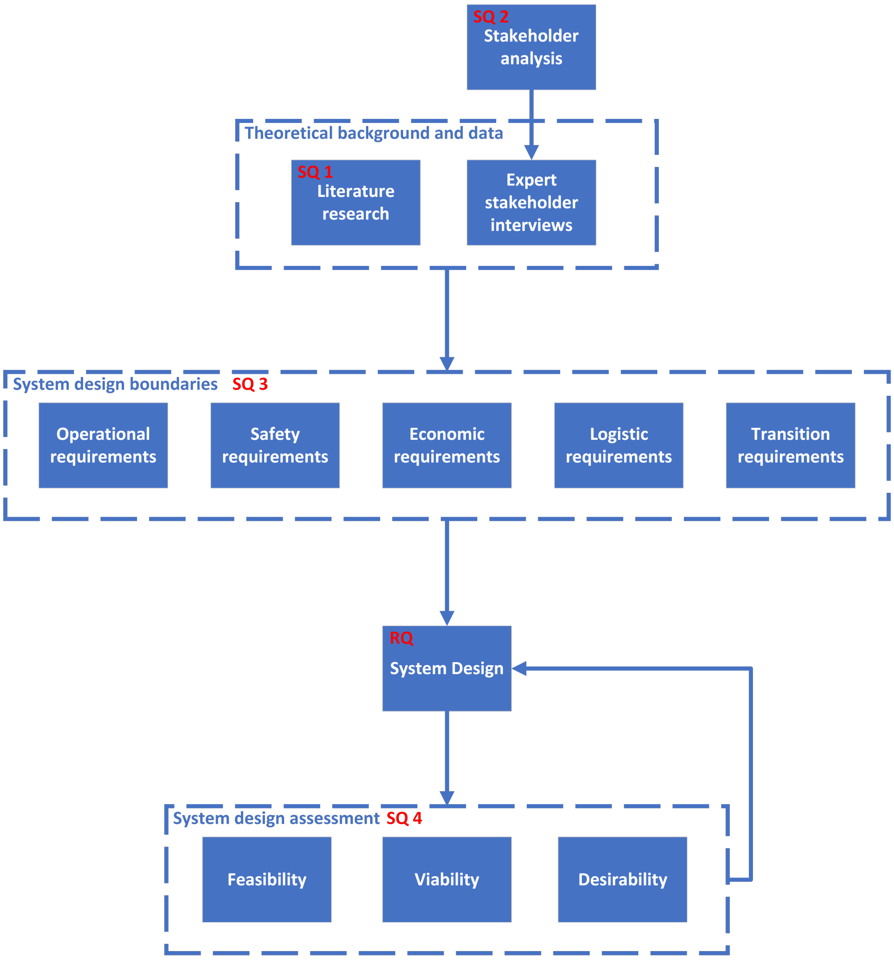

Figure 4: Methodology framework

The used methodology for the literature research is briefly discussed in section 2.1, after which the stakeholder analysis methodology, with which the shortlist of stakeholders for the expert interviews is gathered, is presented in section 2.2. In section 2.3, the methodology to gather the system design boundaries is discussed. The justification for the method with which the conceptual system design is assessed, is provided in section 2.4.

2.1 Literature review

The starting point of gathering the theoretical background for this research is the execution of an extensive literature review in order to retrieve the state-of-the-art of academic research with regard to ultrafine particle production, dispersion and potential mitigation at airports. Conducting a literature review, while considering prior, relevant literature, is essential for all research projects (Snyder, 2019). It plays an important role as the foundation for subsequent research methodologies, since it relates existing knowledge to new research and may generate new ideas and directions. The overview of current academic knowledge is an effective method to substantiate the conclusion that new research is of added value to the academic community: it identifies research questions and justifies future research in said area (Torres-Carrión, González-González, Aciar, & Rodríguez-Morales, 2018). The literature review will cover a variety of academic research on ultrafine particles production by aircraft engines and the formation of UFP accumulations on airport grounds, as well as academic papers dedicated to the potential adverse health effects related to UFP exposure. Furthermore, the review tends to present insights into the state-of-the-art of research regarding UFP mitigation at airport around the world. The articles, papers and studies incorporated in the literature review are retrieved from several online academic databases, e.g. Scopus, Google Scholar, Science Direct (Elsevier) and the research repository of the TU Delft. The key words that were mainly used in these search engines were "UFP production aircraft", "UFP mitigation at airports", "aviation emissions", and "UFP concentrations".

Once the literature review has been completed and an overview of the state-of-the-art of academic research regarding UFP production, dispersion and potential mitigation at airports around the world has been formed, an answer can be provided to the first sub-question of this research:

Sub-question 1: 'What are the sources, locations and health effects of ultrafine particle concentrations at airports around the world and which potential mitigation strategies are available?'

2.2 Stakeholder Analysis

In order to complete the whole theoretical background for this research, an extensive actor analysis needs to be conducted. According to Enserink et al. (2010), an actor is a so-called social entity, a person or an organization, with the ability to react to or influence a certain policy/organizational decision. Stakeholders are actors/beneficiaries that have specific stakes in the preparation and implementation of a project, even though they are often not involved in the execution phase of this project (de Blois & De Coninck, 2008). On the other hand, actors are the ones directly involved during all the phases of the project. The stakes of a stakeholder in the project do not necessarily imply to get a benefice from the project: it indicates that this stakeholder (group) is materially affected by the outcome of the project, which can also be in the form of investments or external costs. The implementation of a project in the airport context takes place in a multi-actor environment, which indicates that policy/organizational problems and processes involve multiple parties. The actors in this environment are interdependent: some form of cooperation between the several involved parties is required in order to reach the desired outcome (Enserink et al., 2010). All involved stakeholders have different interests, objectives and perspectives, which makes it important to map all these goals, as well as the interrelationships between the relevant stakeholders (Bendahan, Camponovo, & Pigneur, 2004). The eventual goal of the actor analysis is to create an overview of all the relevant stakeholders, whose interests and resources need to be considered when designing and implementing a 'water droplet'-based ultrafine particle mitigation system at Amsterdam Airport Schiphol. Besides this, the actor analysis will be an important tool to create a shortlist of stakeholders for expert interviews, with which necessary information for the theoretical background and system design boundaries needs to be gathered. Expert stakeholder involvement is an often used method in the academic world to obtain local knowledge regarding planning policies, technological limitations, environmental impacts, etc. (Berg, Rogers, & Mineau, 2016). It is expected that the complete list of actors is too extensive to arrange interviews with all parties, which, due to time constraints, makes it necessary to make a selection for the expert interviews. By analyzing the dynamics of the stakeholders, as well as their interests and means over time, the involvement of and the communication with the stakeholders throughout the execution of this research can be more valid and meaningful (Elias, Cavana, & Jackson, 2002).

For the stakeholder analysis, the several steps that are usually followed in general actor analyses, as discussed in the book 'Policy Analysis of Multi-Actor Systems' by Enserink et al. (2010), are used as a source of inspiration. These steps are formulated as follows:

1. Formulation of a problem as a point of departure;
2. Inventory of the actors involved;
3. Exhibiting the formal chart: the formal tasks, authorities, and relations of actors and the current legislation;
4. Determining the interests, objectives and problem perceptions of actors;
5. Mapping out the interdependencies between actors by making inventories of resources and the subjective involvement of actors with the problem;
6. Determining the consequences of these findings with regard to the problem formulation.

Step 1 and 2: The problem formulation as stated in the 'research problem' section of chapter 1 is used as a point of departure. By keeping this problem formulation in mind, the actors that are potentially involved with the problem and the design of a 'water droplet'-based UFP mitigation system can be distinguished. There are several methods that help an analyst to make a first selection of possibly involved actors. The most obvious method in this case is the *reputational* approach, where key informants related to the problem/system are asked to identify important actors. As the employees of the Innovation Hub at Royal Schiphol Group are directly involved in these projects, they may provide a nearly comprehensive list of stakeholders and other actors. If necessary, complementary methods can be deployed to make the list of involved actors complete. The *positional* approach for instance reviews existing policy making structures and previously conducted studies to identify actors with a formal position in the project. The *imperative* approach identifies stakeholders who have a strong opinion about a certain problem/project and want to be involved in the decision making process. These are actors who have a certain stake in the project, in terms of interest or feeling the consequences of the issues around which the problem revolves, or the implementation of considered solutions.

Step 3: After the inventory of the actors involved has been completed, the formal relations between these actors can be mapped. The analysis, in order to understand the actors and their environments, should begin by mapping out the formal authorities and formal hierarchical relations. As Enserink et al. (2010) indicate, legislation and formal procedures do shape the interaction and influence the behavior of parties significantly. It is important to know which laws and procedures the involved stakeholders have or will have to deal with, as well as to identify the resource dependencies between actors in a network. The formal positions of actors and their tasks and responsibilities, the formal relations between these actors and the most important laws, legislation, procedures and authorities can all be visualized in a diagram, the so-called formal chart.

Step 4: After the stakeholders and their interdependencies have been identified, the problem formulation as perceived by these different actors can be systematically drafted by looking at their interests, objectives and their causal beliefs. The interests of a stakeholder are the issues that matter the most for them and are not directly linked to the concerning problem situation, which is the case for the objectives of these stakeholders. Identifying the interests of an actor will help to estimate to what extent the proposed solution will be accepted by the actor. The objectives are what an actor wishes to achieve in the problem situation and are used as a measure to judge the existing situation, as they can translate an actor's interests into specific, measurable terms. For the perceptions of the stakeholders on the problem situation, it is of importance to map out the similarities and differences in the actor analysis. The end result of this step will be an overview table of the stakeholders with their interests, objectives and problem perceptions, of which an example template is provided in table 2. Such a summary table is a convenient tool to compare the problem formulations of the several stakeholders and helps to identify the similarities and differences, as well as shared interests and common objectives, or potential conflicts.

Table 2: Overview table of actors' problem formulations

Actor	**Interests**	**Desired situation/ objectives**	**Existing or expected situation and gap**	**Causes**	**Possible solutions**
Problem owner					
Actor 1					
Actor 2					
....					
Actor N					

Step 5 and 6: In step 5, the resources, power and influence of stakeholders will be addressed, especially from the point of view of (in)formal power relations. This will eventually result in an overview of the dependency relations between the stakeholders and the networks of power. The resources of a stakeholder are the means that are available for them to realize their objectives, i.e. knowledge and skills, money, authority/formal power, manpower, etc. (Enserink et al., 2010). An overview of the different types of stakeholders and the interdependencies between the problem owner and these actors can be realized by completing the cells of the template provided in table 3.

Table 3: Overview table for classification of interdependencies

	Dedicated actors		**Non-dedicated actors**	
	Critical actors	*Non-critical actors*	*Critical actors*	*Non-critical actors*
Similar/supportive interests and objectives	Actors that will probably participate and are potentially strong allies	Actors that will probably participate and are potentially weak allies	Indispensable potential allies that are hard to activate	Actors that do not have to be involved initially
Conflicting interests and objectives	Potential blockers of certain changes (biting dogs)	Potential critics of certain changes (barking dogs)	Potential blockers that will not act immediately (biting dogs)	Actors that need little attention initially (stray dogs)

Besides the overview table for interdependencies (table 3), the provided information can also be visualized in a so-called 'power-interest grid'. In this matrix, the critical actors are those with a high level of power, while the dedicated stakeholders are those with a high level of interest in the problem. A possible template for such a power-interest grid is provided in figure 5.

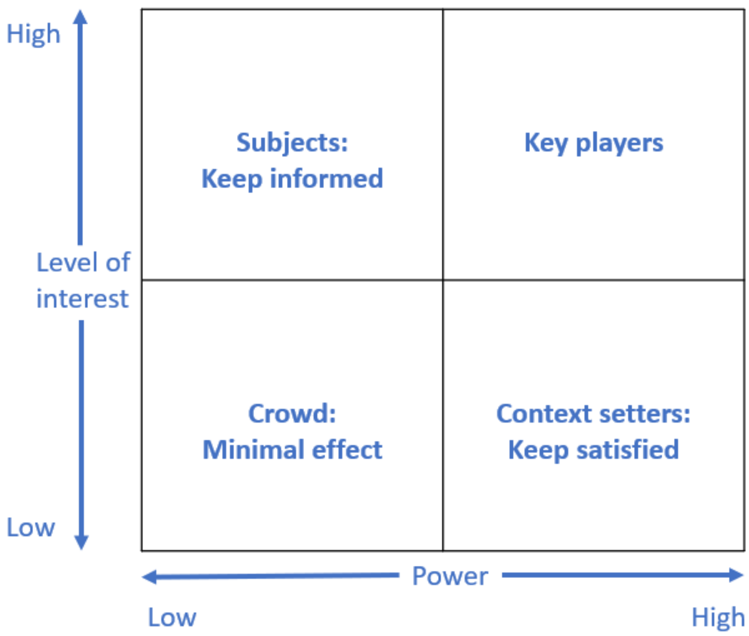

Figure 5: Power-Interest Grid Template

In the final step of the stakeholder analysis, the findings from the previous steps can be put together in order to analyze potential interesting new insights. After listing the conclusions and insights from the different analysis steps, it is possible to turn them into a list of potential threats and opportunities based on the characteristics of stakeholders and networks (Enserink et al., 2010). New insights can be gathered that relate to dealing with other stakeholders in the system: which actors are potential allies in a fruitful cooperation and from which actors can resistance be expected when implementing a certain solution? It provides us with a list of stakeholders that can, or even need to, be involved in the remainder of the research. Another important result from the stakeholder analysis may be additional ingredients for the research approach, such as stakeholder involvement and the necessity to plan expert interviews. These research activities will eventually result in a complete overview of the system and the problem situation.

After concluding the actor analysis and drafting the shortlist of stakeholders for the expert interviews, an answer can be provided for the second sub-question of this research:

Sub-question 2: 'Who are the stakeholders that should be included in the background research into ultrafine particle mitigation at the airport and throughout the execution of this research?'

2.3 System boundaries

An integral part of designing a system is to understand the user requirements, which is critical to the success of interactive systems (Maguire & Bevan, 2002). A thorough understanding of the users requirements and needs should be at the beginning of user-centred design, as several particular problems could be faced by the analyst during the system design process. A few of these problems are: organizational complexity in systems with many stakeholders; traditional thinking by users and designers, reflecting the current system and processes, rather than being innovative; and ignorance with regard to the system's potential. By using clear process steps, these problems can be addressed while executing the (user) requirements analysis. En example of such a user requirements analysis process is visualized in figure 6.

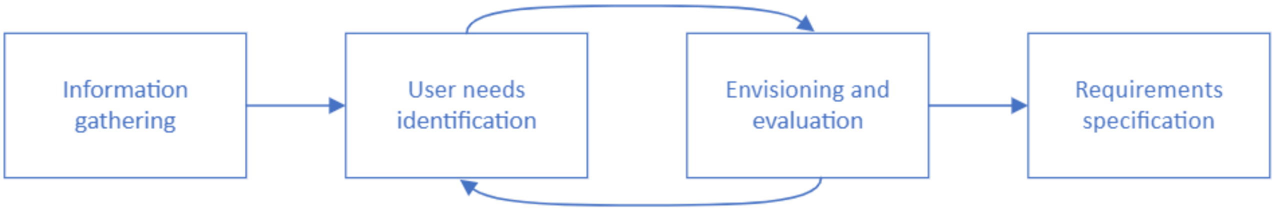

Figure 6: User requirements analysis process

The 'information gathering' phase involves the gathering of the theoretical background, which will be done to a large extent by the literature research in the next chapter (chapter 3) and will be supplemented with insights and information from chapter 4. Once the background information is gathered, the user needs for a potential 'water droplet'-based UFP mitigation system design need to be identified. For this research, most of the involved stakeholders will not be the potential users of this system, but they all have their interests in safe, sustainable and future-proof airports and they have a lot of knowledge about several aspects of the design and implementation of such projects. These stakeholders become the knowledge partners for this research by stepping into the role of the users and identifying the user needs for a UFP mitigation system. The implementation of this research methodology will be further discussed in section 2.3.1 of this chapter, whereas the processing of the results of this research phase will be explained in section 2.3.2.

2.3.1 Stakeholder interviews methodology

Besides the literature review, stakeholder interviews are also used as a qualitative method for the data compilation. Stakeholder interviews are commonly used as an information gathering technique to retrieve more insights and know-how regarding a certain topic or industry. Usually, the academic body of work can already offer a substantial amount of knowledge with regard to more general aspects of subjects, where interviews are mainly used to discuss less straightforward topics and insider knowledge. The impact of aircraft-produced ultrafine particles on the health of (platform) employees and the airport environment, as well as combating UFP by deploying water droplet production equipment, has mainly received increasing attention over the last decade. As the topic is related to a whole new field of research, it is of importance to gather insights and knowledge regarding the state-of-the-art of aircraft-produced UFP mitigation from different academic and aeronautical points of view.

The final product of the stakeholder analysis, as described in the previous section (2.2), is a shortlist with research institutes, organizations and companies from which potential stakeholders will be selectively sampled. First, an extensive search was carried out for suitable representatives of these stakeholder groups for potential interviews. Information for the identification of these representatives was retrieved from the professional network of Royal Schiphol Group, from the academic community of Delft University of Technology, and from several search platforms, such as LinkedIn. All selected representatives were approached by email or telephone with the invitation to contribute to this research by participating in an interview/discussion about the topic. For the emails a standardized template was used, which was supplemented with personalized information of the organization and the addressed contact person. The initially addressed people were also informed that, in case they were not convinced that the research's topic was a match with their expertise, it was very much appreciated if they could share the invitation with colleagues who could potentially contribute instead. This contributed to an increase in the validity of the stakeholder views as well (Makady et al., 2017).

Some alternative methods for the identification of stakeholder needs are focus groups, scenarios, use cases and workshops (Maguire & Bevan, 2002). With these techniques, users, stakeholders and domain experts are questioned about the new system with regard to their needs or requirements. This can be done individually, but also via a cross-section of stakeholders in a discussion group format. For this research, the decision was made to conduct individual interviews instead of group discussions or workshops. This interpretation was chosen to efficiently gather the stakeholders' knowledge and insights within their field of expertise and give them the opportunity to express their sincere opinions, expectations and concerns regarding the topic. In a group setting, stakeholders might not have enough opportunities to join the discussion and might be more retained to express their opinion. By conducting individual interviews, the one-on-one discussions remained subjective and all stakeholders had sufficient time to share their knowledge.

The conducted stakeholder interviews were semi-structured: a few tailored questions were developed for each stakeholder, but the main focus was to provide sufficient opportunities to create a discussion. Semi-structured interviews usually make better use of the "knowledge-producing potentials of dialogues" by letting the interviewer and interviewee elaborate on the angles that are deemed more important to discuss (Brinkmann, 2014). The handful of questions that were thought out prior to the interviews were a mere guideline to fall back on when necessary, as discussions provide more room for brainstorming and sparring in comparison with "question-answer" interviews. The format of a semi-structured interview also gives the possibility to incorporate the insights, opinions and ideas of stakeholders from previous interviews when this is of added value.

All conducted interviews took place online, which was mainly in order to comply with the social distancing advises and to avoid international travelling due to the COVID-19 pandemic. The audio of the interviews was recorded and additional notes were made, which were subsequently transcribed to further analyze the topics that were discussed. The transcription of the interviews in individual documents was not done in a 'question and answer'-format, but each document is structured by using headings for the several topics that were discussed during the interview. A code is attached to each heading to indicate the topic, after which all individual interviews were processed in one overarching document with all headings to indicate the various discussion topics. Quotes, insights and opinions that were coded with the same subject from all individual stakeholder interviews were subdivided into the several headers of the overarching document. This was done to simplify the data analysis and to make the processing of this data into the content of this research more efficient.

Use of the data collected from the stakeholder interviews:
The collected data from the stakeholder interviews, in the form of knowledge, insights, opinions, advises, quotes, etc., is used throughout multiple chapters of this research. In sections 5.1, 5.2 and 5.3 of chapter 5, the data is mainly used for the theoretical and operational background of the potential UFP mitigation system at the airport. The knowledge and insights of several stakeholders are processed in the content to consolidate the theoretical framework of this research, whereas opinions and advises - sometimes in the form of quotes - are also used to a limited extent to provide a first indication of the potential configuration(s) of the system design. In section 5.4 of that chapter, the data from the stakeholder interviews serve as theoretical background for drawing up the requirements that a 'water droplet'-based UFP mitigation system at the airport must meet according to the interviewees. Chapter 6 incorporates the input from the stakeholders on the system design components, as well as their vision on the configuration and implementation of the system as a whole. In this chapter, the proposed conceptual system design configurations is assessed in terms of its feasibility, viability and desirability, and on the extent to which the design complies with the operational, safety, stakeholder and other requirements.

2.3.2 System design components

Once the initial set of user requirements has been drafted, it is of importance to further validate and refine these user requirements before the eventual list is established. This can be done by discussing the provisional set of user requirements during the subsequent interviews with the other stakeholders, but also in brainstorm sessions with multiple stakeholders once the first round of interviews/discussions has been completed. Maguire and Bevan (2002) also discuss what should be documented within the specification of user and organizational system requirements, namely that the range of relevant users and other stakeholders should be identified; the design goals should be stated clearly; the priority levels of the requirements should be indicated; and measurable benchmarks against which the potential design can be tested should be determined. The user requirements can be divided into different categories to better clarify with which aspect of the system they are associated. First, the operational requirements need to be identified, which integrate how the potential system should perform and which other operational aspects should be taken into account when designing the system. Safety requirements are also very important to incorporate in the system design phase, especially for innovations at the airport that are based on new technologies. The operation of a system should not impose risks on involved people, the environment and on other processes. Economic requirements also need to be taken into account in order to increase the viability of the proposed system. Logistic requirements elaborate on the discussed operational requirements and especially affect the feasibility of the potential system. The final category of requirements are the so-called 'transition requirements' with which the operational changes that are necessary for the implementation of the new system into the current organization and infrastructure are determined. In other words: needed actions to be taken by the airport to transition from the current state to the future state. An overview of the different categories of system requirements is visualized in figure 7.

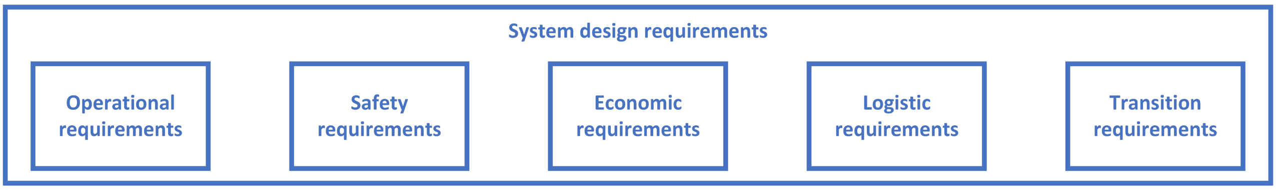

Figure 7: System design requirements

From these requirements, the system design boundaries for the 'water droplet'-based mitigation of ultrafine particles produced by aircraft are determined. The requirements analysis will provide an answer to the following sub-question:

> **Sub-question 3:** 'What are the system design components and the requirements that the 'water droplet'-based ultrafine particle mitigation system at the airport must meet?'

2.4 System design assessment

The system design components will be incorporated into a conceptual system design, while taking all the system requirements into account. The conceptual system design will be assessed in order to determine whether the proposed design might be a well-fitting and promising solution to eventually implement. Bland and Osterwalder (2019) developed a business model testing framework that includes the aspects of feasibility, viability and desirability, which are also commonly used in the sustainable business model process. Sustainable business model innovation is a strategic approach, which integrates environmental and social concerns into the organization's objectives and operations (Baldassarre et al., 2020). A major challenge of this approach is the so-called "design-implementation gap", which addresses that many promising innovative ideas do not reach the market. By exploring potential system designs, for the eventual piloting of a prototype, organizations are forced to simultaneously consider the feasibility, viability and desirability. The trifecta of these three criteria is seen as the ideal innovation process, which is visualized in figure 8. An innovative idea should contain the following essential characteristics (Orton, 2019):

- A feasible solution, which builds on the strengths of the organization's current operational capabilities;
- A viable/profitable solution, which includes a sustainable business model;
- A desirable solution, which is really needed by the organization or system as a whole.

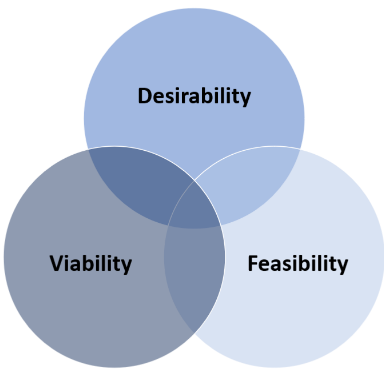

Figure 8: Trifecta for innovation

Feasibility tests whether the innovation is technically achievable, while viability tests the organization's value chain for long-term sustainability (financial possibilities). Desirability tests whether the innovation will be solving the right problem of the organization and/or the customer. One of the aims of conducting the semi-structured interviews, as discussed in section 2.3.1, is to get insights into taking these aspects into account when analyzing the potential of a 'water droplet'-based UFP mitigation system at the airport in order to identify barriers, drivers and success factors (Bocken, Harsch, & Weissbrod, 2022). This assessment method is therefore a logical fit with the previously discussed data collection and analysis methodologies.

The Innovation Hub of Royal Schiphol Group focuses on finding the sweet spot within the intersection of these three main categories, in order to deliver successful innovation projects and strategies. Since this assessment methodology is typically used for the assessment of innovative initiatives within the organization, the decision to incorporate the 'trifecta for innovation' in this research is more substantiated. Usually, when incorporating the feasibility, viability and desirability into an innovation process, making the process iterative is an important learning strategy (Orton, 2019). At each iteration, the innovation will be tested on the three criteria, after which the innovation strategy could be adjusted to keep the process on the right track. However, due to the available time and resources for this research, the number of potential iterations is fairly limited. The feasibility, viability and desirability will therefore only be assessed for the initially proposed conceptual design of the potential mitigation system for combating aircraft-produced ultrafine particles at the airport grounds.

The following sub-question will be answered with the insights and the results from this analysis:

> **Sub-question 4:** 'What is the feasibility, viability and desirability of the 'water droplet'-based ultrafine particle mitigation system design at the airport?'

3 Literature review

This chapter of the research presents the findings of the literature review, carried out according to the method described in chapter 2.1. First, the characteristics, origin and behaviour of ultrafine particles will be described in section 3.1 of this chapter. After this, the state-of-the-art of studies regarding UFP accumulations at and around airports, as well as the measured concentrations, will be discussed in section 3.2. In section 3.3, the current body of academic research on the potential impact of UFP exposure on human health and on the quality of the living environment will be discussed. The final section of this chapter (3.4) will provide a brief overview of the potential mitigation strategies that can be deployed to combat the aircraft-produced ultrafine particles at airports.

3.1 General characteristics of ultrafine particles

As discussed in the introduction of this research (Chapter 1), one of the most harmful forms of air pollution to human health is particulate matter (PM) (Moreno-Ríos, Tejeda-Benítez, & Bustillo-Lecompte, 2022). PM is made up of a complex mixture of several components, both chemical and biological, and, depending on the aerodynamic diameter, can be divided into several categories. The coarse particles ($\leq 10\ \mu m$), such as pollen and dust, can be placed in the category 'PM_{10}', whereas the fine particles ($\leq 2.5\ \mu m$), such as combustion particles (smoke) are categorized as '$PM_{2.5}$'. The smallest form of particles can be defined as ultrafine particles (UFP), which are less than 100 nm (0.1 μm) (Donaldson, Stone, Clouter, Renwick, & MacNee, 2001). In figures 9 and 10, an overview of these PM categories, in comparison with a human hair and with each other, is presented.

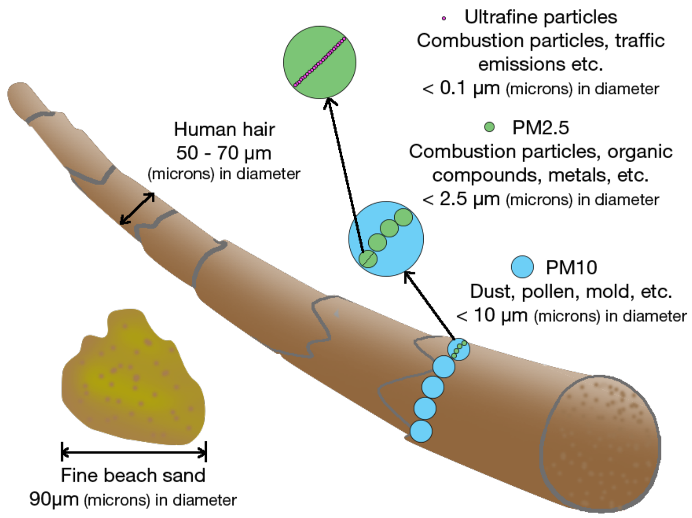

Figure 9: Comparison particle sizes of particulate matter (Source: VFA Solutions (2022))

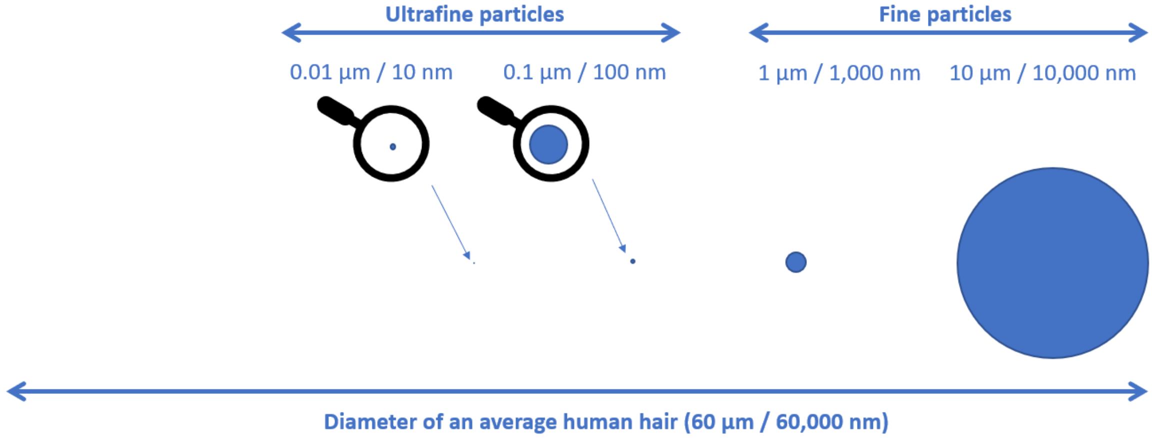

Figure 10: Comparison cross-sections of particle sizes of particulate matter

Ultrafine particles are incidentally produced by different sources and dynamic processes, such as the combustion of fossil fuels, the condensation of volatile compounds, and with industrial emissions (Ramirez, da Boit, Blanco, & Silva, 2020). The first dynamic formation process during which UFPs are generated is also called 'nucleation', which describes the formation of particles from exhaust gases, or from the oxidation of gases in the atmosphere (Moreno-Ríos et al., 2022). The 'condensation' of volatile compounds represents the union between oxidised molecules, which creates more complex ones and augments the sizes of the particles (Andronache, Grönholm, Laakso, Phillips, & Venäläinen, 2006). During 'coagulation', collisions between particles can occur, which results in the formation of conglomerates (one new particle instead of two separate particles). and thus reduces the UFP concentration. The distinction between UFPs and the other pollutants is their dynamic nature: the transformation of their physical and chemical properties is an on-going process (Kumar et al., 2014). This on-going transformation, including number and size distributions, contributes to their greater spatial and temporal variability, which increases with decreasing size of particles (WHO, 2021). Ultrafine particles are eventually removed from the atmosphere by dry and wet deposition processes, of which dry deposition of particles to the surface happens directly and wet deposition of particles to the surface happens through rain or snow ("washout") (Kumar, Ketzel, Vardoulakis, Pirjola, & Britter, 2011; Laakso et al., 2003). Andronache et al. (2006) state that a large collection of rain droplets is an effective mechanism to remove aerosols from the atmosphere, while it also limits the number of (ultra)fine particles growing to the sizes needed for activation of cloud droplets.

The emergence of these ultrafine particles over the last decade has added an additional dimension to the already complex problem of aircraft pollutants at airports around the world. Due to their size, ultrafine particles can remain suspended in the air significantly longer than larger-sized particles, which creates more opportunities for the particles to do harm to the environment and to human health (Abdel-Shafy & Mansour, 2016). The fact that UFPs, in comparison with larger-sized particles, have the potential to deposit in the lungs and translocate to other parts of the human body, due to their variability, also creates a more substantial hazard to human health (Kumar et al., 2014). The potential impact of UFP exposure on health and the environment will be further discussed in section 3.3 of this chapter.

3.2 Ultrafine particle concentration accumulations at and around airport grounds

Ultrafine particles are produced during the combustion of fuels and the engines of aircraft have been proven to be emitters of large quantities of UFP under a wide range of operating modes, the jet turbines used in commercial airliners in particular (Stacey, 2019). Aircraft emit significant amounts of UFP according to engine types, fuel consumption rates, aircraft weights and operating cycles, which eventually results in increased UFP levels on the airport grounds and in nearby neighborhoods (Hu et al., 2009). In order to provide an objective and fair indication of the actual level of concentrations of emissions, established emission standards or advisory values are usually used to compare these levels. However, there is currently no advice established by the World Health Organisation for safe concentrations of ultrafine particles (RIVM, 2018) and there is even the question whether emission standards for UFP concentrations will ever be established (Gezondheidsraad, 2021). That is why, for now, other measured UFP concentration levels are needed to be used as some sort of benchmark. For reference, the urban background concentrations of ultrafine particles in the Dutch cities Amsterdam and Rotterdam were measured to be 9,500 (2015) and 8,000 (2012) $\#/cm^3$ respectively (Bezemer et al., 2015). In other European countries, these measured urban background UFP concentrations were measured between 7,300 and 11,000 $\#/cm^3$. These urban background concentrations are a necessary benchmark in order to be able to compare the measured UFP concentrations at and around the airports, which will be presented in the upcoming sections.

In order to assess the impact of the produced UFP concentrations and the potential mitigation, the source(s) of the concentration production and the dispersion of these concentration accumulations at the airport grounds need to be established. Various studies have been conducted with regard to ultrafine particle concentration accumulations at the airport grounds. These accumulations arise during the different activities that are carried out for the aircraft operation. Ground idle, during which an aircraft is taxiing from the aircraft stand at the pier to the runway, is an important part of the operation of an aircraft. The activities related to ground idle can normally be executed while the aircraft operates under low thrust settings ($< 30\%$). Several studies regarding ultrafine particle size distribution have found that the finest particles (< 30 nm) can be associated with low thrust settings, while the larger particles (30-90 nm) are associated with the higher thrust settings of 35% and higher (Lobo, Hagen, Whitefield, & Raper, 2015; Vander Wal, Bryg, & Huang, 2014; Yu et al., 2017). These studies also concluded that a similar trend in thrust settings is being followed by the particle number concentrations. Voogt, Zandveld, Wesseling, and Janssen (2019), a cooperation between RIVM and TNO, calculated an average contribution to the concentration of UFP by taxiing aircraft at Schiphol Airport as a function of the distance to the taxiway. They retrieved an average contribution of 70,000 $\#/cm^3$ at a 200 meter distance which decreases to 20,000 $\#/cm^3$ at a 1200 meter distance, both on an hourly average basis.

Besides ground idle, the LTO (landing and take-off) processes are also an important part of the operation of an aircraft. These processes take place at the runways, where aircraft arrive or where they are positioned for take-off after the ground idle procedure. Durdina et al. (2014) evaluated UFP emissions by measuring the mass of PM and the effective density in the aircraft engine exhaust. They concluded that the average particle density is lowest at lower thrust settings for all particle sizes, while higher trust settings corresponded with higher particle densities. These findings state that smaller particles, such as UFP, are associated with higher thrust settings of the aircraft engines (e.g., during the start and during take-off), and vice versa. UFP concentration measurements which relate to the aircraft take-off, next to the runways, have been conducted at several airports worldwide. TNO conducted a study at Rotterdam The Hague Airport (RTHA) where, on either side of the runway, a yearly average UFP concentration contribution of 13,000 $\#/cm^3$ was registered (Duyzer & Moerman, 2018). In 2016, an average concentration of 150,000 $\#/cm^3$ was calculated at a distance of 150 meter from the Southern runways at Los Angeles Airport (LAX) during the day (Shirmohammadi et al., 2017). At Ciampino Airport nearby Rome a similar study was conducted, where during the day average concentrations of 23,400 to 55,300 $\#/cm^3$ were measured at a distance of 380 meter from the runway (Stafoggia et al., 2016). During take-off and landing at Ciampino, 5 minute average values of 25,700 to 100,800 $\#/cm^3$ were measured. During the Autumn of 2016, monthly average values of 9,000 and 8,000 $\#/cm^3$ were measured at a distance of 170 and 600 meter respectively from the runways at London Heathrow Airport, where the monthly average concentrations at a distance of 1200 meter were measured around 20,000 $\#/cm^3$ in 2014 (Masiol, Harrison, Vu, & Beddows, 2017; Stacey, Harrison, & Pope, 2020). At a distance of 4 to 5 kilometers from Frankfurt Airport, yearly average concentrations of around 8,000 – 9,000 $\#/cm^3$ were measured, while at the airport grounds itself a yearly average concentration of around 60,000 to 75,000 $\#/cm^3$ was measured (Janicke et al., 2019).

Table 4: Measured UFP concentrations at airports around the world

Airport	**Location**	**Concentration ($\#/cm^3$)**	**Time average**	**Process**	**Year**	**Study**
AMS	200 m from taxiway	70000	hourly	Ground idle	2018	(Voogt et al., 2019)
AMS	1200 m from taxiway	20000	hourly	Ground idle	2018	(Voogt et al., 2019)
RTHA	either side of runway	13000	yearly	LTO	2017	(Duyzer & Moerman, 2018)
CIA	next to runway	25700 - 100800	5-minute	LTO	2012	(Stafoggia et al., 2016)
CIA	380 m from runway	23400 - 55300	daily	General	2012	(Stafoggia et al., 2016)
LAX	150 m from runways	150000	daily	General	2016	(Shirmohammadi et al., 2017)
LHR	1200 m from runway	20000	monthly	General	2014	(Masiol et al., 2017)
LHR	170 m from runways	9000	monthly	General	2016	(Stacey et al., 2020)
LHR	600 m from runways	8000	monthly	General	2016	(Stacey et al., 2020)
FRA	4 - 5 km from airport	8000 - 9000	yearly	General	2015	(Janicke et al., 2019)
FRA	the airport grounds	60000 - 75000	yearly	General	2015	(Janicke et al., 2019)

Table 4 provides an overview of the discussed UFP concentration measurements at the above-mentioned airports. It is important to indicate that the table is purely intended as an overview of the several studies, regarding the measured ultrafine particle concentrations at these airport, and is not meant as a tool for comparison between the studies. Comparing the UFP concentrations is actually not possible, as all the measurements have been carried out in their own unique way. First of all, the distance between the source (aircraft engines) and the measurement locations is different for each study. Besides this, the aircraft operation process during which the measurements were done also differs. The conditions during which the measurements were carried out also had an impact on the study results, as the studies were done at different airports in different countries in different years. Since there is still no standard/norm for the measurement procedures, every study will end up with different results.

At all above-mentioned airports, high incidental peak UFP concentrations could be measured. At AMS hourly average peak concentrations higher than 100,000 $\#/cm^3$ were measured at a 200 meter distance from the taxiway, where hourly average concentrations up to 500,000 $\#/cm^3$ were measured at the Polderbaan (Dinther, Blom, van den Bulk, Kos, & Voogt, 2019). Incidental peak concentrations above 100,000 $\#/cm^3$ (minute average) could also be measured at RTHA during landing and take-off (Duyzer & Moerman, 2018). At around 2 kilometer from the runway the impact of departing and arriving aircraft was still visible, with minute average peak concentrations up to 20,000 $\#/cm^3$. Such incidental peak concentrations were also registered at the airports of LAX (up to 2,000,000 $\#/cm^3$), Ciampino (minute average up to 2,000,000 $\#/cm^3$), London Heathrow (monthly average up to 150,000 and 90,000 $\#/cm^3$ at a distance from the runways of 170 and 600 meter respectively) and Frankfurt (daily average up to 25,000 $\#/cm^3$). Figure 11 shows a comparison between the measured average UFP concentration and the measured peak concentration at that same airport, in which the light blue bar on the left indicates the average concentration and the dark blue bar on the right shows a peak concentration. For both CIA and LAX, UFP concentration peaks up to 2,000,000 $\#/cm^3$ were measured. However, the vertical axis of the figure only goes up to concentrations of 500,000 $\#/cm^3$ for visual convenience. For LHR, two comparisons are shown for the found measurements at both the 170 and 600 meter distances from the runways. The peaks can be associated with so-called 'jet blast events' of aircraft and are the consequence of starting aircraft motors near piers and terminals (cold start) and of taxiing and departing aircraft on and along runways (Tromp et al., 2021). The cold start of an aircraft is the activity that takes place before the ground idle processes and is normally executed at the stand where the aircraft is positioned at the pier. During 'jet blast events' the exhaust gases of aircraft, with high concentrations of UFP, are blown in the direction of the terminal.

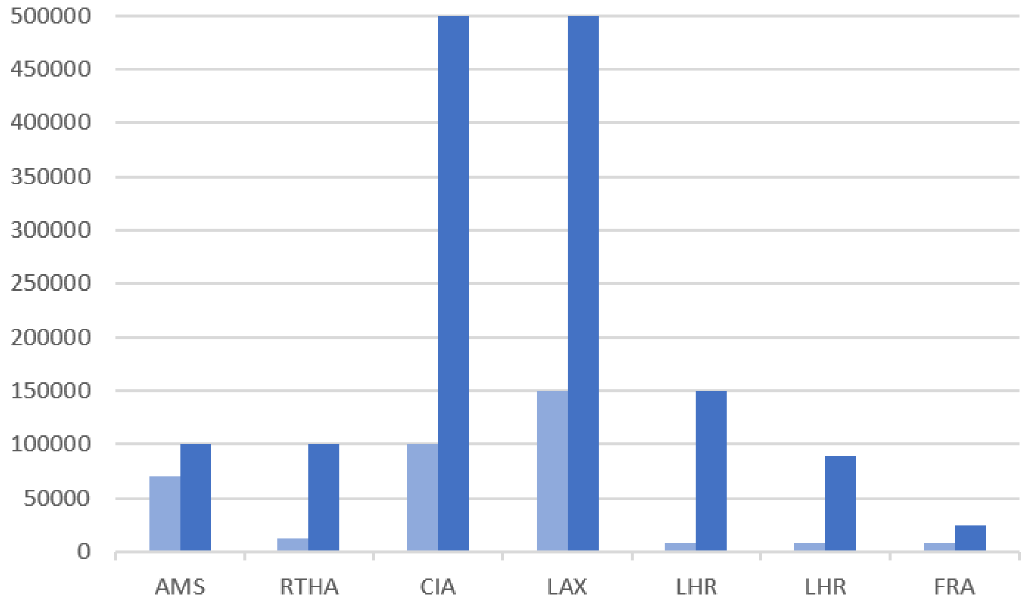

Figure 11: Measured average UFP concentrations (light blue) and peak concentrations (blue) [$\#/cm^3$]

As previously discussed, a decrease in the size of UFP concentrations can be seen as the distance to the aircraft activity locations increases. RIVM calculated the yearly average contribution to UFP concentrations of Amsterdam Airport Schiphol to be up to 3,000 $\#/cm^3$ for a distance up to 15 kilometer (Bezemer et al., 2015). At the living areas that are located the closest to AMS, the measured yearly average of UFP concentrations in 2015 could be up to 15,000 $\#/cm^3$. In 2018, RIVM and TNO (Voogt et al., 2019) ran a measurement campaign around Schiphol Airport were yearly contributions of UFP concentrations from 2,900 to 12,200 $\#/cm^3$ were measured at distances to the airport from 1.3 to 5.1 kilometer. Besides this, a yearly contribution to the UFP concentration of 30,000 $\#/cm^3$ was calculated at a 400 meter distance from the Polderbaan.

There can be concluded that the measured ultrafine particle concentrations at various airports around the world are significantly higher than the usual urban background UFP concentrations, as well as the concentrations that are measured at a certain distance from the airports. This already indicates that it may be of importance to mitigate the production and dispersion of ultrafine particles at the source of the production. At Amsterdam Airport Schiphol an extensive study with regard to UFP concentrations was conducted in 2021, which will be discussed in the following section of this literature review.

3.3 Impact of ultrafine particles exposure on health and environment

As mentioned by the found academic knowledge discussed in the previous sections of this chapter, high UFP concentration accumulations are measured at and around the grounds of airports around the world. These high measured concentrations are already a possible reason for airports to mitigate the ultrafine particle production at the source, namely at the locations where the aircraft operate. A more important reason to invest in a UFP mitigation system at the airport is the risk of adverse health effects after a certain exposure time. Multiple researches have investigated these potential health risks caused by (long-term) exposure to UFP.

After entering the human body, ultrafine particles are able to rapidly reach the bloodstream and spread through all organs because of their small size (Lopes et al., 2019). As they have a very high 'specific surface area to mass'-ratio, small diameter and high number concentration, UFPs are able to carry greater quantities of toxic air pollutants into cardiovascular target sites (Alvarado, 2018; Selley et al., 2021). They can also cross the cell membranes and damage intracellular proteins, organelles and DNA.

While the health impacts of UFP are not fully understood, several studies have provided evidence of adverse health effects and a lower quality of the living environment, which can be directly related to the exposure of ultrafine particles produced by aircraft. A prolonged exposure to higher UFP concentrations may be responsible for worse functioning lungs and/or aggravation of respiratory diseases, e.g. asthma or chronic obstructive pulmonary disease (Lopes et al., 2019). Oxidative stress and inflammatory reactions are also adverse health effects that can possibly be associated with exposure to UFP (Ungeheuer et al., 2021). Besides this, UFP exposure has been independently associated with adverse birth outcomes in the vicinity of LAX (Hudda, Durant, Fruin, & Durant, 2020).

These findings thus confirm the credibility of concern with regard to aircraft-produced ultrafine particles exposure and health, which makes it necessary for airports around the world to further look into possible ways to mitigate the UFP concentrations at the airport grounds. Implementing a potential UFP mitigation system may have a substantial impact on the health and the quality of the living/working environment of airport workers and residents.

3.4 Ultrafine particle mitigation strategies

In their report, Tromp et al. (2021) also briefly discuss the quick wins that can be achieved on the short term when potential mitigation strategies are implemented at airports. As the measured UFP concentrations are higher around the terminals and piers, dealing with these aircraft emissions at these locations is likely to result in the most effective mitigation strategy. As these are the locations where also the most platform employees, baggage handlers and other ground staff execute their tasks, the impact on the health of the involved parties will be significant when the UFP concentration accumulations can be prevented here. An obvious approach is the removal of emission sources in order to reduce the UFP concentrations at the terminals and piers Tromp et al. (2021). Effective solutions are currently mainly directed towards the electrification of road vehicles and towing the aircraft away from the terminals and piers to zones where no employees are located, after which the motors can be started.

Over the last few years, the implementation of water droplet production equipment has been introduced as a dust mitigation strategy in various industries (i.e., manufacturing, storage and demolition). Several companies have specialized in the field of dust control in construction: combating the produced dust at construction sites by atomizing water at high pressure. These companies, e.g. MB Dustcontrol and Erkho, address that the very fine water droplets can be used well for the suppression of dust and fine particles and that their equipment can be placed for many different applications (Erkho BV, 2022). So-called "SprayCannons" and "SprayWalls" are examples of water droplet machines that are used to produce a curtain of micro water droplets (MB Dustcontrol, 2022e). This curtain works in such a way that it suppresses dust in open spaces by binding dust particles in the air so that they fall to the ground through gravity, so-called 'air cleansing'.

4 Case study Amsterdam Airport Schiphol

This chapter of the report elaborates on the findings and insights from the literature review in chapter 3, by focusing on the current situation at Amsterdam Airport Schiphol. This case study first provides a brief overview of insights from previously conducted studies in section 4.1, after which an extensive stakeholder analysis is provided in section 4.2.

4.1 Ultrafine particle concentrations at Amsterdam Airport Schiphol

This section of the AMS case study elaborates on the discussed topics of the literature review (chapter 3), by associating the insights regarding ultrafine particle concentrations at the airport grounds to the situation at Schiphol. The UFP accumulation locations at AMS will be discussed, as well as the contribution of aircraft to these concentrations and the concentrations throughout the day. Potential mitigation strategies at AMS, of which literature is available, will also be briefly mentioned.

4.1.1 Ultrafine particle concentration accumulation locations

In order to mitigate ultrafine particles production and dispersion at airports, it is important to gain insight into where these UFP concentration accumulations are created and located. When this becomes clear, a UFP mitigation system can be implemented at the locations on the airport grounds where it can significantly reduce these emissions in the most effective and efficient way. In 2021, TNO conducted a research commissioned by Schiphol Group for which mobile measurements on the Amsterdam Airport Schiphol grounds were carried out. The study resulted in the report 'Verkennend onderzoek ultrafijnstof op het Schiphol terrein met behulp van mobiele metingen' (Tromp et al., 2021), in which insights with regard to the UFP concentration levels on the airport were obtained.

The mobile measurements on the airport grounds of Schiphol resulted in a map showing the measured average UFP concentrations, which are visualized in appendix B. This map shows relatively high measured concentrations at the area (north)eastern of the airport building, especially at terminals 1 to 3 and piers B to G. An overview of the measured UFP concentrations for the several different areas at Schiphol is presented in table 5 (Tromp et al., 2021).

Table 5: Average, median and 90 percentile UFP concentrations for different areas at AMS

Areas	**UFP concentration** ($\#/cm^3$)		
	Mean	**Median**	**90 percentile**
Terminals and piers	100,000 - 120,000	44,000 - 68,000	210,000 - 270,000
Boulevard/Ceintuurbaan	62,000	42,000	130,000
Taxi- and runways	26,000 - 76,000	7,600 - 26,000	56,000 - 110,000
Platforms	36,000 - 140,000	13,000 - 36,000	37,000 - 200,000
Business parks	22,000 - 52,000	16,000 - 47,000	43,000 - 98,000
Motorway bypasses A4	54,000	30,000	110,000

Different types of statistical measurement data are linked to these areas, namely the average number, the median and the 90 percentile of the measured ultrafine particle concentrations. The concentration measurements are expressed in the number of particles (#) per cubic centimeter (cm^3). The data in table 5 shows that at the terminals and piers and at the platforms high average- and 90 percentile values for the UFP concentrations were measured on the airport grounds, as well as on the Boulevard/Ceintuurbaan. In figure 40 (Tromp et al., 2021) in appendix B, the measured concentrations are more specifically indicated for the individual piers, (taxi)roads, runways, platforms and business parks. Especially at the locations 'piers B-G, C-E and F-G' and 'platforms A/B, -J and -R', higher average-, median- and 90 percentile values of UFP concentrations were measured by TNO. Relatively high values can also be seen for the Boulevard/Ceintuurbaan and the business park 'Bedrijventerrein Schiphol Zuidoost en –Rijk'.

The UFP concentration "heat maps" identify certain 'hot spots' where high incidental (a few minutes) peak concentrations were measured. At multiple locations, higher measured UFP concentrations can be attributed to aircraft operations at Schiphol Airport. Around piers C, D, E and F increased concentrations are most likely caused by arriving and departing aircraft, as well as by 'jet blast events' (Tromp et al., 2021). On the runways 'Kaagbaan' and 'Zwanenburgbaan' higher concentrations can be attributed to starting and landing aircraft.

On taxiways along several runways higher UFP concentrations can be linked to taxiing aircraft, especially on intersections and at turns. On and around the S-, H- and A/B-platforms the increased concentrations can very likely be caused by taxiing aircraft, with potentially also a 'jet blast event'.

4.1.2 UFP concentrations contribution of aircraft and road traffic

Tromp et al. (2021) also investigated the contribution of aircraft, road traffic and other machinery to the total measured concentrations of UFP at AMS to determine the impact of airport operations on the air quality. The study showed that emissions by road traffic and other diesel motors at the airport in general have a relatively small contribution to the UFP concentrations at airport grounds. On a large scale, aircraft emissions are the biggest contributor to the concentration of UFP at Schiphol, which can be substantiated by several studies at other airports around the world (Stacey, 2019). There are some exceptions, as "non-aircraft emissions", by for instance road vehicles and aggregates, contribute to increased UFP concentrations under the terminals and along piers C and D. For now it is still difficult to measure this contribution, but it can be stated that, in general, aircraft emissions are by far the main contributor to the UFP concentrations at the grounds of Schiphol.

4.1.3 UFP concentrations throughout the day

Besides analyzing the ultrafine particle concentrations at different locations at Amsterdam Airport Schiphol, TNO also measured the UFP concentrations for the different parts of the day (Tromp et al., 2021). More insights into the coherence between the number of flights and the UFP concentrations at the airport grounds was obtained by plotting them against each other for each part of the day (6-hour period). The highest UFP concentrations were measured during the morning and the afternoon, which highly correlates with the high number of aircraft movements in these periods. The results of the study of Lopes et al. (2019) also showed a significant positive correlation between the measured ultrafine particle concentrations and the total number of flights.

UFP concentrations can substantially fluctuate during the day; incidental (seconds to minutes) high peak concentrations of more than 500,000 parts per cm^3 can occur, as previously discussed in the section 'Ultrafine particle concentration accumulations at airport grounds'. As the airport activities that usually cause these peaks mainly take place during the morning and afternoon (Stafoggia et al., 2016), the measured high UFP concentrations during these periods can be explained.

4.1.4 UFP mitigation strategies at AMS

Royal Schiphol Group, Wageningen University & Research (WUR) and the Netherlands Aerospace Centre (NLR) saw potential in implementing this technique to mitigate the distribution of ultrafine particles at the airport grounds and combined forces to conduct further research into this technique (Schiphol, 2021). After finetuning this method, the hypothesis is that UFP produced by aircraft may exhibit the same behavior while interacting with mist droplets as fine particles and dust. In March 2022, Schiphol and TNO collaborated with Corendon and KLM to put the use of mist for the reduction of the amount of UFP, in the air and around the airport, to the test (Schiphol, 2022b). Water droplet clouds and -screens were produced by SprayCannons and -Walls while the engines of the aircraft were running at high power (landing and take-off procedures) and when they are switched on. TNO measured the amount of ultrafine particles in the air during the several experiments. All parties involved believe in the potential of the water droplets to reduce concentrations of UFP produced by aircraft, but the collected data needs to be analyzed thoroughly before expectations can be confirmed.

Sub-question 1: 'What are the sources, locations and health effects of ultrafine particle concentrations at airports around the world and which potential mitigation strategies are available?'

As can be concluded from the conducted literature review and the first subsection of the case study at Amsterdam Airport Schiphol, large accumulations of ultrafine particle concentrations have been measured at and around multiple airports. These concentrations can be associated with the several processes of which the aircraft operation consists: the cold start, ground idle and the landing and take-off procedures. Most of the platform employees, baggage handlers and other ground staff execute their tasks at the airport locations where the higher ultrafine particles concentrations were measured. While the health impacts of the exposure to UFP are not completely understood yet, several studies have provided evidence of adverse health effects and a lower quality of the living environment, which can be directly related to the exposure of ultrafine particles concentrations produced by aircraft. It is thus of importance to mitigate the UFP production by aircraft, as well as the dispersion of the concentrations around the airport. The impact on the health of the involved parties will be substantial when the production of UFP can be mitigated at the locations where the aircraft operate. An interesting solution direction with potential is the implementation of an ultrafine particle mitigation system based on the production of water droplets. The produced water droplets are able to capture a certain share of the produced ultrafine particles by the aircraft, after which the particles clump together in the water droplets and descend to the ground. This decreases the risk of harm to the health of employees and prevents the UFP of dispersing around the airport grounds.

While little to nothing is currently known about designing and implementing an ultrafine particle mitigation system, let alone a mitigation system that is using water droplet production equipment, it is of substantial added value to conduct a research about this topic. Not only for Amsterdam Airport Schiphol and other airports around the world, but also for the academic community as a whole. This knowledge gap in the current academic body of work gives room for new research concerning this topic. A study regarding the design of a 'water droplet'-based UFP mitigation system at the airport can provide a complete overview of all the stakeholders that need to be involved, all the requirements that the system must meet and the feasibility, viability and desirability of the potential system design. Once the use of water droplets to mitigate ultrafine particles at the airport is proven to be effective and efficient, the suggested system design and gained knowledge from the research can be used as a stepping stone for the actual implementation of such a system.

4.2 Stakeholder analysis

This section of the Amsterdam Airport Schiphol case study provides a deep dive into the system of stakeholders that are commonly involved in problem situations within the Dutch aviation industry. The overview of stakeholders is related to the ultrafine particle mitigation issue at the airport, but is generally involved in other similar projects at AMS as well. The stakeholder analysis integrates the use of several tools, which will result in an overview of the key stakeholders for this research. These methodologies will be further discussed in the following sections, after which a stakeholder shortlist is presented that will be used for the substantiation of the conducted semi-structured expert interviews.

4.2.1 Stakeholder inventory list

In the second step of the stakeholder analysis, the inventory of involved actors is drafted. Enserink et al. (2010) mention some specific points for attention while making this list of stakeholders. One of these points of attention is how to deal with composed actors, as (governmental) organizations usually consist of several departments and sections with different functions, interests and objectives. Multiple parts of an organization can be involved in the problem situation, which makes it not always sufficient to include an entire organization as a stakeholder in the analysis. In this analysis, different departments and sections of a (governmental) organization are included when they are involved with the problem, based on their own, distinctive objectives and responsibilities. The inventory of actors who are active in the Amsterdam Airport Schiphol environment and the aviation industry as a whole, and are potentially stakeholders in the problem situation, are presented in the overview below. A brief description of most of these stakeholders can be found in appendix C.1.

- Royal Schiphol Group (RSG):
  - Innovation Hub;
  - Strategy & Airport Planning (S&AP);
  - Airport Operations (OPS);
  - Safety, Security & Environment (SSE): Health, Safety & Environment HSE;
  - Procurement & Contracting (PC);
- European Union:
  - European Union Aviation Safety Agency (EASA);
  - TULIPS consortium;
- Dutch government:

  - Ministry of Infrastructure and Water Management:
    * Directorate-General for Aviation and Maritime Affairs: Aviation;
    * Directorate-General for the Environment and International Affairs: Air quality;
  - Ministry of Social Affairs and Employment;
- Knowledge institutes:
  - National Institute for Public Health & the Environment (RIVM) and the Health Council of the Netherlands;
  - TNO;
  - The Netherlands Aerospace Centre (NLR);
  - Wageningen University & Research (WUR);
  - Delft University of Technology;
  - University of Twente;
  - etc.
- Air Traffic Control the Netherlands (LVNL);
- FNV Schiphol + Platform employees, baggage handlers and other ground staff;
- Aircraft Manufacturers;
- Airlines;
- Other (inter)national airports;
- Residents of the Amsterdam Airport Schiphol surrounding areas;
- Investors;
- Water droplet production equipment providers;

4.2.2 Formal chart

All the actors that were mentioned in the previous section can be presented in a diagram, the so-called 'formal chart', in which the formal relations between these actors can be mapped. A formal chart does not depict all the existing formal relations between the actors, but only those deemed most important for the problem analysis. The rectangles in the diagram represent the individual stakeholders, whereas the boxes with dashed lines stand for an overarching organisation/government. These dashed boxes include multiple stakeholders. Each arrow in the formal chart represents a resource needed for analyzing dependencies: single-sided arrows indicate hierarchical relationships, where two-sided arrows indicate formal representation relationships/membership. Most of the arrows are labelled with the contract, regulation or other agreement in force between the actors. The formal chart with all the stakeholders for the UFP mitigation problem at AMS is visualized in figure 12.

4.2.3 Problem formulations stakeholders

After the formal relations have been determined, it is important to gain more insight into the problem formulations of all the actors that are involved in the problem situation. An overview of all the actors' problem formulations can be realised by formulating their interests, objectives and potentially important resources within the problem situation. For the ultrafine particle mitigation problem situation at Amsterdam Airport Schiphol, this overview is presented in table 20 in appendix C.2.

4.2.4 Stakeholder interdependencies analysis

An overview of the interdependencies of the stakeholders within the system can be visualized in a so-called 'power-interest matrix'. In such a matrix, the power and interests of actors classify the different actors in the problem situation. An actor with a high level of power, i.e. important resources, is usually a critical stakeholder, whereas actors with a high level of interest in the problem are usually the dedicated stakeholders. The level of power is indicated on the y-axis of the grid, where the level of interest in the problem is shown on the x-axis. The power-interest grid is divided into quadrants, in which the actors that are placed in the upper right

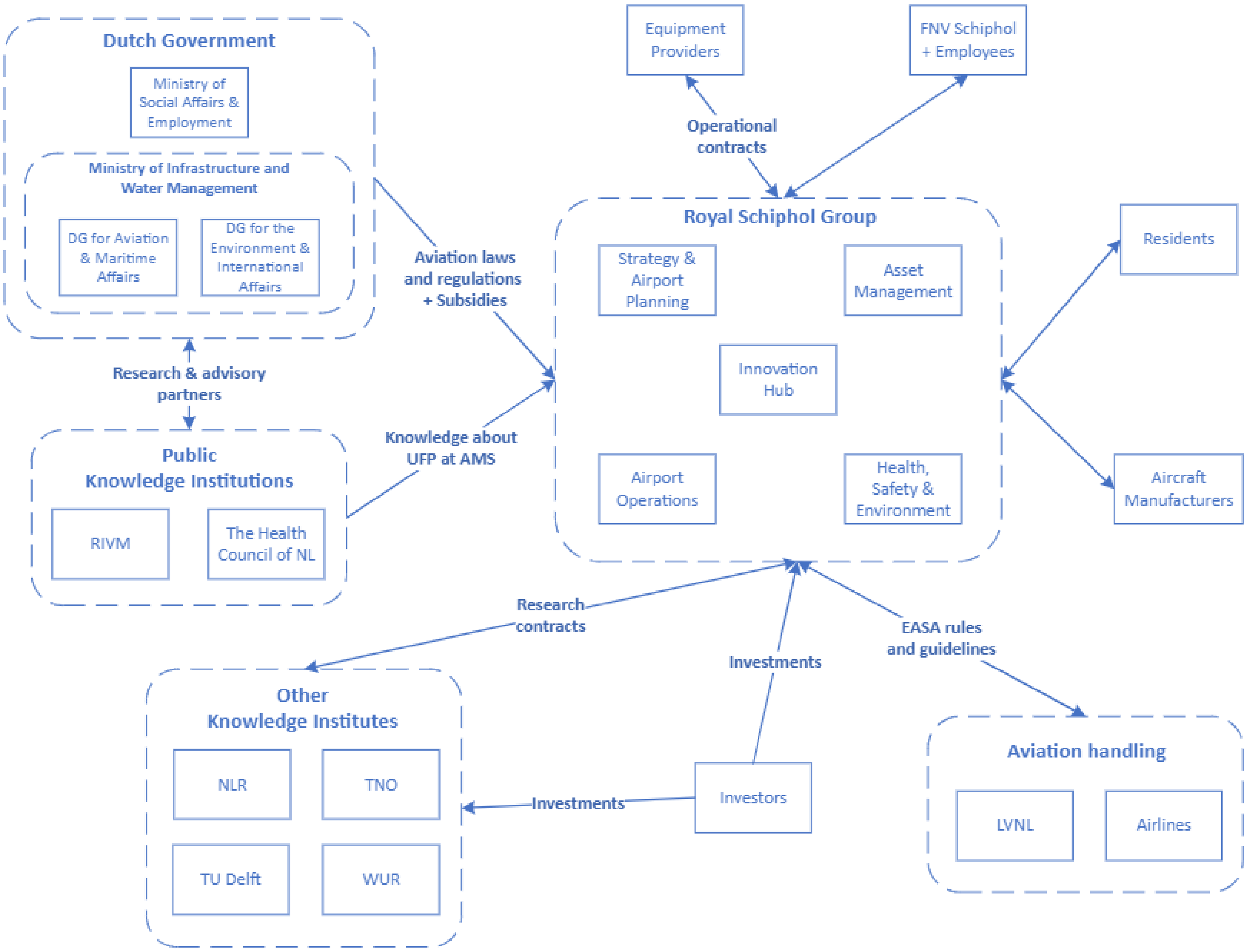

Figure 12: Formal chart for the ultrafine particle mitigation problem at AMS

quadrant are the key players in the system. These key players have a high level of interest in the problem, but also have a lot of important resources. The stakeholders that are placed in this quadrant of the matrix are the ones that could play an important role during the knowledge collection process of this research. With the input from these stakeholders, the theoretical background can be finalized with which the requirements for the design of a potential 'water droplet'-based mitigation system, to tackle the ultrafine particle production by aircraft at the airport, can be formulated. The Power-Interest Grid is presented in figure 13.

As one could expect is Royal Schiphol Group the actor with the highest level of interest and the most power in the system, as can be observed in the matrix. Most departments of RSG have an important role in the problem situation, as the company is the problem owner in this situation. The departments S&AP, OPS, HSE and ASM all have their interest in the problem and together have a lot of know-how in several fields of expertise and have experience in the preparation and execution of a project. Besides RSG, the Dutch government also has a high level of power in the problem situation. However, this is power in the form of authority and the possibility to grant subsidies, while RSG does have power in the form of knowledge and expertise. TNO and NLR have a relatively high amount of power in the problem situation, as they have the capabilities and facilities to conduct research on the ultrafine particle production, concentrations and dispersion at the airport. As they are non-governmental organizations, they provide their research services in exchange for a monetary fee, which means that they are in a position to negotiate. RIVM and the Health Council of the Netherlands are also renowned in conducting research and providing the Dutch government with advice. However, as they are usually commissioned by the government, they are not providing their services for monetary purposes.

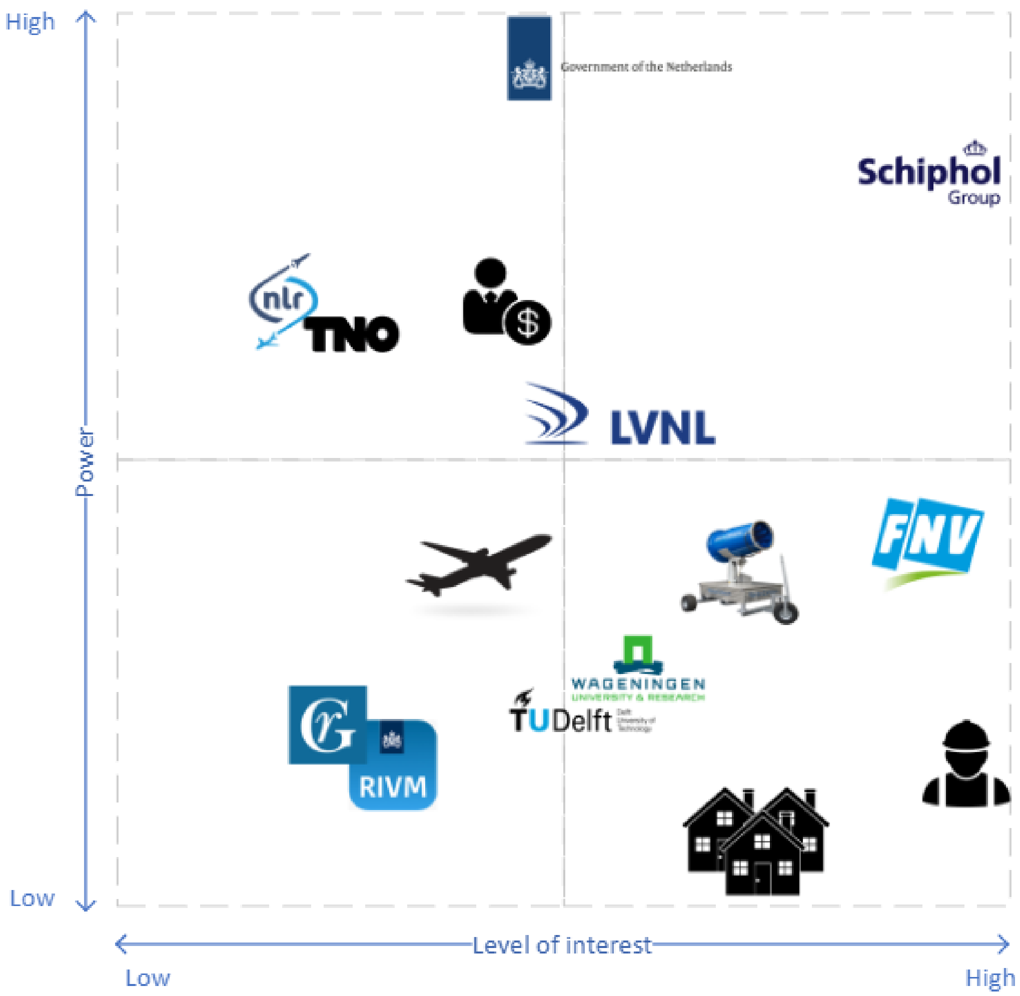

Figure 13: Power-Interest Grid for the ultrafine particle mitigation problem at AMS

As can be seen in figure 13, a lot of the potential stakeholders are located in the bottom-right quadrant of the grid. This means that they have a above-average level of interest in the problem, but do usually not have the means to exercise that much power. Knowledge institutes, such as the TU Delft and WUR, are potential partners for ('water droplet'-based) UFP mitigation research at Schiphol, as well as the providers of the equipment that can possibly be deployed in this system. FNV Schiphol, the (platform) employees and the residents of the surrounding areas of AMS all have a high level of interest in the problem, but do not have power in the form of knowledge/expertise, authority or money. They want their objectives to be incorporated in the projects of RSG, but cannot operate as an important knowledge partner within this research. The airlines, aircraft manufacturers, LVNL and other investors all have a certain position in aviation projects at AMS, but will most likely not play a substantial role in the projects with regard to UFP mitigation at the airport.

4.2.5 Conclusion and insights

All previous steps of the stakeholder analysis provide an overview of all the actors involved in the system, as well as their interdependencies. All the mentioned interests, objectives and important resources of each actor resulted in a Power-Interest Grid in which all the stakeholders in the problem situation were placed. For this research, it is of great importance that further knowledge in the field of aviation, meteorology and air quality, sustainability and the environment is gathered in order to create a well-founded theoretical framework. The stakeholders who will be involved in the next phase of this research should thus, within their field of expertise, be able to provide knowledge and information to further complement this foundation. From the analysis can be concluded that several stakeholders within this system have a lot of knowledge on different aspects of the aircraft operation at AMS and all necessary processes to ensure safe, efficient and effective handling. There are also multiple (non-)governmental parties with the capability and facilities to conduct research with regard to ultrafine particle concentrations at the airport grounds, with the ability to go deeper into the production, dispersion and potential mitigation of these emissions. All in all, the actor analysis has provided sufficient information in order to create a shortlist for the expert stakeholder interviews.

Sub-question 2: 'Who are the stakeholders that should be included in the background research into ultrafine particle mitigation at the airport and throughout the execution of this research?'

Table 21 in appendix C.3 shows the initial shortlist of stakeholders that resulted from the conducted stakeholder analysis, with their potential role in the design of a 'water droplet'-based UFP system at airports, as well as the necessary knowledge for the theoretical foundation that they might be able to provide. However, while conducting this study, adjustments were made to the initial list of potential stakeholders to involve within this research. These adjustments were made, as opportunities to have interviews with other interesting stakeholders arose, or interviews with representatives from the organizations of the initial list could not be organized within the period of this research phase. An overview of all the stakeholders that will be included in the further research to form the theoretical framework for this study is presented in table 6. Their function/expertise, the organization/institution where they work, and the department/faculty of the place where they work are all presented in this table. The transcriptions of the conducted interviews with these stakeholders can be found in appendix F, from which insights, knowledge, quotes and advises will be used throughout the following chapters of this study. There will be referred to the individual interviews when these findings are incorporated in sections.

Table 6: Overview of conducted stakeholder interviews

	Function/Expertise	Organization/Institution	Department/Faculty
1	Air Transport & Operations	TU Delft	Aerospace Engineering
2	Safety Consultant	KLM Royal Dutch Airlines	-
3	Meteorology & Air Quality	WUR (Wageningen)	Environmental Sciences
4	Head of Sustainability Development	Copenhagen Airport	-
5	Air Quality and Pollution	TU Delft	Aerospace Engineering
6	Researcher in (Nano) Particles	TNO	-
7	Flight Performance and Propulsion	TU Delft	Aerospace Engineering
8	Senior Manager & Aircraft Architect	Airbus Technology Bremen	-
9	(Nano) Particle-Droplet Interaction	University of Twente	Science and Technology
10	Senior Process Advisor	Royal Schiphol Group	Airport Operations
11	Stakeholder Strategy & Development	Royal Schiphol Group	Strategy & Airport Planning
12	Senior Environmental Advisor	Royal Schiphol Group	Safety, Security & Environment
13	Sourcing Manager	Royal Schiphol Group	Procurement & Contracting
14	Process Owner Aircraft	Royal Schiphol Group	Airport Operations

5 System design components

Three important questions to ask when coming up with any system design are 'When?', 'Where?' and 'How?'. When designing a new system, it is essential to determine during which activities/processes the system must operate. Besides this, insights with regard to the location where the system should be implemented and the dimensions that the potential construction will cover must be gathered. By answering 'How?', an overview of potential solutions and system configuration can be provided, which is necessary to eventually come up with a conceptual system design. The interpretation of these three questions regarding 'water droplet'-based ultrafine particle mitigation at Amsterdam Airport Schiphol are discussed in sections 5.1, 5.2 and 5.3. The insights and knowledge from the conducted stakeholder interviews, of which an overview can be found in table 6 and appendix F, is incorporated into the analysis of the system design components, as well as in the comprehensive requirements analysis presented in section 5.4. The list of requirements that is the final product from this requirements analysis is essential for the design of the conceptual UFP mitigation system for Amsterdam Airport Schiphol. The conclusion of this chapter can be found in section 5.5.

5.1 Moment of mitigating UFP

For the mitigation of ultrafine particles at the airport, there needs to be determined during which process(es) of the aircraft operation the system is deployed. Besides relating the operation times of the system to the aircraft processes, the system can also be operated during different periods throughout the day. As previously discussed in chapter 3.2, the operation of a departing aircraft can be roughly divided into three subsequent processes: the 'cold start', ground idle and take-off (LTO process).

5.1.1 Cold start of the engines

The cold start of the jet engines is currently executed at the aircraft stand at the pier, after which the aircraft taxis away from the apron via the taxiways to the runway. During the cold start, the jet engines heat up again after being completely cooled down, which takes several minutes before the aircraft can taxi away from the stand at the pier. A lot of kerosene is needed for the combustion, which results in the production of large amounts of UFP and other (partial) emissions during this process. A professor in meteorology and air quality (appendix F.3) related 'cold starts' of aircraft engines to additional emissions, which mostly has to do with engine residuals that stick to the engines once they are switched off. Once the engines are turned back on, the aircraft produces some "bonus" emissions, which is basically the old emission residue that also gets burnt. UFP concentration accumulations occur at the airport terminals/piers, which are also the locations at the airport where most ground staff and platform employees are walking around. Tackling the problem when the aircraft is positioned and is not moving seems like the most effective and efficient alternative. Besides this, implementing a system closer to the airport buildings and platforms will result in the most benefits for all employees involved.

5.1.2 Ground idle

Once the aircraft has left the aircraft stand at the pier, it continues its operation under 'idle' engine settings while taxiing over the apron and taxiways. The wide-spread layout of AMS may result in relatively long taxi times from the aircraft stand to the runway for a share of aircraft. These distances, in combination with the lower operational engine settings, can cause the ground idle procedures to take much more time than the cold start of the engines. While the engine settings are relatively low, the taxi times might result in a comparable production of UFP and other emissions. However, mitigating the production of ultrafine particles while the aircraft is taxiing might be a complex logistical challenge. A mitigation system during ground idle will include constructions alongside all taxiways and/or movable solutions that follow the aircraft. Besides this, the ground idle procedures take place on the taxiways further away from the platforms and in the open field, which means that almost no (platform) employees perform their tasks close to this part of the aircraft operation. These first observations might imply that a UFP mitigation solution for taxiing aircraft imposes far more costs than benefits that can be related to this system.

5.1.3 LTO procedures

Arriving aircraft can usually return to the piers under low engine power settings as they land with sufficient thrust to taxi back for a certain distance. Instead of taxiing back to the aircraft stand at the pier, a tow-truck can be deployed to assist the arriving aircraft. Both procedures require a relatively limited amount of fuel, which also results in lower emission concentrations production. For potential UFP mitigation implementations during the LTO procedures, the focus will thus mainly be on the ultrafine particle production of departing aircraft. The final step of the ground idle procedure is the positioning of the aircraft at the head of the designated runway, after taxiing from the aircraft stand at the pier over the taxiways. The jet engine settings are turned to full power once the departing procedure of the aircraft on the head of the runway has started. The ground idle distances may differ significantly between airports and even between pier-runway combinations at the same airport, but the take-off distances on the runways of an aircraft will be the same for the same type of aircraft. For instance, a wide-body aircraft such as the Boeing 747 requires 3,100 meters of runway to take off fully-loaded, while the Boeing 737, a narrow-body aircraft, can operate fully-loaded on runways of 1,830 meters (Simple Flying, 2022). Implementing a UFP mitigation system at each runway is accompanied by a clear demarcation of where the operations should take place, which is an advantage of producing the water droplets during take-off. However, as the aircraft operate at (or close to) full power for a relatively large distance, a potential 'water droplet'-based ultrafine particle mitigation system should move along with the departing aircraft at high speeds for a substantial distance. Since implementing the system at a certain position on the runway will not be effective, the costs and the complexity of the system will increase exponentially. These findings might indicate that the implementation of a UFP mitigation solution for departing aircraft taking off from the runway imposes far more costs than societal benefits.

5.1.4 Moment of the day

As discussed in chapter 4.1.3, it might also be of importance to determine during which period of the day the 'water droplet'-based UFP mitigation system is deployed at the airport. The most aircraft emissions will be captured by the water droplets when the system is operating throughout the whole day, but this might not be the most efficient configuration. For instance, Royal Schiphol Group (2022a) analysed the air transport movements at AMS for the month July of the year 2022 and determined that only 7.4 percent of all movements are night and early morning flights. Tromp et al. (2021) created scatter plots to retrieve insights into the correlation between the number of flights at AMS and the UFP concentrations at the airport grounds. In figure 14, the average UFP concentrations are plotted against the number of aircraft movements for each part of the day (six-hour period), for all measurements over the entire airport grounds of AMS. The scatter plot of the average UFP concentrations against the number of flights around the terminals and piers for the six-hour periods (part of the day) is presented in figure 15. In both figures, the concentrations are expressed in [$\#/cm$], where the colours red, green, blue and purple represent the morning, afternoon, evening and night aircraft movements respectively.

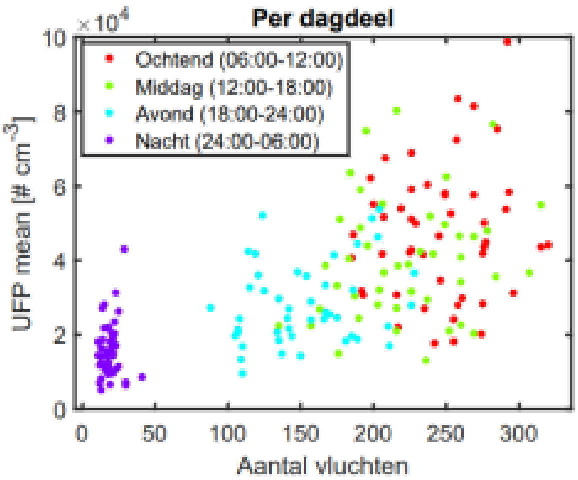

Figure 14: Scatterplot average UFP concentrations AMS grounds

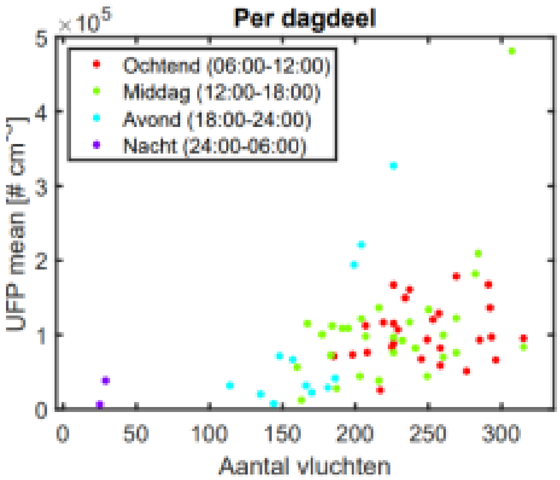

Figure 15: Scatterplot average UFP concentrations AMS terminals and piers

As can be seen in figures 14 and 15, the number of aircraft movements is low during the night, which means that the background concentrations are mainly measured. The number of flights is highest during the morning and afternoon, where the number of evening flights is usually half compared to the morning and afternoon flight numbers. Even though the ultrafine particle concentrations are widely spread, an increase in the number of aircraft movement generally goes paired with an increase in the six-hourly mean UFP concentrations. In figure 15, a bigger scale is used to indicate the UFP mean [$\#/cm$] on the y-axis. The difference between the scales for the UFP measurements across the entire AMS airport grounds and for around the terminals and piers is an indication of the potential severity of health hazards for (platform) employees.

5.1.5 Conclusion

Determining the moment(s) during which the UFP mitigation activities should be executed is not an easy task, as it is still unclear under which engine power settings ultrafine particles are mainly produced. During the cold start, the jet engines need to be heated up completely from scratch and, under relatively high power settings, large amounts of UFP and other emissions are produced. Aircraft can operate under relatively low power settings during ground idle procedures, for which less kerosene is needed for the combustion in the engines. However, several studies (chapter 3.2) related lower power settings to relatively high shares of the smallest form of particles in the total aircraft emissions. These higher shares of UFP in the total of emissions do not necessarily imply that the amount of ultrafine particles exceeds the amount of UFP under higher engine settings. During the take-off from the runway, the aircraft engines operate at full throttle. However, as this process takes tens of seconds, the amount of fuel that is needed for the combustion is somewhat compensated for.

Currently it is difficult to determine during which part of the aircraft operation the most ultrafine particles are produced and thus during which processes, between the cold start of the aircraft at the aircraft stand and the departure from the runway, it is most urgent to implement 'water droplet'-based UFP mitigation strategies at AMS. However, certain aspects of the aircraft operation activities provide some insights regarding the efficiency and effectiveness of capturing the ultrafine particles with the produced water droplets during these processes. According to a professor with expertise in flight performance and propulsion and several other stakeholders, the best-case scenario is represented by a system where the produced water droplet cloud moves along with the aircraft throughout the whole aircraft operation (appendix F.7). After the cold start the aircraft will continue with the production of UFP, which will not be captured anymore after the aircraft taxis further away from the mitigation system. Several stakeholders state the importance of not just solving the problem during one aircraft operation process, but during the complete operation. However, as previously discussed, the logistical challenges involved in the mitigation while the aircraft is moving make it a lot more difficult to introduce ultrafine particle mitigation during ground idle and/or landing and take-off. As the aircraft is positioned at a dedicated space during the cold start, this seems like the most suitable aircraft operation activity to implement a potential entry-level UFP mitigation strategy.

The various periods of the day have also been analysed in order to determine whether the system should be active during the morning, afternoon, evening and/or night. In the most favorable situation for the mitigation of ultrafine particles, the system operates throughout the entire day to capture as much UFP as possible during the operation of all aircraft. However, this strategy might not be the most efficient way to reduce the ultrafine particle concentration accumulations at the airport grounds, because the number of aircraft movements during the night (six-hour period) is much lower than the flight numbers during the morning and afternoon. The number of aircraft movements in the evening is also relatively low in comparison with the morning and afternoon numbers. The initial focus should thus mainly be on the mitigation of UFP produced by the aircraft that depart during the morning and afternoon, in order to retrieve the most benefits after implementation of such a system. Once the 'water droplet'-based UFP mitigation system has been proven to be efficient and beneficial during these periods of the day, the mitigation strategy can be expanded to the evening and night aircraft movements.

5.2 Location of mitigating UFP

After the moment, during which the UFP mitigation strategy will be active, has been determined, the locations where a potential ultrafine particle mitigation system could be implemented need to be analysed. Even though the execution of certain parts of the aircraft operation seems more fitting to include a water droplet system that combats the produced ultrafine particles, it is still interesting to investigate all potential locations of such a UFP mitigation system. The upcoming headers in this section will discuss the locations where the mitigation strategies might be implemented.

5.2.1 The aircraft stand at the pier

The aircraft operation starts at the aircraft stand, located at one of the piers of one of the airport terminals. The final checks for the aircraft are performed by the crew and the jet engines are turned on. After 2-5 minutes the engines are warmed up and the aircraft is ready to start the ground idle procedures. The aircraft stand is the location where the aircraft operation is closest to the airport building, which also makes it the most dense and hectic area at the airport grounds. Ground personnel and platform employees are walking around the platforms and there are many other processes and activities happening near the airport building. Tromp et al. (2021) and other studies around the world (chapter 3.2) have shown that UFP concentration accumulations are formed around the airport terminals, platforms and piers throughout the day, which addresses the need to combat the problem at these locations. Implementing a system that produces water droplets to capture the ultrafine particles at the aircraft stands will eventually be significantly beneficial for the platform employees and other ground personnel who are walking around this vicinity.

However, there are serious doubts with regard to the implementation of such a system at the aircraft stands. First of all, the construction costs of implementing a mitigation system at every aircraft stand will be extremely high, especially for an airport with the amount of piers and aircraft stands as AMS. When the system is dedicated to be operational at the piers and aircraft stands, the amount of installation work and the number of water pipes on and/or underneath the infrastructure next to the terminals will be excessive. A Safety Consultant at KLM, among other stakeholders, addresses the safety risks of the installations and water production of a system so close to the airport building and in the vicinity of the employees (appendix F.2). Large water puddles will arise at the locations where larger amounts of water might result in complications with higher risks due to combating the production of UFP locally, instead of at central/remote locations. Implementing a mitigation system at these locations is thus accompanied by larger risks for the safety and health of (platform) employees and for the performance of the aircraft. Besides the installation costs and the safety risks, the mitigation of ultrafine particles at the aircraft stands also means that the water droplets need to be produced fairly close to the jet engines, as there is not a lot of space available to place the system further away from the aircraft. As it is not yet clear at what distance the production of a water droplet screen/cloud will result in the best-performing mitigation system, it is wiser to opt for a location where this distance can be adjusted according to the findings regarding system performance. Therefore, several stakeholders argued that implementing a potential UFP mitigation system further away from the piers and terminals seems more suitable and implementable than placing constructions and producing water droplets at the aircraft stands (appendix F).

5.2.2 Remote starting positions

In the current situation, at almost all airports around the world, the aircraft engines are started at the designated aircraft stand next to the piers of the airport building. As the jet engines are cold once they are turned on, a lot of polluted air and emissions are blown towards the piers and all the (platform) employees that are working there. Implementing a UFP mitigation system at this location can be a good start to combat the formation of emission concentration accumulations, but employees still working so close to the aircraft operation might induce eventual health and safety hazards. A Senior Process Advisor in the department of Airport Operations at RSG introduced the concept of 'remote starting positions' in the stakeholder interview, which is an alternative for the local start of the aircraft at the aircraft stand (appendix F.10). The idea of introducing these new starting positions is based on the need to remove the production of aircraft emissions further away from the piers. From the interviews with experts within the organisation of Royal Schiphol Group, three categories of new potential remote starting positions can be proposed: the semi-central starting positions, the central starting positions and starting from the head of the runways.

Semi-central starting locations

The category of semi-central starting positions consists of potential remote starting locations that are further away from the piers, but are still fairly close to the bay. A few interesting examples of semi-central starting locations are the E- and P-platforms, also called the Echo and Papa buffer respectively, which are located northeast of the airport building (figure 16). The possible positions for the aircraft at the buffers are better visible in figure 17, which shows that the E-platform consists of the stands E72, E75 and E77, whereas positions P1, P2 and P3 are available at the P-platform.

From interviews with stakeholders from several departments of RSG, information regarding the characteristics and aspects of the remote starting locations was gathered (appendices F.10, F.12 and F.14). In the current situation, the aircraft stands at the Echo buffer are used for the cold start, while the Papa buffer is mainly used as a temporary parking spot for inbound aircraft that arrived too early. Both the buffers are located between the D- and the E-piers, which makes them convenient starting locations for the aircraft that are positioned at the aircraft stands in the DE-bay. Besides this, multiple runways are relatively easily accessible from these positions, i.e., the Aalsmeerbaan and the Buitenveldertbaan, but also the Kaagbaan and optionally the Schiphol-Oostbaan. The E- and P-buffers are therefore good starting positions for aircraft that have one of these runways as their dedicated runway. The use of the semi-central starting locations might be efficient for the aircraft operation, as the aircraft can be easily positioned at the remote stand after which they can continue the ground idle procedure. The positions are still relatively close to the piers, which keeps the the risks associated

Figure 16: Location of the Echo and Papa buffers at the AMS airport grounds

Figure 17: Location of the Echo and Papa buffers at the AMS airport grounds (zoomed in)

with remote starting remaining low. In case technical complications or problems in the cabin or cockpit occur, the aircraft can return to the pier fairly quickly, where in turn the aircraft can be unloaded and the (technical) complications can be resolved. In order to move the cold start of the aircraft to a remote starting location, tow trucks (e.g, TaxiBots) should be deployed to help taxi the aircraft from the aircraft stand at the pier to the remote starting position.

Both examples of semi-central starting locations also have their own advantages and disadvantages with regard to the implementation of a 'water droplet'-based ultrafine particle mitigation system. The Echo buffer is a more difficult alternative to implement as several aircraft stands need to be sacrificed when this platform is used as a remote starting location. Positions D88, D90, D92, D93, D94 and D95 (as can be seen in figure 17), which are located south of the E-buffer, cannot be deployed as aircraft stands due to the risk of a second push-back (interview Senior Process Advisor (OPS), appendix F.10). Besides this, there is a mandatory taxi direction for the aircraft to leave the bay after the cold start. The E-platform is also still located relatively close to the piers and terminal, which does not prevent the development of UFP concentration accumulations at the covered and wind-free areas. These aspects may affect the effectiveness of combating the problem when no other mitigation strategies, such as producing water droplets to capture the ultrafine particles, are implemented.

The P-platform seems to be an ideal remote starting location, as the aircraft can taxi forward through this buffer. The fact that aircraft do not have to make a turn there could save a lot of time and effort. The nose of the plane can be turned to both directions at the Papa buffer, which makes it possible to combat the production of ultrafine particles on both sides of the platform in a future scenario. As previously discussed, this buffer is currently mainly deployed as a parking position for inbound aircraft after an early arrival at AMS. This could imply that there is potentially not enough start-and-go capacity available for the remote cold start of aircraft when the function of an inbound buffer is preserved (interview Senior Process Advisor (OPS), appendix F.10). In a potential situation where the buffer is assigned both the function of inbound buffer as well as the function of remote starting location, inbound and outbound air traffic flows will mix at this location. This might not be a desirable situation and thus needs to be taken into account when analysing potential implementation strategies.

Central starting locations

While the semi-central starting locations are still located fairly close to several piers of the AMS terminals, the alternatives in the category 'central starting locations' are generally located further away from the piers. Stakeholders from different departments at Royal Schiphol Group suggested some locations at the airport grounds that might have potential to offer remote, centralized starting positions (appendices F.10, F.12 and F.14). North-west of the airport building the remote deicing platform of KLM and the Juliet(J) platform are located, which can be seen in figure 18. In figure 19, the potential remote starting positions of the platforms are better visible: spots P10, P12, P14 and P16 for the remote deicing platform and positions J80 up to J87 for the J-platform.

In terms of location, both platforms are mainly conveniently located for the aircraft that are positioned at the F-, G- and H-piers and/or that are departing from the Zwanenburgbaan or the Polderbaan. There is a lot of space at the platforms, which makes it easy for the aircraft to turn. As the deicing procedures for a substantial share of aircraft take place at the deicing platform during the Winter, water tanks, drainage, and other spraying facilities are already available here throughout the year. In a potential future situation where water droplet production equipment is deployed in order to mitigate aircraft-produced ultrafine particles, there might already be sufficient water storage and drainage capacity at the remote deicing platform to implement such a system (interview Senior Process Advisor (OPS), appendix F.10).

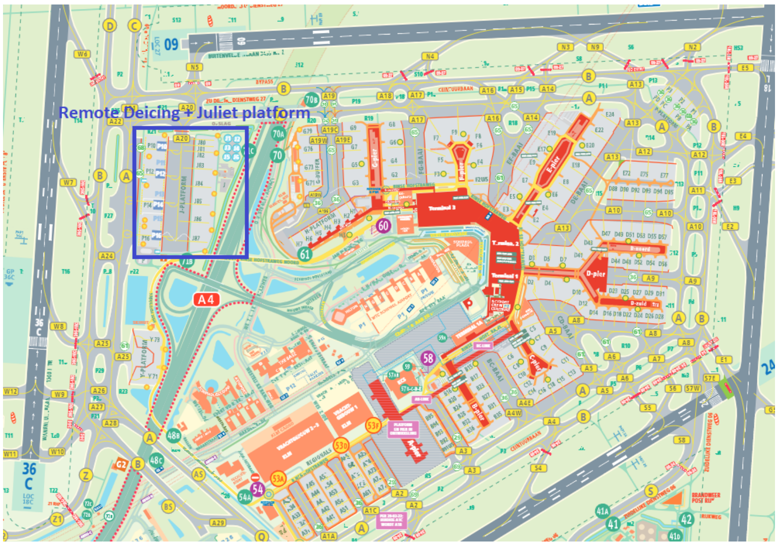

Figure 18: Location of the remote deicing platform and the Juliet platform at the AMS airport grounds

Figure 19: Location of the remote deicing platform and the Juliet platform at the AMS airport grounds (zoomed in)

However, these remote starting locations are located further away from most piers and from the runways on the eastern side of the airport building, which means that aircraft need to be towed or have to taxi longer from the aircraft stand at the pier to the dedicated remote starting position. Besides the taxi times, the response time and eventual presence of security and technical services in case of aircraft complications might also take longer. The capacity of the remote starting locations is also seasonal and dependent of the weather conditions, as the deicing procedures need to be executed when aircraft are operating at temperatures under 0 degrees Celsius. When the deicing facilities need to be used, the capacity for remote starting is much lower at these locations, which probably makes it necessary to deploy other remote starting positions in order to facilitate all aircraft.

Starting at the head of the runway

The last category of potential remote starting locations at AMS is starting the aircraft engines at the head of the dedicated runway. A remote starting position at the head of the runway where the aircraft will depart from means that the aircraft will be towed from the aircraft stand at the pier up to the runway. These potential remote starting positions for the AMS case are visualised for each runway, including the direction(s), in figure 20. The main advantage of this category of remote starting locations is the fact that the cold start of the jet engines will be paired with the least amount of safety and health risks for (platform) employees, as well as the least amount of nuisance for other airport processes. The harmful emissions that are produced by the aircraft are now blown into the open field instead of directed to the terminals, which reduces the potential hazards for the employees involved.

However, moving the cold start from the aircraft stands to the runways also results in moving the UFP concentration accumulations from the covered and wind-free areas close to the airport building to the open field. The ultrafine particle concentration accumulations in the undeveloped airport grounds induce a negative impact on the quality of the (living) environment and on the health and safety of residents in neighboring areas. Besides this, as the remote starting locations that are located the furthest away from the pier, there are probably more risks regarding accidents and (technical) complications associated with warming up the engines at the runway.

The long taxi distances that need to be travelled by the tow truck/TaxiBot are accompanied by a significant increase in taxi times before the aircraft is positioned at the runway. This has a substantial impact on the starting capacity of Amsterdam Airport Schiphol, as longer turnaround times lower the initial amount of starting aircraft (interview Process Owner Aircraft (OPS), appendix F.14). In order to tow the next aircraft that is already positioned at the aircraft stand at the pier, the TaxiBot or tow truck needs to return from the runway all the way to the bay, which can be quite some distance at AMS.

Figure 20: Remote starting positions at the head of the runways

Interviews with a Senior Environmental Advisor from the department of Safety, Security & Environment (SSE) at Royal Schiphol Group stated the importance of taking the relevant (EASA) rules and regulations at the airport grounds into account while analysing remote starting locations (appendix F.12). The amount of these EASA regulations, that the system needs to comply with, increases with the distance that the aircraft operation moves further away from the terminal, which means that it peaks on the runways. The risks that are related to electronics and technology, for the aircraft with crew and passengers as well as for the direct (living) environment, might make it harder to implement this new remote starting strategy at the head of the runways. Remote starting positions at the head of the runways shows some interesting advantages, but the impact on the quality of the environment, on the starting capacity of AMS, and on the amount of (EASA) regulations make it a difficult alternative to implement.

5.2.3 Alongside the taxiways

The airport infrastructure that is dedicated for the ground idle procedures are the taxiways between the bay and the runways. Amsterdam Airport Schiphol is an airport with a wide layout, which means that the length of some taxiways can be rather long and that the distances that are covered during ground idle might be significantly higher for the operation of certain aircraft. As mitigating the production of ultrafine particles during ground idle procedures might be just as important as UFP mitigation during the cold start, it could be of added value to analyse the areas alongside the taxiways as potential locations for 'water droplet'-based mitigation systems.

Although it may be the most efficient to install water droplet production equipment alongside all taxiways on the airport grounds, the construction, maintenance and operational costs for the implementation of such a system will be immense. It is also a logistical challenge to let the water droplet cloud move along with all the operating aircraft, besides making sure that the right amount of water is available to spray at the right place and the right time. Not only the water supply is hereby of importance, but also the water storage, drainage and potential filtering are all aspects of the system that need to be determined beforehand. An advisor in Stakeholder Strategy and Development (department S&AP at RSG) rightly pointed out that Royal Schiphol Group is currently already investing substantial resources into research with regard to sustainable taxiing, as well as the purchase of sustainable tow trucks (TaxiBots) (appendix F.11). Implementing UFP mitigation strategies alongside the taxiways, which is the infrastructure where the ground idle procedures take place and where RSG is planning to implement sustainable alternatives in the future, thus seems less essential and not compatible with future strategies.

5.2.4 At the runways

The collection of runways at AMS is the infrastructure that is dedicated to facilitate the LTO processes at the airport grounds. The runways are mainly surrounded by undeveloped infrastructure, mainly lawns, which means that the jet blast during take-off is directed to the open field. Several professors with expertise in airport operations state the importance of taking the position of the aircraft during the UFP mitigation process into account: the back of the aircraft should be facing the open field (lawns) to ensure that not all the produced water will be blown towards the taxiways and other airport infrastructure (appendices F.1, F.5 and F.7). Implementing a 'water droplet'-based ultrafine particle mitigation system at the runways thus seems like an interesting configuration as it does not interfere with other airport processes and it does not seem to create any disturbances on the used airport infrastructure.

A system that is dedicated to facilitate the mitigation of UFP at the runways can be implemented in several configurations. Firstly, a system can be designed with which the production of water droplets moves alongside the departing aircraft. The water droplet production equipment is installed next to, or integrated in, the infrastructure of the runways, or at least that part of the runway that is relevant for the departure of the aircraft. This UFP mitigation strategy could be an efficient and effective solution to combat the aircraft-produced ultrafine particles, due to the water droplet cloud moving along with the departing aircraft and only being present at that part of the runway where the mitigation must take place.

A second system alternative for ultrafine particle mitigation at the runway focuses on combating UFP at the start of the runway, during that part of the LTO process where the aircraft engines are switched to full power. A researcher from TNO, with expertise in, among other things, (nano) particles and atmospheric composition, discussed the potential of a system where a water droplet cloud is produced just outside of the "safe zone" of the aircraft during the start of the take-off on the runway (appendix F.6). The jet blast from the engine start at the runway is known for its strong wind forces and high turbulence, which decrease at a certain location when the distance from the jet engines increases. The vortex from the engines is known to be strong and stable, which means that its characteristics stay the same for a relatively long distance. The emissions in the vortex are still concentrated after a significant distance, which means that high UFP concentrations can still be measured and eventually encapsulated by the produced water droplets at that distance. However, the mitigation system should not be placed too far outside of the aircraft's safe zone as the effectiveness of the system will reduce significantly after a certain distance.

Although the mitigation of ultrafine particles at the runways seems like an interesting and well-fitting solution, some critical side notes need to be discussed as well. Constructions on the runways and the surrounding (undeveloped) infrastructure can be associated with safety risks regarding potential collisions between the aircraft and the placed installations. Operating the aircraft at higher speeds on the runways is accompanied by stricter EASA regulations with regard to safety, i.e.: the first 40 meters on both sides of the middle line of the runway need to be obstacle-free and constructions/equipment that are placed outside of this "safe zone" must be able to break down easily to minimize the damage in case of a collision with an aircraft (interview Senior Environmental Advisor (department SSE of RSG), appendix F.12). These regulations put restrictions on the potential design of the UFP mitigation system when it is going to be implemented close to the runways, which might result in not being able to choose the most effective and efficient system for AMS. Besides this, the descended water droplets with captured ultrafine particles have a bigger chance to end up in the lawns and the natural environment, which makes the water much harder to collect for potential filtering and reuse. In order for Amsterdam Airport Schiphol to become circular and more sustainable, collecting the polluted water and not letting it end up in the environment is of great importance.

5.2.5 Conclusion

Several potential locations where a 'water droplet'-based UFP mitigation system could be implemented have been discussed in the previous sections of this chapter. The eventual location to combat aircraft-produced ultrafine particles during the operation will depend on the processes during which the system is decided to be deployed. As these two system design components are strongly associated with each other, it is currently too premature to conclude the most optimal location. All the advantages and disadvantages of the potential locations, as well as the insights and knowledge from the several stakeholders, will be taken into account when deciding on this component of the conceptual system design in chapter 6.1.

5.3 Way of mitigating UFP

Besides determining the moment(s) and the location(s) of the deployment of the ultrafine particle mitigation system, the configuration and the operational aspects of the system need to be determined as well. As the creation of the water droplet screen/cloud is the pivot of the system, investigating the available production equipment alternatives is of great importance. The mitigation strategy, based on combating the dispersion of UFP and the formation of UFP concentration accumulations across the airport grounds, is not coming from extensive scientific research but is based on completely natural principles. After the ultrafine particles leave the jet engines as a product of the combustion process, their fate is controlled by several processes, i.e., coagulation, turbulent mixing, condensation-evaporation, and wet and dry deposition (Andronache et al., 2006), which has previously been discussed in chapter 3.1.

The whole reasoning behind the potential UFP mitigation strategy can also be described in the following way. UFP as a product of the combustion process is airborne and will quickly disperse through the air above the airport grounds. Ultrafine particles and clumps of UFP (conglomerates) can be captured in tiny water droplets, wherein they might further interact with each other. A professor from the University of Twente, with expertise in the interaction between (nano) particles and droplets and their behavior during evaporation/drying processes, stated in an interview that once an ultrafine particle has interacted with a water droplet, it will stay inside of that droplet as it is almost impossible for the particle to exit (appendix F.9). Water droplets that have interacted with (clumps of) UFP are initially airborne but will eventually descent to the ground, as long as the droplets do not evaporate. Wet deposition of UFP might thus lead to lower concentrations and implementing mitigation strategies that contribute to this process are interesting to investigate and potentially implement at AMS.

In chapter 3.4, a few providers of such equipment and the product alternatives that they offer have already been briefly mentioned. Water droplet (mist) production equipment is currently mainly used as a solution for dust control/suppression in the construction and quarrying industries, but is proven to also be effective in combating the formation of fine particle concentrations (Erkho BV, 2022). Most providers in the dust control sector offer relatively similar products, which can be subdivided into two main equipment categories: water spraying cannons and water pipes with spraying nozzles mounted onto them. These categories also offer alternative configurations for the mitigation of UFP, which will be presented in the following subsections.

5.3.1 Water spraying cannons

Technical aspects
The operation of so-called 'water spraying cannons' is based on the technique of guiding the water supply through a powerful turbo-fan, which produces a turbulent airflow containing fine water droplets. This plume is blown into the air to effectively suppress dust and/or (ultra)fine particles over wide areas, preventing further dispersion into the environment (Corgin, 2022). The design of the spraying cannons itself has a lot of similarities between the several equipment providers, and can usually be described as follows: a metal tube/cut off cone, which is mounted onto a platform, with a turbo-fan on one side of the cannon and a ring-shaped water pipe with nozzles mounted onto it on the other side. Examples of water spraying cannons are displayed in figures 21 and 22, which visualise the ring-shaped water pipe with nozzles on the front and the turbo-fan on the back respectively.

Alternatives
As the essence and design of the water spraying cannons has been discussed, the several alternatives of this category of water droplet production equipment can be presented. On the websites of the providers a wide range of spraying cannons is offered, mainly varying in the spraying distance potential of the cannons, as well as in water

Figure 21: Example of spraying cannon - front (MB Dustcontrol, 2022d)

Figure 22: Example of spraying cannon - back (Yugong Machinery, 2022)

usage, the spraying surface, the number of nozzles, etc. (e.g., https://www.mb-dustcontrol.com/products#products-category-1, https://www.airspectrum.com/systems/dust-suppression/dust-cannon-range/, and https://www.corgin.co.uk/products/dust-and-odour-suppression/mist-cannon/mist-cannon). The spraying distance potential, under wind-still circumstances, ranges between tens of meters and a current maximum of 150 meters. The spraying distance of the cannons can be varied by adjusting the pressure on the nozzles, the water supply, the rotation speed of the fan, etc. Besides the technical aspects of the equipment, the mounting construction of the spraying cannons also widely varies. The cannons can stand-alone by themselves, but they can also be mounted onto trucks, (moving) platforms and even walls/ceilings. A collection of water spraying cannon configurations is presented in figures 23, 24, 25, and 26.

Figure 23: Stand-alone SprayCannon on platform (MB Dustcontrol, 2022b)

Figure 24: SprayCannon mounted onto tank trailer (MB Dustcontrol, 2022c)

A stand-alone spraying cannon, which is mounted onto a platform on wheels and can be moved as a trailer behind a car/truck, can be seen in figure 23. The water supply for the creation of the water droplet plume is managed by attaching the spraying cannon via hoses/pipes to a local water supply point. This type of spraying cannon can be placed on undeveloped infrastructure (lawns) at dedicated locations, where there is a water supply point and where the construction does not interrupt the airport operations. In this case, the platform on wheels can be replaced for a construction integrated in the infrastructure. Instead of the water output of

Figure 25: SprayCannon mounted onto truck (MB Dustcontrol, 2022f)

Figure 26: SprayCannon on mast - movable (MB Dustcontrol, 2022a)

the spraying cannon being attached to a fixed water supply point, the water supply can also be provided by a refillable water tank mounted onto a trailer (figure 24). This configuration takes up a relatively large amount of space and can be of visual and spatial nuisance, but it might be a convenient alternative to implement at locations where there is no fixed water supply point available. However, the tank needs to be refilled relatively often for operational purposes that require a lot of water usage. A moving alternative of a spraying cannon attached to a water tank can be seen in figure 25. A truck with a spraying cannon and water tank is a lot more flexible, as it can move along with the produced emissions and thus switch operational locations. The downsides of this alternative are the fact that it imposes safety risks for the truck driver due to potential collisions between the aircraft and the truck (interview Senior Environmental Advisor (department SSE of RSG), appendix F.12), as well as the need to refill the water tank relatively often due to intensive water usage during the operation. Another variation of the spraying cannon is shown in figure 26, where the cannon is mounted onto a hydraulic mast that is placed onto a platform with tracks underneath. This configuration of the spraying cannon alternative is very versatile, as it is adjustable in multiple dimensions: the tracks underneath make it possible to move to different locations and the mast enables the spraying cannon to customize the height and spraying angle.

Potential implementation for UFP mitigation at AMS

The potential implementation of spraying cannons for the mitigation of aircraft-produced ultrafine particles during the operation at Amsterdam Airport Schiphol has been discussed with stakeholders within the organisation of Royal Schiphol Group, other stakeholders within the aviation industry and with experts from different relevant disciplines (appendix F). Several stakeholders have addressed the question whether the water droplets need to be directed into the jet engines during the operation, or whether the water droplet cloud should be placed further away from the aircraft to maximize the effectiveness of this mitigation strategy. A professor from the faculty of Aerospace Engineering at Delft University of Technology (TUD) argued that it is probably necessary to spray the water droplets into the core of the jet engines to make sure that the ultrafine particles have the best chance to interact with the water droplets (appendix F.1). A safety consultant from KLM also stated that the spraying system should be compatible with the jet engines for every type of aircraft to guarantee that a directed water droplet cloud reaches the core of the engines (appendix F.2). Water spraying cannons might be a well-fitting solution in the situation where it is determined that the water droplets should be directed into the jet engines as they are relatively easily adjustable, as well as the spraying angle and direction. There will be elaborated upon this discussion in chapter 5.4.1.

5.3.2 Water pipes with spraying nozzles

Technical aspects

Another form of equipment that can be deployed to mitigate the concentrations of UFP at the airport grounds is based on water pipes with spraying nozzles mounted onto them. The water pipes are similar to fire hoses that can differ in diameter and have special exchangeable nozzles and supports that make it possible for the produced water droplets to reach every corner of the dedicated spraying area (Environmental XPRT, 2022). MB Dustcontrol offers this type of equipment as the so-called 'SprayWall NM20', which is shown in figure 27 (MB Dustcontrol, 2022g). The black blocks underneath the hose are the supports that help position the SprayWall.

Figure 27: SprayWall (Scott Vickers, 2022)

On the left side of the figure it is visible that the SprayWall is attached to a normal water hose, which in turn is connected to a water supply point. The maximum pressure on the hose can result in a water droplet "wall" up to ten meters high and the separate hoses, with a length of 20 meters, can be attached to each other so a wide droplet screen can be created.

Alternatives

In this water droplet production equipment category there are not infinite alternative configurations available as the essence of this mitigation strategy is to create a water droplet screen by stretching the water hose(s) in one straight line. In figure 27 it is visible that the water hose is placed onto the infrastructure, which makes the SprayWall protrude around eight centimeters from the ground. This is inconvenient for the aircraft operation and might impose safety risks for the aircraft (including crew and passengers) when it taxis over the hose(s). A better fitting UFP mitigation system at the airport might be achieved by integrating the water hoses with nozzles into the airport infrastructure, without parts of the system protruding above the surface causing physical and visual hindrance for the aircraft. However, maintenance is much more difficult for this alternative as the hoses and nozzles cannot be reached as easily as when they are above the ground. It can be expected that the wear and tear level of the system is fairly high as it has to endure excessive amounts of water and all kinds of weather conditions throughout the year, which increases the necessity of regular maintenance.

A configuration of the system where the SprayWall is mounted onto a construction above the ground has also been discussed during several stakeholder interviews (appendix F). A TUD professor from the faculty of Aerospace Engineering, with expertise in flight performance, propulsion and flow physics, argued that these overhead water spraying installations should be implemented over all the taxiways in order to retrieve the most optimal UFP mitigation system (appendix F.7). The idea of these overhead SprayWalls is similar to the operation of showers that spray the water droplets down, creating a slowly descending water droplet cloud. A potential configuration of such a system is shown schematically in figure 28. The angled line in blue represents the construction on which the water hose is mounted, with the red dots being the spraying nozzles.

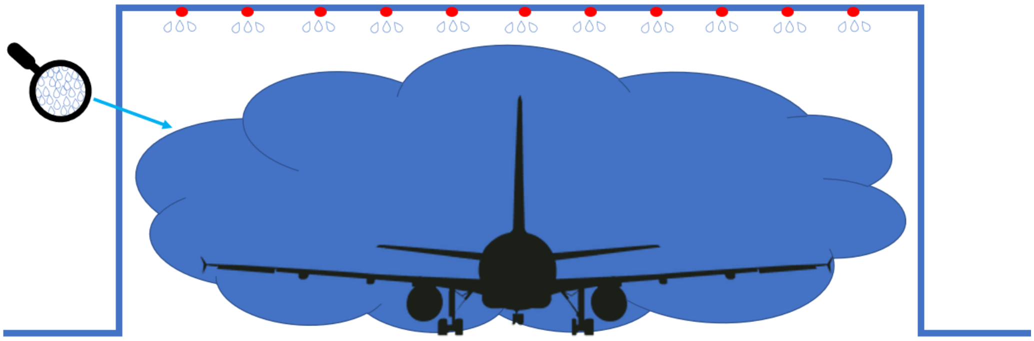

Figure 28: System configuration of overhead SprayWall

A direct advantage of an overhead SprayWall, in comparison with the deployment of water hoses with spraying nozzles on the ground, is the lower pressure on the hose(s) and the nozzles that is required for the system operation. The water droplets do not have to be sprayed into the air, but can descent to the ground by means of gravity. The lower required pressure results in less energy consumption needed for pumping the water from the supply point through the hose(s), as well as significantly less water use needed for the creation of the droplet screen (interview researcher from TNO, appendix F.6). Besides this, the overhead spraying installation might be a better fitting configuration in a situation where a significant share of the jet blast from the aircraft engines blows over the water droplets produced by the original SprayWall. The air that would normally blow over the initial configuration of the SprayWall, and would mix with the "filtered" air, will now have opportunities to interact with the water droplets. However, the construction of the overhead configuration of this system imposes some disadvantages regarding the implementation at the airport grounds as well. The construction on which the water hoses are mounted will cause visual and physical nuisance at the airport grounds, with risks of aircraft colliding with the system during the operation. Besides this, it is most likely that the wear and tear level of the system will be high due to exposure to all kinds of weather conditions throughout the year and to large amounts of water. The overhead SprayWall will thus impose high potential costs with regard to regular maintenance, and to safety and reparation in case of an impact.

Potential implementation for UFP mitigation at AMS

The implementation of the water hoses with nozzles mounted onto them, also called SprayWalls by the equipment providers, has also been discussed with the involved stakeholders during the analysis of potential aircraft-produced UFP mitigation strategies. Discussions with several stakeholders addressed the operational benefits of this solution space, as the adjustment of the water droplet production equipment to create the right dimensions is more straightforward (appendix F). The water droplets should at least be distributed over the complete cross-section of the aircraft vortex, which is accomplished more efficiently when a single droplet screen is produced, instead of droplet clouds from multiple sides. SprayWalls cannot directly spray water droplets into the aircraft engines, as their usual configuration creates a vertical cloud when looked upon from the side. This configuration of a 'water droplet'-based UFP mitigation system design might be a well-fitting solution in the situation where it is determined that it is more efficient and effective to let the ultrafine particles from the jet engines interact with the water droplets at a certain distance from the aircraft. As mentioned in the previous section of this chapter (5.3.1), the debate whether the water droplets need to be sprayed into the core of the jet engines or whether a water droplet cloud needs to be produced further away from the aircraft has not yet resulted in consensus. The elaboration upon this discussion can be found in section 5.4.1 of this chapter.

5.4 Ultrafine particle mitigation system design boundaries

This section of the research is dedicated to the requirements analysis, which is necessary to set the system design boundaries for the analysis of the several components with which eventually a conceptual system design will be assembled. Each design project should incorporate an overview of the set requirements to be able to substantiate the chosen design alternatives, as well as those that were omitted. All necessary requirements for a potential 'water droplet'-based ultrafine particle mitigation system are drawn up by using the academic knowledge gathered from the literature review (chapter 3) and the case study at AMS (chapter 4), as well as the gathered insights and ideas from the stakeholder interviews with experts in the field (appendix F). The analysis of the collected data resulted in the choice to use three overarching categories into which the relevant system design requirements could be subdivided. The operational requirements for the system are discussed first in section 5.4.1, after which the requirements that are associated with safety are presented in section 5.4.2. A collection of other relevant requirements is discussed in section 5.4.3.

5.4.1 Operational requirements for ultrafine particle mitigation

This section will present the operational system design boundaries that were drawn up as a result of the requirements analysis. These requirements are associated with the operations of the potential UFP mitigation system, which include the creation of interaction opportunities between water droplets and ultrafine particles, the use of water for the deployment of the system, and the relevant meteorology and weather conditions. Besides these operational requirements of the system itself, a few requirements regarding the impact of the system on the aircraft operation at the airport are also provided.

Creation of opportunities for water droplets-UFP interaction

The debate whether water droplets should be sprayed directly into the core of the jet engines or whether the water droplet cloud should be created further away of the aircraft for the mitigation of ultrafine particles has been raised during most of the stakeholder interviews (appendix F). A professor from the University of Twente, with expertise in the interaction between (nano) particles and droplets and their behavior during evaporation/drying processes, stated that the essence of the system should be to create as many opportunities for the water droplets to interact with the aircraft-produced UFP as possible (appendix F.9). The ultrafine particles that are collected in a water droplet will eventually clump together, which results in conglomerates. These large clumps of particles will eventually descent to the ground once the water droplet is evaporated, which results in less associated health risks than those of airborne particles. He also mentioned that the effectiveness and the efficiency of the system is dependent of the aerosol particle concentrations in the air: the goal is to collect as many ultrafine particles per water droplet as possible, which can be realized by spraying the water droplets in the area where the highest concentration of UFP is present.

In order to create more opportunities for the water droplets to interact with the ultrafine particles, the air circulation behind the aircraft is also of great importance (interview professor from University of Twente, appendix F.9). The flow of the water droplets need to be engineered in such a way that it collides more efficiently with the ultrafine particles flow, as a perfect mix between the flows in the field cannot be taken for granted. Motion is necessary for the ultrafine particles to reach and interact with the water droplets, but the wind also dilutes the ultrafine particle concentration in the air. The currents need to be mixed, as the usual air flows in the open field are not complex enough. The vortex from the aircraft engines should be able to take care of this, as the turbulence and whirlwinds behind the aircraft are of a complex nature. It is thus of importance to spray the water droplets into the jet blast and create a droplet cloud/screen that at least covers the cross-section of this vortex.

The system performance is also affected by the size of the used water droplets for the UFP mitigation. Relatively large water droplets, such as raindrops, have a significant mass which will result in them falling to the ground with a considerable speed. This droplet size is not ideal for the deployment of a mitigation system to capture ultrafine particles, as the water droplets will descent to the ground as soon as they are produced by the spraying devices. Due to this falling velocity and the short time they are present in the air, the number of interaction opportunities is very limited. Several stakeholders addressed that the water droplets should therefore be relatively small to keep them airborne as long as possible (appendices F.6 and F.9). However, the use of very small water droplets (i.e. mist) will most likely cause a counterproductive effect, as the water droplets with captured (clumps of) UFP will stay airborne for a very long time. As one of the objectives of the mitigation system is to "wash away" the particles from the air, it is of importance that the water droplets, with as many captured particles as possible, will eventually descent to the ground to be collected. The most ideal water droplet size, which is slightly bigger than mist droplets, thus needs to create many interaction opportunities with UFP while remaining airborne for a significant amount of time.

Another strategy to create more opportunities for droplet-particle interaction is to increase the evaporation time of the water droplets, which is usually realized under high relative humidity conditions. The droplets produced by the system should remain a liquid for as long as possible in order to be able to encapsulate many ultrafine particles (interview professor from University of Twente, appendix F.9). The relative humidity in the Netherlands is usually very high, as will be further elaborated in the third sector of this chapter. A recent study from Seyfert, Rodríguez-Rodríguez, Lohse, and Marin (2022) investigated the impact of adding salt to respiratory-like droplets on the evaporation dynamics of these droplets in the air, under different relative humidities (H_r). Their findings stated that adding a small amount of salt (sodium chloride) to the droplets results in them staying in liquid form for a longer time, as the evaporation time of the droplets is slowed down significantly. This is a completely natural solution, as this is also the reason why respiratory aerosols remain in a liquid state for a long time after having entered the human body. The pH-value is the same as the human body, so there is no adverse impact on health and safety regarding the implementation of this complementary strategy. By keeping the H_r high and the temperature relatively low, the number of opportunities for condensation of particles and absorption in water droplets increases (interview with professor from University of Twente, appendix F.9).

Conclusion:
The performance of the potential system to combat aircraft-produced UFP by using water droplets depends on the adjustment of several system characteristics that might increase the number of interaction opportunities between the particles and the droplets. The water droplets should encapsulate as many (clumps of) ultrafine particles as possible, which can be achieved by having complex air flows, using droplets with the most optimal size, creating a higher evaporation time and spraying the droplets in the areas with high UFP concentrations. The system needs to enable the ultrafine particles to stay encapsulated inside the water droplets and needs to make sure that the droplets do not evaporate before reaching the ground, once the descended water has been collected. All relevant operational requirements associated with the performance of the 'water droplet'-based UFP mitigation system are presented in table 7.

Table 7: Operational requirements for system performance

Category	1	Operational requirements
Constraint	1	The system must create as many opportunities for the UFP to interact with the water droplets as possible.
Requirement	1	The water droplets should be sprayed in the area with the highest concentration of UFP.
Requirement	2	The air flows behind the aircraft should be complex and turbulent.
Requirement	3	The evaporation time of the water droplets should be as high as possible.
Requirement	4	The water droplet cloud should at least cover the complete cross section of the jet blast.

Operational use of water for the UFP mitigation system

The operation of the water droplet production equipment, for the mitigation of ultrafine particles during the aircraft operation, will be accompanied by the use of excessive amounts of water. According to the websites of the equipment providers and the calculations of researchers at TNO, the water consumption of the in chapter 5.3 presented apparatus is at least 10,000 litres per hour. During the stakeholder interviews, the water supply was an often discussed topic. Mainly in the discussions with people from several departments at Royal Schiphol Group, the various requirements and aspects involved in determining the water supply source were a reoccurring topic. Discussions with someone from the department of S&AP, who is also part of the 'Taskforce UFP Mitigation' at RSG, resulted in an overview of the various potential water supply sources that are available for the system (appendix F.11). Using drinking water for the production of water droplets, so connecting the system to the Dutch network of water pipes, is probably the most appropriate way of mitigating UFP at the airport. Implementation should be relatively easy, as Amsterdam Airport Schiphol is already connected to the network of water pipes in the Netherlands and has sufficient water supply points. Besides this, the use of clean, filtered water is also the safest for the quality of the environment and the health of the (platform) employees. However, the use of drinking water for this purpose can most likely count on a lot of resistance from external parties, as the Netherlands has just recovered from a nationwide water shortage (Rijksoverheid, 2022). As the shift from an impending to an actual water shortage can become a reality with a next period of drought, the perception of external stakeholders (e.g., Rijkswaterstaat, the water boards, the ministries concerned, etc.) on the use of this water supply at AMS is not positive.

Other categories for potential water supply sources are ground-, surface-, and industrial water, which have approximately the same characteristics and aspects. Without filtering, the use of this water to create droplets for the mitigation will most likely be accompanied by a lot of opposition from (platform) employees working on the airport grounds, residents of the neighbouring areas, and environmental activists (appendix F.11). This is due to the fact that unfiltered water from the ground or surface, as well as water as a waste product of the industry, has a filthy and unhealthy/unsafe image. Besides the health aspect, the potential impact on the operational use of the mitigation system is also of importance when considering the use of water with this quality. A Sourcing Manager from the department of Procurement & Contracting (PC) at RSG mentioned that not only (chemical) waste can be present in the water, but it can also contain larger particles (e.g., dirt and sand) that can cause blockages in the nozzles of the water spraying equipment and can eventually cause damage to the apparatus (appendix F.13). Filtering seems necessary to be able to use this water for the UFP mitigation purposes, which automatically implies additional investments and construction challenges for the potential implementation of the system.

Rainwater might be the most interesting water supply source to investigate, as using this water does initially not require any filtering or the need for using the drinking water supply. On average, there is about 900 millimeters of precipitation in the Netherlands every year, which offers the potential of collecting a significant volume of rainwater on and around the airport grounds of AMS (Koninklijk Nederlands Meteorologisch Instituut, 2021). Schiphol is not new with the sustainable concept of using rainwater, as it is currently building Pier A, of which the toilets will be flushed by using rainwater (Schiphol, 2022b). The use of collected rainwater for the production of water droplets to combat aircraft-produced ultrafine particles will most likely receive sufficient support from internal and external stakeholders, as it is the most sustainable solution. However, the implementation of an additional system to collect the rainwater and take care of the water supply for the mitigation system requires a lot of investments and construction challenges. Besides this, extensive calculations and analyses must be carried out to guarantee that the collected rainwater supply meets the necessary amount of water for the system, as additional water supply from other sources might be needed.

Conclusion

As the operation of the aircraft-produced ultrafine particle mitigation system at the airport is based on the use of water droplets, the search for the most optimal water supply source for this system is essential. Quite a wide range of water supply sources is available at the airport to connect to the mitigation system, which all have their own operational advantages and disadvantages. The water provision should be sustainable and socio-economically accepted by the airport community and by external stakeholders, and the need for (re)collection and filtering facilities should be analyzed thoroughly. In table 8, all requirements, that the potential source for the water supply of the UFP mitigation system must meet, are presented.

Table 8: Operational requirements for water supply

Category	**1**	**Operational requirements**
Constraint	**2**	The water supply source must result in the most optimal system, in terms of filtering, health and investments.
Requirement	**1**	The water supply must originate from a socio-economically accepted source.
Requirement	**2**	The water supply must originate from a sustainable source.
Requirement	**3**	The used water must be collected for reuse (as much as possible).
Requirement	**4**	The collected water should be filtered before reuse.

Meteorology and weather conditions

Meteorology and the weather conditions at the airport might also have an impact on the establishment of functional requirements that need to be met by the 'water droplet'-based UFP mitigation system. Weather aspects such as temperature, humidity, wind and forms of precipitation all might affect the efficiency and effectiveness of this system, and certain conditions might even result in the system not working at all. Almost all interviewed stakeholders addressed the importance of taking meteorology and the weather conditions at the airport into account (appendix F), which resulted in the following overview.

A first weather aspect that will be discussed is the outside temperature during the deployment of the potential system. Even though the temperatures at Amsterdam Airport Schiphol will not be that extreme throughout the year, it is important to take the potential extremes into account. Experts in the field of meteorology rightfully stated that temperatures under zero degrees Celsius will eventually result in the freezing of the produced water droplets, which might create a problem on the used infrastructure of the airport. It cannot be afforded that aircraft or other processes at the airport are limited in the operation due to the formation of ice and it is therefore important to establish design principles of the system that take the prevention of icy and slippery run- and taxiways into account. Such a design principle can thus be that the 'water droplet'-based UFP system should not be used when the temperature at the airport grounds is below zero. An adjustment to the system that might make it operational during freezing temperatures is applying deicing techniques to the process: the addition of additives to the spray-water in order to lower the freezing point. However, an extra design principle will be involved here, as the water should not become toxic and create health and safety hazards for the environment and (platform) employees. The other extreme to this weather condition spectrum is high temperatures at the airport, which may result in a relatively faster evaporation of the small water droplets. However, for the evaporation of water droplets a lot of energy is needed and therefore relatively high outside temperatures will have (almost) no effect on the evaporation speed of these water droplets. A design principle in case there are high temperatures at the airport during the aircraft operation is thus not necessary.

Another weather aspect that has an impact on the evaporation rate of water droplets, and thus might impact the performance of the UFP mitigation system, is the relative humidity. The average humidity in the Netherlands is around 80-85%, which is very high (AirSain, 2022). The relative humidity at AMS will affect the effectiveness of the technique that is based on capturing ultrafine particles by using water droplets. At Copenhagen Airport (CPH), lower concentrations of UFP were measured during weather conditions with high relative humidity (Interview with Head of Sustainability of CPH, appendix F.4). At a high relative humidity, were (near) mist conditions are applicable, the concentration level of UFP at the airport grounds might already be much lower than during the average conditions. A professor with expertise in (nano) particles-droplets interaction mentioned that in high relative humidity conditions of $\geq 75\%$ droplets will not naturally evaporate anymore, as the vapour pressure of the droplets is reduced in these conditions (interview professor from University of Twente, appendix F.9). No design principles that incorporate the relative humidity at the airport have to be established for this system, as these weather conditions will only affect the effectiveness in a beneficial way.

Wind is also an important weather condition to take into account while creating a design of a potential UFP mitigation system. All experts in the aviation sector agree that windless conditions are optimal for the ultrafine particles to be captured by the produced water droplets, as the droplet cloud will stay at the dedicated position for a longer amount of time. Strong winds may blow the aircraft produced UFP over, under or beside the water droplet screen. The wind blows the water droplets across a large area, which is also visible during the current deicing procedures. However, both the UFP and water droplets will be blown away with the wind, which will give them enough time and space to create opportunities to interact with each other. According to this theory, no design principles that take the wind force into account are necessary to be established for this system.

Another weather aspect that might be important for the efficacy of a UFP mitigation system, based on the use of water droplets, is the presence of a certain form of precipitation at the airport. As Andronache (2004) proved in his study, falling raindrops contribute to a significant collection of UFP, which increases with the rainfall rate. Coagulation and rainfall scavenge the smallest forms of UFP in the most effective way, at all rainfall rates. Air pollution levels are generally moderately lower after rainfall, due to the direct washing effect of the rain (Kwak, Ko, Lee, & Joh, 2017). A side note here is that rain droplets are much bigger than the water droplets that are proposed to be used for the mitigation of ultrafine particles, which makes the total volume of the rainfall much lower than the volume of the to be used water droplet cloud in the same area. Many small droplets create a much higher volume with which the UFP can interact and result in a bigger effective area size. Precipitation will potentially complement the mitigation system, which results in lower UFP concentrations at the airport grounds. A design principle that incorporates natural precipitation therefore does not seem necessary at first glance.

Conclusion

From the conducted interviews it became clear that the impact of the weather conditions at the airport on the operating performance of the ultrafine particle mitigation system is one of the first points of attention of stakeholders when reviewing a system's potential. The temperature, the relative humidity, the wind and other forms of precipitation all influence the production of the water droplet cloud/screen in their own way. The few operational system requirements that can be related to meteorology and the present weather conditions are provided in table 9.

Table 9: Operational requirements regarding meteorology and weather conditions

Category	**1**	**Operational requirements**
Constraint	**3**	The system must take meteorology and weather conditions into account for the operation.
Requirement	**1**	The system shall not operate when the outside temperature at the airport grounds is below zero degrees Celsius (when using water without additives).
Requirement	**2**	The water droplets must not instantly evaporate when the outside temperature at the airport grounds is relatively high.

Impact on starting capacity and turnaround time

A reoccurring point of discussion, mainly during the interviews with stakeholders from the different RSG departments, was the importance of taking the impact of the UFP mitigation system implementation on the other airport processes into account. The aircraft operation requires very tight scheduling and flawless execution of the processes is necessary to guarantee a safe and profitable airport environment. As the analysis of potential mitigation moments in section 5.1 concluded, the implementation of a UFP mitigation system during the processes where the aircraft is positioned in a fixed position might result in the most optimal mitigation situation. In this situation, the aircraft might have to be positioned for a longer period as the mitigation strategy could require more time than scheduled for, for instance, the cold start of the engines. Especially in a future situation where remote starting locations are implemented for the cold start (section 5.2, the operation times of the aircraft at AMS might increase significantly. Interviews with a Senior Process Advisor (appendix F.10) and a Process Owner Aircraft (appendix F.14) from the department Airport Operations of Royal Schiphol Group provided insights regarding the potential impact of the implementation of UFP mitigation strategies on the starting capacity and turnaround times of the aircraft at AMS.

The Senior Process Advisor stated that the handling of the aircraft at AMS, in terms of starting capacity, will most likely not deteriorate due to the combined implementation of remote starting locations and the additional mitigation of UFP, perhaps it might even improve (appendix F.10). In the current situation, aircraft need to depart one after the other from the same aircraft stand at the pier, which means that the tow truck drivers are always waiting for a longer period of time than the duration of the actual pushback of the aircraft. The time that it takes for the tow truck to execute the pushback and return to the aircraft stand of the next aircraft in line is currently often accompanied by 10 to 12 minutes of waiting time. The current separation time between two departing aircraft is relatively spacious, which means that there are sufficient reserves available to use. In the potential future situation, aircraft are taxied further away from the bay to a (semi-)central starting position by the tow truck, after which the truck returns to the next aircraft stand at the pier. Due to the longer pushback procedure, the next aircraft is ready for handling and can be towed away to the remote starting position almost straight away.

This new 'cold start' strategy implies that the actual cold start of the aircraft engines at the remote position will be executed later than it would be in the current strategy, and the connection times of the push and pull procedures will be longer. However, the current waiting time of the tow truck before the aircraft can be taxied away from the stand is very dominant, which means that the time that is needed for towing the aircraft to the new remote starting position can compensate this waiting time. The increased towing time should basically fit in the available standby time between two consecutive aircraft, which means that this new aircraft handling procedure should not affect the starting capacity of AMS too much during a standard day. However, during a day when towing/taxi services are already lagging behind, the amount of standby time and thus the potential overtaking capacity might be limited.

From discussions with the Process Owner Aircraft from the OPS department at RSG, a less optimistic view on the impact of the potential UFP mitigation system implementation on the starting capacity of AMS was created (appendix F.14). The expectation from this person's point of view is that the starting capacity would decrease significantly, as the amount of available airport infrastructure and tow trucks (as well as their drivers) is currently already relatively scarce. The (semi-)central starting locations that were introduced in section 5.2.2 offer seven aircraft stands, without taking the Juliet-platform into account, while in the current situation there are sometimes even 60 aircraft stands at the piers in use at the same time. The Process Owner Aircraft mentioned in the interview that at least 15 remote starting positions should be available to maintain the starting capacity. The tow trucks are only operational on and around the aircraft stand near the piers in the current situation, while after the implementation of remote starting locations and the UFP mitigation they will have to travel quite far and are unavailable for a longer period. To maintain a successful system, multiple tow trucks ('taxibots') need to be deployed simultaneously, as no aircraft should be waiting at the stand until its pushback procedure can start.

In conclusion, the vision of the Process Owner Aircraft on the implementation of remote starting locations for the mitigation of UFP at AMS is that this will not be possible within the current airport capacity (F.14). She addresses a first option which entails accepting a lower starting capacity needs to be accepted: Amsterdam Airport Schiphol will operate less aircraft movements per year, but it is more sustainable and profitable for the health of the (platform) employees. Another discussed option is based on preserving the current starting capacity, by investing in the construction and adjustment of (new) infrastructure for remote starting locations, as well as by investing in new tow trucks or taxibots with a proportional expansion in drivers. The needed capacity for available infrastructure and tow trucks (with drivers) could be similar to the needed capacity in a scenario where the deicing procedures are executed completely remotely. Potential investments to maintain the current capacity in future scenarios will be elaborated on in section 5.4.3.

A similar debate has been on the agenda at Copenhagen Airport (CPH) in Denmark, where ultrafine particle mitigation and the introduction of remote starting positions have also been points of discussion over the last couple of years (interview with Head of Sustainability of CPH, appendix F.4). A pilot was carried out at CPH to investigate the potential implementation of (semi-)central starting positions at the airport to move the production of aircraft emissions further away from the piers. This research was initially not conducted to link the insights and results to the additional implementation of an ultrafine particle mitigation system, but CPH also performed some tests to analyze the effects of a created water haze on the UFP concentrations. (...)

Conclusion:
The debate whether the current available resources, in terms of infrastructure, tow trucks and manpower, are sufficient to maintain the current starting capacity at AMS without additional investments did not end in consensus between the stakeholders. The expected impact of the potential mitigation system, on the aircraft operation and Amsterdam Airport Schiphol as a whole, needs to be determined by conducting impact analyses and thoroughly studying the measurements and performed calculations. These expectations will severely affect the feasibility and viability of the system, which will be further discussed in chapter 6. In table 10, the few operational requirements that the system must comply with to guarantee a profitable aircraft operation are presented.

Table 10: Operational requirements for aircraft operation in general

Category	**1**	**Operational requirements**
Constraint	**4**	The system must not negatively affect the aircraft operation.
Requirement	**1**	The operation of the system should limit the increase in the turnaround time (as much as possible).
Requirement	**2**	The operation of the system should limit the decrease in the starting capacity (as much as possible).

5.4.2 Safety requirements 'water droplet'-based ultrafine particle mitigation

Another important category of system design boundaries are the safety requirements. The use of water on and around the aircraft during the operation could induce safety risks, which makes it necessary to draw up a set of requirements that takes the potential hazards into account. The health of platform employees is of severe importance during the analysis of implementing new projects at the airport, which is why it is integrated in the set of safety requirements. Potential safety hazards that could be related to the construction of a UFP mitigation system at the airport grounds were also integrated into a set of safety requirements. These can all be found in the following subsections.

Safety requirements for the use of water on and around the aircraft
Besides the potential impact of natural precipitation on the system and the aircraft itself, it is also important to take the use of water for the production of the water droplets into account. As, according to TNO and the equipment providers, the water droplet production equipment uses more than 10,000 litres of water per hour, the airport infrastructure, and potentially the aircraft itself, will have to endure large amounts of water during each mitigation procedure. A first point that needs to be raised, while taking the use of water into account, is the potential risk that arises when this water ends up in the jet engines during the operation. While all stakeholders agree that spraying the water droplets into/directed to the outlets of the jet engines does not seem to impose any safety hazards, spraying water directly into the front of the jet engines seems a lot less safe for the operation (appendix F). There may even be a counterproductive effect when spraying the water droplets into the jet engine inlet, with UFP production increasing due to less complete combustion in the engine. A design principle that results from this theory is that the creation of the water droplet cloud should always be directed to the outlet of the jet engines and the equipment should be installed behind the jet engines. Another design principle that takes this safety aspect into account is that the produced water should not disturb the aircraft operation.

Airlines are very careful with their aircraft, due to the involvement of large investments and the safety of passengers and flight crew. All projects at the airport that involve additional engineering and maintenance activities from the airlines are usually not desired by these airlines (interview with Safety Consultant of KLM, appendix F.2). The fleet services (aircraft manufacturers and Engineering & Maintenance department of KLM) have to give a green light to the airlines, which indicates that the new system and technologies are not associated with additional risks to the aircraft. The use of large amounts of water should not affect the condition of the aircraft in such a way that the usual decay of the aircraft is accelerated by the use of this system. To generate greater support from the aviation sector for the implementation of this system, it is important to involve KLM and other airlines operational at AMS in the analysis of the system design to show that the water droplets do not damage the aircraft (interview with associate professor from the faculty Aerospace Engineering at TU Delft, appendix F.5). A Senior Manager and Aircraft Architect from Airbus Technology Bremen stated that, at first glance, spraying the water droplets on and around the aircraft during the operation should not induce any risks to the aircraft (appendix F.8). This stakeholder did address the importance of preventing corrosion and other impacts on electrical circuits and the operational systems at the aircraft stand at the pier, as the aircraft including occupants are in a more vulnerable position at that location. Taking the potential of freezing into account when the outside temperatures are around zero degrees is also important when spraying water droplets near the aircraft.

Besides the impact of the production of large amounts of water in the vicinity of the aircraft, it is also of importance to assess the potential risks of the used water ending up in the environment or on the used infrastructure at the airport grounds. When a lot of water is used for the mitigation of UFP, it is imaginable that large puddles will form on the infrastructure and/or in the environment nearby. This will mainly be a problem when the spraying of water happens locally, so near the piers, and less when the mitigation is executed at remote/central starting locations. The use of natural water for this system is in principle harmless, as the only environmental risk is caused by nitrogen deposition. It is important to decide whether additives to the used water are necessary, i.e. for lowering the freezing point of the water during the Winter months, as water with additives may become toxic in some form (e.g., rain). The system will be more circular and sustainable when the descended water with collected ultrafine particles is collected, after which it is cleaned/filtered, and then reused for the production of new water droplets for the UFP mitigation. As the polluted water should not end up in the environment (e.g., ground water and polders), especially when the water contains additives that are potentially harmful, a design principle that states the need to collect the water and, if necessary, filter it afterwards needs to be established.

Conclusion:
Analyzing the impact of a system, in terms of safety, on the aircraft operation is of enormous importance for the eventual implementation of the potential system. As the use of large amounts of water is a substantial part of this system, the safety requirements regarding the production of water on and around the aircraft are important to take into account. These requirements are associated with the presence of the water used for the system inside the jet engines and on the aircraft itself, but also with the situations where the water ends up in the environment or on the airport infrastructure. An overview of the safety requirements for the use of water on and around the aircraft is provided in table 11.

Table 11: Safety requirements for the use of water on and around the aircraft

Category	**2**	**Safety requirements**
Constraint	**1**	The use of water must not cause damage to the airport, aircraft and environment in any form.
Requirement	**1**	The water droplets should not be sprayed into the inlet of the aircraft engines. / The water droplet production equipment should be installed behind the jet engines.
Requirement	**2**	The large amounts of water (with additives) must not cause a significant impact on the decay of the aircraft.
Requirement	**3**	The large amounts of polluted water (with UFP and additives) must not end up in the environment.
Requirement	**4**	Large puddles of water should not arise at the used airport infrastructure.

Safety requirements regarding the health of platform employees

The main reasoning behind the search for ultrafine particle mitigation strategies by Royal Schiphol Group is to better protect the health of airport employees and limit the risks of people being in contact with these emissions. As has been discussed in chapter 3.3, ultrafine particles that have entered the human body exhibit similar behavior as absorbed viruses. Respiratory viruses can be spread through respiratory droplets, such as

UFP can be encapsulated by droplets, and airborne viruses are collected by similar methodologies as airborne particulate matter (Kumar et al., 2021). After inhalation, viruses and aerosol particles in airborne state can efficiently pass through the respiratory tract and are able to reach the alveoli (Kwon, Ryu, & Carlsten, 2020). The use of water droplets to encapsulate these airborne particles, resulting in the droplets with (clumps of) UFP eventually descending to the ground, might therefore be an interesting solution direction for this health problem. Once the encapsulated particles have reached the ground, they will not further disperse across the airport grounds. However, it is not the case that there are no health risks associated with UFP after descending to the ground, as the water droplets with particles might still evaporate. After evaporation, the clump of UFP reduces in mass and size, which might result in returning to an airborne state. A professor from the University of Twente, specialized in the interaction between (nano) particles and droplets and their behavior during evaporation/drying processes, therefore stated that these particles should stay in droplets for as long as possible (appendix F.9). A side note here is that respiratory aerosols in liquid state and other droplets with sizes up to 100 microns (μm) will still remain airborne for a significant amount of time, especially in humid conditions.

Even though the water droplets with (conglomerates of) UFP might remain airborne due to their minuscule size and weight, there can still be benefits associated to capturing the particles by deploying water droplets. As mentioned in the stakeholder interview in appendix F.9, inhaled viruses and (clumps of) ultrafine particles that are encapsulated by water droplets will typically be stopped in the upper part of the human respiratory system. In liquid state, these harmful particles are not able to get deeper into the respiratory system. Encapsulating UFP in water droplets might thus already have a direct impact on the health of (platform) employees at the airport and of residents in neighbouring areas.

When the water droplet production happens near the terminals, it is necessary to prevent the creation of a "Legionella shower" (interview with Safety Consultant of KLM, appendix F.2). The bacteria in the water droplets may induce health risks for the (platform) employees that are working near the mitigation system, which should not be the case for a solution direction that is used precisely to combat hazards to health. It is thus important that the use of large amounts of water for the UFP mitigation system do not induce risks for the (platform) employees that are present near the mitigation location. A side note provided by the stakeholder of KLM Royal Dutch Airlines is that a central water droplet spraying installation for the mitigation of aircraft-produced UFP will keep itself relatively clean due to the high intensity of use. The airport infrastructure will be cleaned every time an aircraft leaves from a central remote starting position and the water will not stand still in the pipes for a long time. This will not be the case when a mitigation system is implemented at many different locations and thus might result in future safety and health risks.

Conclusion:
The main goal of the potential implementation of an ultrafine particle mitigation system is to reduce the health impact of aircraft emissions for the employees that are working at the airport grounds. It is thus of importance that the deployment of large amounts of water for the UFP mitigation does not result in risks itself. Just as for the creation of opportunities for the ultrafine particles to interact with the water droplets (section 5.4.1), it is of great importance that the droplets stay in liquid form for as long as possible. UFP in a liquid state is less hazardous for the human body than in their original state. Droplets will most likely be stopped by the small hairs in the upper part of the respiratory system, whereas separate ultrafine particles have a much higher chance to reach the lower parts of the respiratory system. Overall, it is beneficial for the health of the employees that they are not working in the vicinity of the departing aircraft and the operational mitigation system. The requirements that the future system must meet to guarantee a safe and healthy working environment for (platform) employees at the airport are presented in table 12.

Table 12: Safety requirements to guarantee the health and safety of (platform) employees

Category	**2**	**Safety requirements**
Constraint	**2**	The use of water must not cause health risks and safety hazards for employees.
Requirement	**1**	The water droplet cloud must not be created in the vicinity of airport employees.
Requirement	**2**	The water droplets should stay in liquid form for as long as possible.

Safety requirements for the construction of the UFP mitigation system
No specific EASA regulations come into mind when analysing the potential implementation of a 'water droplet'-based UFP mitigation system at the airport, as the use of large amounts of water does not necessarily imply immediate risks for the aircraft, according to several stakeholders within the aviation industry (appendices F.1

and F.3). However, the safety issues that are mainly related to the construction of the equipment on or near the used infrastructure are important to consider when establishing the safety requirements of such a system. A Senior Environmental Advisor from the department HSE of RSG and a researcher from TNO both state the importance of taking the 'safe zone' of an aircraft into account while analysing the construction of the mitigation equipment on the airport infrastructure (appendices F.6 and F.12). When the construction is installed in the safe zone behind the jet engines of the aircraft, there is a risk that the water droplet production equipment will be blown over due to the high wind forces of the jet blast. A safety requirement regarding the implementation of constructions for the UFP mitigation system in the 'safe zone' of an aircraft should thus be included, unless the construction is proven to be capable of enduring the jet blast.

The previously stated design principle mentions the importance of establishing a safety requirement that takes the potential impact of the jet blast on the system construction into account. Even more important is to analyse the safety risks of a potential collision of an aircraft with the implemented construction for the UFP mitigation system on the (unused) infrastructure. Stakeholders who are involved in the operation of the aircraft mention that the amount of EASA regulations significantly increases when the operation moves further from the terminals/piers to the taxiways and, eventually, the runways. For instance, the (unused) infrastructure needs to be obstacle-free the first 40 meters on both sides of the middle of the runway (interview Safety Environmental Advisor at RSG, appendix F.12). For this regulation, a safety requirement should be included which addresses that installations and equipment that is placed next to the taxi and runways must be able to break off easily in the event of impact, in order to minimize the damage of a collision with an aircraft.

Another point of attention regarding the safety requirements is related to the implementation of the system itself. A stakeholder from the Airport Operations department of RSG stated the importance of avoiding the implementation and operation of hybrid systems at the airport, as the main goal is to keep the processes/system simple, unambiguous and uniform (appendix F.14). In order to guarantee safe aircraft handling and a safe airport environment as a whole, it is important that there are not multiple system alternatives that serve the same goal. For instance in this context, all cold starts of the aircraft should take place at remote starting locations or all cold start of the aircraft should take place at the aircraft stands at the piers, instead of operating both aircraft processes.

Conclusion:
The implementation of any system at the airport needs to meet the safety requirements that are applicable in that area of the airport grounds where the construction will be located. An overview of the safety requirements for the actual construction of the UFP mitigation system at the airport grounds is provided in table 13.

Table 13: Safety requirements for the implementation of the UFP mitigation system

Category	2	Safety requirements
Constraint	**3**	The system implementation must not cause safety risks during the aircraft operation.
Requirement	**1**	The system should not be implemented in the 'safe zone' of the aircraft, unless it is proven to be capable of enduring the jet blast.
Requirement	**2**	The first 40 meters on both sides of the middle of the runway must be obstacle-free.
Requirement	**3**	The construction of the system must be able to break down easily in the event of a collision.
Requirement	**4**	The system implementation and processes must be kept simple, unambiguous and uniform.

5.4.3 Economic, logistic and transition requirements

The previous requirement categories consist of the operational and safety requirements that the system must comply with in order to increase the innovation's feasibility, viability and desirability. There are some additional requirements that do not necessarily fit in the previous two categories and are therefore discussed in a separate section of this chapter. This final set consists of requirements that are related to the financial aspects, the logistical challenges, and the transition (from the old system into the new situation) of the implementation of a potential UFP mitigation system. These requirements could also be integrated into the feasibility and viability assessment of the potential system, but a brief overview of these additional requirements is convenient to fall back on during the design.

Economic requirements for the implementation of the UFP mitigation system

Each new solution needs to be proven viable prior to implementation of that system at the airport. Economic design principles are usually established by determining a budget for a certain project, but can also be stated in the following form: 'the costs of the project implementation must not outweigh the (societal) benefits of the system'. The use of a (societal) cost-benefit analysis is an often used methodology for policy projects in the transportation and infrastructure sectors, in which, for instance, the improvement of the quality of life and the living environment is integrated in the evaluation. However, certain projects that require high investments are often implemented even though the potential benefits do not outweigh the costs, as the involved parties might see it as a necessity to show that they are making an effort to tackle a certain problem. For Royal Schiphol Group and the aviation industry as a whole, achieving a reduction of the UFP concentrations at the airport to benefit the health of the (platform) employees and the quality of the air and the airport environment is a priority on the agenda. This might make the use of a (societal) cost-benefit analysis less necessary and results in a better fit for the eventual use of a requirement that integrates a budget cap for the involved stakeholders. However, as the implementation of ultrafine particle mitigation strategies is still in its exploratory phase, it is not yet possible and of added value to draw up a budget cap requirement.

Even though the quantification of implementing a potential UFP mitigation system at the airport has been disregarded in this research, there are some financial aspects that could be integrated to substantiate the system design boundaries. During the discussions with several involved stakeholders (appendix F), the construction and implementation costs of the future system were mentioned. The decision to implement mitigation strategies locally or at central locations could be affected significantly by the associated implementation costs. For instance, building a UFP mitigation system at every pier will result in many construction activities and many installations. Such a decentralized system is not only economically inefficient, but will also result in many installations of water pipes on and underneath the used infrastructure close to the terminals (interview with Safety Consultant of KLM, appendix F.2). Besides the fixed installation costs, the variable costs of power, water usage, maintenance, reparation and monitoring will also increase when the system operates in more different locations. The number of installations and the corresponding costs are significantly reduced when the system is only implemented at a few central locations at the airport.

The water droplet production equipment that is necessary for the mitigation strategy is thus implemented most cost-efficiently at a limited amount of remote starting locations, which in turn results in the need for airport infrastructure to implement and set up these locations. A Safety Consultant from KLM Royal Dutch Airlines mentioned during the interview that there is currently very limited space on the airport grounds left, which means that additional locations for remote starting positions are not selected that easily (appendix F.2). In a potential configuration of the system where the cold start of the engines is moved further away from the piers, this new procedure needs to fit in the current infrastructure or more infrastructure needs to be made available for remote starting locations. It is most viable to implement a UFP mitigation system that requires a limited amount of extra dedicated infrastructure and makes optimal use of the already available infrastructure and facilities. This financial aspect of the potential UFP mitigation system, as well as the previously discussed fixed and variable costs, are integrated in the economic requirements that are presented in table 14.

Table 14: Economic requirements for the implementation of the UFP mitigation system

Category	**3**	**Economic requirements**
Constraint	**1**	The system must be as cost-efficient as possible.
Requirement	**1**	The fixed and variable construction costs of the system should be as low as possible.
Requirement	**2**	Available airport infrastructure and facilities should be optimally used by the system.

Logistical challenges of the UFP mitigation system

The implementation of a 'water droplet'-based UFP mitigation system at the airport also imposes some logistical challenges. Creating interaction opportunities for the water droplets produced by the system with the ultrafine particles produced during the aircraft operation is a challenge in itself, as discussed in section 5.4.1. This mitigation strategy also imposes logistical challenges, as the aircraft and the water droplet devices both need to be at the right place at the right time. The deployment of a mitigation system that needs to create a droplet cloud at the dedicated position while the aircraft is taxiing is much more challenging then in the situation where the aircraft is parked at a certain position. Mitigating UFP while the aircraft is positioned at a central location seems significantly more efficient and effective than trying to create droplet-particle interaction opportunities during ground idle. The logistical challenges for the aircraft are limited when the mitigation strategy is deployed centrally, but the challenges with regard to the implementation of the system, the water supply, and maintenance are also within limits in this scenario. A system that includes a few central locations requires significantly less construction then a system that covers a large share of a certain airport infrastructure. To limit the logistical challenges that are associated with the implementation of a UFP mitigation at the airport, it is important that the aircraft is brought to the system instead of the other way around (interview with Safety Consultant of KLM, appendix F.2). This principle is integrated in a logistic requirement, which is presented in table 15.

Table 15: Logistic requirements for the implementation of the UFP mitigation system

Category	4	Logistic Requirements
Constraint	**1**	The logistical challenges associated with the system must be as limited as possible.
Requirement	**1**	The aircraft should be brought to the system, instead of the other way around.

Transition requirements for the implementation of the UFP mitigation system

Besides monetary investments, a significant amount of time also needs to be invested into the construction and setting up of the potential new remote starting locations (interview with Safety Consultant of KLM, appendix F.2). The amount of time and the necessary resources, such as man hours and equipment, that are put into the implementation of the new system cannot be dedicated to other projects that are running simultaneously. The implementation of the UFP mitigation strategy requires the construction of the system equipment, and potentially the creation of new infrastructure at the airport grounds as well. These activities might impact the operation of a certain share of aircraft, as well as other airport processes, which could influence the turnaround time of aircraft and the starting capacity of the airport. The impact of the transition from the old situation into the new situation should be limited to maintain the feasibility and viability of the proposed system.

The airport should also decide whether the transition into the new situation needs to happen incrementally or all at once. In the situation where the new system is implemented completely, all separate components of the system will reinforce each other to create a more efficient and effective system. However, incremental implementations of the several system components might be easier for the stakeholders and included parties to comprehend, even though the separate components of the system will result in a less well-functioning system. It is also possible that the implementation of the first system components stimulate the introduction of the other components, as they have proven to be beneficial for the airport operation. However, as discussed in section 5.4.2, the system implementation and processes should be kept simple, unambiguous and uniform. Transitioning incrementally into the new situation might jeopardize these principles, which makes this implementation strategy less desirable for the airport. Table 16 provides the relevant requirements for the conceptual UFP mitigation system design that are associated with the system transition.

Table 16: Transition requirements for the implementation of the UFP mitigation system

Category	5	Transition Requirements
Constraint	**1**	The impact of the transition from the old situation into the new system must be limited as much as possible.
Requirement	**1**	The transition from the old situation into the new system should interfere with the aircraft operation and other processes as little as possible
Requirement	**2**	The transition from the old situation into the new system should be implemented as completely as possible.

5.5 Conclusion

Sub-question 3: '*What are the system design components and the requirements that the 'water droplet'-based ultrafine particle mitigation system at the airport must meet?*'

The system design components are based on three pillars, which are led by the questions 'When?', 'Where?' and 'How?'. First, the moment of the deployment of the potential 'water droplet'-based ultrafine particle mitigation system needs to be determined. The aircraft operation can roughly be subdivided into three processes, which are the 'cold start', ground idle and take-off (LTO proces). The current priority of AMS seems to be on combating the UFP concentrations that are produced during the cold start of the aircraft engines, as a substantial amount of UFP is emitted during this process and it also the process that takes place the closest to were (platform) employees are working. Besides this, the logistical challenge of implementing mitigation strategies during this process is also limited, as the aircraft is positioned at a dedicated location. The periods of the day are also an important aspect of this system design component, as operating the system throughout the whole day might not be efficient. Most aircraft movements at AMS take place during the morning and afternoon periods of the day, so it seems that mitigating UFP during these periods of the day has priority over the evening and night periods.

After the potential moments of mitigation were analyzed, the potential locations for the implementation of the system at the airport grounds needed to be mapped. The current locations that the aircraft passes during the operation are the aircraft stand at the pier, the taxiways and the runway. The taxiways at the airport do not seem to be the best fitting location for the implementation of mitigating strategies to combat aircraft-produced UFP concentrations, as this infrastructure category covers an enormous surface of the airport grounds. Mitigating ultrafine particles at the runways seems more interesting at first glance, but the operational area that needs to be covered by the system is still relatively large, and most EASA regulations regarding safety are applicable at this area, which limits construction possibilities. The previously discussed cold start of the engines usually takes place at the aircraft stand next to the pier, which thus seems the most suitable location. However, the implementation of the potential mitigation system at the piers is associated with several health and safety risks, as most (platform) employees are walking around at these locations and many other airport processes are taking place there. Several airport (e.g., AMS and CPH) started to explore the potential of moving the cold start further away from the piers to remote starting locations. The positions at these potential remote starting locations offer dedicated areas to implement the UFP mitigation system, which makes the mitigation strategy clearer than at the taxiways and runways. Besides this, the produced water droplets do not interfere with the operations of the (platform) employees and the other airport processes. The available capacity and facilities, as well as the impact on the turnaround time and starting capacity of the airport, need to be analyzed thoroughly before (semi-)central starting locations can be implemented.

A third important component of the potential system designs is the way in which the aircraft-produced particles will be mitigated. As this research is based on the idea of combating UFP by using water droplets to encapsulate the particles, equipment that will produce these droplets is the basis of the potential system. Water droplet (mist) production equipment is currently mainly used as a solution for dust control/suppression in the construction and quarrying industries, but is proven to also be effective in combating the formation of fine particle concentrations. Most providers in the dust control sector offer relatively similar products, which can be subdivided into two main equipment categories: water spraying cannons and water pipes with spraying nozzles mounted onto them. These categories also offer several alternative devices for the production of fine water droplets. The operation of so-called 'water spraying cannons' is based on the technique of guiding the water supply through a powerful turbo-fan, which produces a turbulent airflow containing fine water droplets. This equipment category seems to be a well-fitting solution in the situation where it is determined that the water droplets should be directed into the jet engines, as they are relatively easily adjustable, as well as the spraying angle and direction. The other equipment category, which is based on the use of water pipes with sprayin nozzles mounted onto them, might be a better solution in a situation where it is determined that it is more efficient and effective to let the ultrafine particles from the jet engines interact with the water droplets at a certain distance from the aircraft. These so-called 'SprayWalls' project a vertical water droplet cloud into the air, which covers the necessary spraying dimensions more easily. An overhead spraying installation is another interesting alternative, as it requires less energy consumption and less water usage due to the lower pressure on the hose(s) and the nozzles.

An analysis was executed to provide an overview of all the relevant system requirements, with regard to the operation and safety. Besides this, economic and transition requirements were also taken into account, as well as the logistical challenges that are associated with the implementation of the new system at the airport. A complete overview of these requirements is presented in tables 18 and 17.

Table 17: All operational and safety requirements

Category	1	Operational Requirements
Constraint	1	The system must create as many opportunities for the UFP to interact with the water droplets as possible.
Requirement	1	The water droplets should be sprayed in the area with the highest concentration of UFP.
Requirement	2	The air flows behind the aircraft should be complex and turbulent.
Requirement	3	The evaporation time of the water droplets should be as high as possible.
Requirement	4	The water droplet cloud should at least cover the complete cross section of the jet blast.
Constraint	2	The water supply source must result in the most optimal system, in terms of filtering, health and investments.
Requirement	1	The water supply must originate from a socio-economically accepted source.
Requirement	2	The water supply must originate from a sustainable source.
Requirement	3	The used water must be collected for reuse (as much as possible).
Requirement	4	The collected water should be filtered before reuse.
Constraint	3	The system must take meteorology and weather conditions into account for the operation.
Requirement	1	The system shall not operate when the outside temperature at the airport grounds is below zero degrees Celsius (when using water without additives).
Requirement	2	The water droplets must not instantly evaporate when the outside temperature at the airport grounds is relatively high.
Constraint	4	The system must not negatively affect the aircraft operation.
Requirement	1	The operation of the system should limit the increase in the turnaround time (as much as possible).
Requirement	2	The operation of the system should limit the decrease in the starting capacity (as much as possible).
Category	**2**	**Safety Requirements**
Constraint	1	The use of water must not cause damage to the airport, aircraft and environment in any form.
Requirement	1	The water droplets should not be sprayed into the inlet of the aircraft engines. / The water droplet production equipment should be installed behind the jet engines.
Requirement	2	The large amounts of water must not cause a significant impact on the decay of the aircraft.
Requirement	3	The large amounts of polluted water (with UFP and additives) must not end up in the environment.
Requirement	4	Large puddles of water should not arise at the used airport infrastructure.
Constraint	2	The use of water must not cause health risks and safety hazards for the employees.
Requirement	1	The water droplet cloud must not be created in the vicinity of airport employees.
Requirement	2	The water droplets should stay in liquid form for as long as possible.
Constraint	3	The system implementation must not cause safety risks during the aircraft operation.
Requirement	1	The system should not be implemented in the 'safe zone' of the aircraft, unless it is proven to be capable of enduring the jet blast.
Requirement	2	The first 40 meters on both sides of the middle of the runway must be obstacle-free.
Requirement	3	The construction of the system must be able to break down easily in the event of a collision.
Requirement	4	The system implementation and processes must be kept simple, unambiguous and uniform.

Table 18: All economic, logistic and transition requirements

Category	**3**	**Economic requirements**
Constraint	**1**	The system must be as cost-efficient as possible.
Requirement	**1**	The fixed and variable construction costs of the system should be as low as possible.
Requirement	**2**	The available airport infrastructure and facilities should be optimally used by the system.
Category	**4**	**Logistic Requirements**
Constraint	**1**	The logistical challenges associated with the system must be as limited as possible.
Requirement	**1**	The aircraft should be brought to the system, instead of the other way around.
Category	**5**	**Transition Requirements**
Constraint	**1**	The impact of the transition from the old situation into the new system must be limited as much as possible.
Requirement	**1**	The transition from the old situation into the new system should interfere with the aircraft operation and other processes as little as possible.
Requirement	**2**	The transition from the old situation into the new system should be implemented as completely as possible.

6 Conceptual system design(s)

This chapter proposes a conceptual design for the potential implementation of a future mitigation system that combats aircraft-produced ultrafine particles at the airport grounds. It provides an overview of all the system components and relevant requirements, which have been thoroughly discussed in chapter 5, and presents the most fitting and promising layout, while using the gathered knowledge from the literature research and conducted stakeholder interviews as a common thread. For clarification, the conceptual system design that is presented in this chapter will probably not match the generally known image of such a design, as it mainly describes the potential system instead of visualizing it. Visualizations are used when deemed to be of added value for the conceptual system design description. Section 6.1 presents the conceptual design choices regarding the moment and the location of UFP mitigation during the aircraft operation, following the analyses provided in chapters 5.1 and 5.2 respectively. The relevant dimensions of the potential water droplet screen/cloud will be discussed and presented in section 6.2.1, after which the actual water usage of the system is decided upon in section 6.2.2. The conceptual design choices with regard to the currently available alternatives of water droplet production equipment (5.3), which is the core concept of this aircraft-produced UFP mitigation strategy, are discussed in section 6.3.

6.1 The functional implementation of the conceptual system design

6.1.1 Moment of mitigating UFP

This section of the conceptual system design, of a potential strategy to combat ultrafine particles produced by a aircraft at Amsterdam Airport Schiphol by using water droplets, discusses the most promising and best fitting aircraft operation process during which the system should be deployed. As discussed in chapter 5.1, the aircraft operation can be roughly divided into the cold start of the engines, the ground idle procedure and the LTO procedures. That chapter already provided a comprehensive conclusion on the potential mitigation moments, which will be elaborated in this section.

From an operational point of view and according to the interviews with stakeholders within RSG, the aviation sector and the academic world, implementing UFP mitigation strategies during the cold start of the aircraft engines seems the most efficient and effective. One of the initial reasons to explore UFP mitigation strategies is the impact of the emissions concentrations near the platforms on the health of employees that are working there. As the cold start of the aircraft engines currently takes place at the aircraft stand next the pier, the produced emissions are blown in the direction of the terminals (interview with senior environmental advisor of HSE within RSG, appendix F.12). Concentration accumulations arise throughout the day, as the emissions remain located in wind-free areas and close to the buildings. AMS and RSG see it as a priority to first tackle the problem in the area where employees are the most affected by the aircraft operation, which supports the conceptual system design choice to implement the mitigation strategy during the cold start as it currently takes place in that area. A professor from the faculty of Aerospace Engineering at the TU Delft (appendix F.7) addressed that the cold start of the aircraft is associated with the production of large amounts of UFP and other emissions, due to the engines still containing clumped dirt from the previous operation(s). Mitigating the large share of ultrafine particles being produced during the cold start increases the efficiency of the system, which supports the conceptual design choice to begin with mitigation strategies at the cold start.

Another stakeholder from RSG, within the taskforce UFP mitigation of the department S&AP, also mentioned the important side-note that there are several ongoing projects at AMS that focus on the mitigation of aircraft emissions during the other processes (appendix F.11). Schiphol is currently exploring the deployment of so-called 'Taxibots', which are sustainable aircraft tugs, to take the aircraft to and from the runway (Schiphol, 2022). As this solution direction is focused on combating aircraft emissions during the ground idle procedures of the operation, investigating the potential implementation of a water droplet mitigation system for taxiing aircraft is fairly duplicitous. The time and resources that are available for the research on this solution can be better used while focusing on the potential implementation during the other processes.

The logistical challenge to implement the system during the cold start is also fairly limited, as this procedure of the operation takes place when the aircraft is positioned at a dedicated place and the water droplets do not have to move along with the aircraft (interview professor from the faculty of Aerospace Engineering at TU Delft, appendix F.1). The water droplet production equipment and other necessary facilities can be implemented at a few central locations, which is beneficial for the implementation costs, as well as the variable costs for operating the system. The conceptual design decision is thus supported by the system requirements that were stated in chapter 5.4.3, as the logistical challenges and the necessary investments seem to stay within limits the most during this part of the aircraft operation in comparison with both the ground idle and LTO procedures.

6.1.2 Location of mitigating UFP

The location of the potential UFP mitigation system is strongly related to the determined aircraft operation process during which the system operates. Since the cold start of the engines has been selected as the aircraft operation process priority to focus on within the conceptual system design, the collection of potential mitigation locations has also become smaller. From the potential locations discussed in chapter 5.2, the aircraft stand at the pier and the remote starting positions are the main alternatives to consider for this component of the conceptual design of a 'water droplet'-based UFP mitigation system at Amsterdam Airport Schiphol, which will be elaborated in this section.

As previously mentioned, the cold start of the aircraft operation currently takes place at the aircraft stand next to the pier of the airport terminal. A senior manager and aircraft architect at Airbus Technology Bremen (appendix F.8) stated that the water droplets should probably not be sprayed at the aircraft stand at the gate, as the large amounts of water could result in safety hazards for other operational systems and processes at the apron, as well as in safety risks for the platform employees that are working at these locations. This stakeholder mentioned that UFP mitigation by spraying water droplets at this level of locality is most likely not desirable. This point of attention was also raised during the interview with the safety consultant of KLM Royal Dutch Airlines (appendix F.2), who stated that the use of water droplets during the cold start at a starting position located further away from the pier is a more desirable alternative than UFP mitigation at the aircraft stand. The possibility of creating a 'Legionella shower' at the locations where people are walking around is a risk that should be avoided at the airport grounds. Stakeholders from within Royal Schiphol Group and other interviewees (appendix F) also addressed their concerns regarding the production of large quantities of water close to the terminals, which were translated into several safety requirements (tables 11 and 12 of chapter 5.4.2).

The safety consultant from KLM mentioned in the interview that the aircraft should be brought to the mitigation system, instead of bringing the system to the aircraft. Instead of implementing a mitigation system at every pier or aircraft stand, it is way more efficient to dedicate some airport infrastructure further away from the bay into remote starting locations where the mitigation strategy can be implemented. In the busiest and most dense area of Copenhagen Airport, aircraft are currently being towed away from the aircraft stand for 200-300 meters after which the engines are started (appendix E). This is not considered to be fully remote starting, but the first analyses regarding the current system at CPH show some beneficial results. The concentration accumulations of UFP at the involved platforms and piers in the dense and busy area have decreased significantly and arriving aircraft had a better punctuality as inbound parking was not necessary anymore. This was only at the expense of a slight decrease in the starting capacity of departing aircraft. The head of sustainability development at CPH mentioned during the stakeholder interview that fully remote starting is currently not an interesting option for Copenhagen Airport, as the airport layout does not facilitate an optimal situation when that system is implemented. He mentioned that Amsterdam Airport Schiphol might be a better fit for the fully remote starting system, as the extensive layout of AMS results in longer taxi times during which the pilot can stabilize the engines and execute the final checks prior to departure.

The conclusion of chapter 5.2 and the final sub-section of chapter 5.4.1 clearly shows the current debate at Schiphol whether the impact of introducing remote starting of the aircraft operation on the starting capacity of AMS is not too big, which also resulted in the requirements from table 10. Before a conclusion can be drawn about the actual impact of remote starting at Amsterdam Airport Schiphol, an extensive analysis needs to be conducted that provides calculations regarding the impact on the turnaround time and on the starting capacity. For now, it is taken into account that the majority of the interviewed stakeholders addressed the importance of moving the cold start of the engines, and thus the potential future UFP mitigation strategy, further away from the aircraft stand at the pier. Remote starting locations that consist of a to be determined number of aircraft positions currently seem like the most interesting location to further investigate for the potential implementation of a 'water droplet'-based UFP mitigation system at the airport.

The Papa buffer (P-platform) and the remote deicing platform, including the Juliet buffer (J-platform), seem to be interesting locations for the potential implementation of remote starting positions. The Papa buffer is currently mainly a parking location for inbound aircraft. However, AMS wants to stop with inbound parking in the near future, which creates possibilities for other purposes. The remote deicing platform is in use during the Winter months, but offers a lot of capacity and additional facilities during the rest of the year. The Juliet platform also offers sufficient space for the implementation of multiple remote starting positions, whereas the possibilities regarding remote starting of the aircraft engines at the Echo buffer (E-platform) can also be further investigated. A senior process advisor from the OPS department of RSG mentioned an expected need of 5-10 remote starting positions (appendix F.10), while the expectation of a process owner aircraft from the same department tended towards 15 positions (appendix F.14). The expected needed capacity of the collection of remote starting locations according to the senior process advisor corresponds approximately with the actual available infrastructure, while the expectation of the process owner aircraft is that infrastructure needs to be adjusted and a significant amount of remote starting positions needs to be created. These potential investments, as well as the potential need of scaling up the current fleet of aircraft tugs with drivers, will be further discussed in section 6.5.

6.1.3 The way of mitigating UFP - Infrastructural implementation

The final component of the functional implementation of the conceptual system design that needs to be determined is the way in which ultrafine particles will be mitigated at the airport. As exploring the use of water droplets to combat the aircraft-produced UFP is the initial essence of this research, the potential solution directions for the system were also analyzed by keeping this principle in mind. Chapter 5.3 discussed two main water droplet production equipment categories that are usually offered by most providers in the dust and (ultra)fine particle control sector, which are: water spraying cannons and water pipes with spraying nozzles mounted onto them. Several alternative configurations were also presented for both categories. Relevant operational requirements for this component of the conceptual system design have been presented in table 7, while relevant safety requirements can be found in tables 11 and 13.

The main difference between the equipment categories is the way in which the produced water droplets are sprayed into the air, which determines how the water droplet cloud eventually is projected. A few stakeholders stated that the water spraying devices should be connected properly to the cores of the aircraft engines in order to spray the water droplets into the area of the engine where the largest amounts of UFP are produced (appendices F.1 and F.2). Water spraying cannons, which were extensively discussed in chapter 5.3.1, are probably the best alternative when the water droplets need to be sprayed into (the core of) the aircraft engines, as the devices can be adjusted in spraying angle and direction. However, the dissension between the stakeholders regarding this issue was clearly evident in the various interviews. A professor in meteorology and air quality from the department of Environmental Sciences at WUR stated that it is probably impractical to spray the water droplets into the core of the engine, as the thrust is the strongest there with therefore high wind velocities (appendix F.3). The temperatures that close to the engine are also extremely high, which results in relatively fast evaporation of the water droplets in comparison with water droplets that are produced further away. The effectiveness of the UFP mitigation system is not high when the particles cannot be encapsulated by the water droplets due to the thrust and temperature of the aircraft engine core. The measurements from the conducted UFP-water droplet experiments by RSG and TNO confirm these expectations (for now), as the water droplets from the spraying cannons did not reach the core of the engines (appendix F.6). A researcher in (nano) particles from TNO mentioned that the water droplets mainly flew around the engines and that the cloud increased in width, even though the cannons were aimed at the core of the engines. The droplets were mixed with a large volume of air, which caused the water to evaporate. The water droplets did not reach the ground, which means that the amount of water that could be used was not sufficient, even when two cannons were aimed at one engine. Spraying the water droplets into the core of the aircraft engines thus seems to not result in an effective strategy to mitigate ultrafine particles.

The other category of water production equipment consists of devices that are based on a construction of water pipes with spraying nozzles mounted onto them, which was extensively discussed in chapter 5.3.2. These so-called 'SprayWall's project a relatively vertical water droplet cloud into the air and are not really able to adjust their spraying angle and direction due to their placement on the ground. This equipment seems like a good fit for a system that should be placed further away from the aircraft, as it is not able to spray the water droplets into the jet engines. Besides this, the necessary cloud dimensions that cover at least the cross-section of the aircraft vortex are generated more easily and straightforward by these water pipes with spraying nozzles mounted onto them, which results in a more efficient mitigation strategy. This meets one of the requirements from table 7, from which the constraint from that table states that "the system must create as many opportunities for the UFP to interact with the water droplet as possible". During the conducted experiments from TNO there seemed to be a sufficient amount of water and enough time for UFP-droplet interaction opportunities, as the jet blast went through the water droplet cloud and the water even reached the measurement van, which was placed at a significant distance from the aircraft (interview with researcher from TNO, appendix F.6). However, the measurements showed no significant reduction in the UFP concentrations due to the water droplet cloud. The researcher from TNO linked these findings with the extreme winds and high temperature so close to the jet engines, which thus resulted in apparently not enough interaction opportunities between the ultrafine particles and the water droplets from the spraying installations. Besides this, the water droplets produced by the spraying installation did not reach a height of more than four meters, even though the equipment provider indicated that a height of six meters could be reached and there was sufficient pressure on the water hoses and the spraying nozzles. A significant share of the jet blast was therefore blown over the water droplet screen.

In order to make a deliberate decision regarding this component of the conceptual system design, more experiments need to be executed for measurements of the performances of different device configurations from both water droplet production equipment categories. The first experiments from RSG and TNO showed that the water droplet cloud produced by the spraying walls behind the aircraft provided more opportunities for interaction with UFP, in comparison with the cannons that sprayed water droplets into the core of the engines. However, the measurements were not significant, possibly due to the water droplet cloud being produced so close to the outlets of the jet engines. For now the water droplet production equipment based on the water pipes with spraying nozzles, placed on the ground, is linked to a slightly better performance. Some other conceptual system design decisions that are associated with this design component are discussed in sections 6.2 and 6.3.

6.2 The technical implementation of the conceptual system design

6.2.1 Relevant water droplet cloud dimensions

The set requirements for the creation of interaction opportunities between the aircraft-produced ultrafine particles and the water droplets, as presented in table 7, result in some criteria to assess the performance of the potential UFP mitigation system, based on the use of water droplets, at the airport. The relevant set of dimensions of the water droplet screen/cloud is a design criterion that needs to be investigated in order to create an effective and efficient UFP mitigation system. The potential dimensions of the water droplet screen/cloud need to be determined in such a way that the system creates sufficient opportunities for the water droplets to capture as many ultrafine particles as possible, in order to enable the creation of larger UFP conglomerates in the droplet. A significant share of the aircraft-produced ultrafine particles should interact with the water droplets, which means that the water droplets should be sprayed into the area behind the aircraft where the highest concentration of UFP is present. As the jet blast from the core of the engines contains almost all of the aircraft-produced emissions (appendix D), the water droplet screen should be created across the relevant dimensions of this produced, polluted air flow.

The dimensions, with which a potential water droplet screen/cloud should comply, were discussed with several stakeholders within the organisation of RSG and the aviation sector in general. During the interview, the researcher in (nano) particles of TNO addressed that the concentration of UFP in the vortex is highest in the core and has a Gauges profile (appendix F.6). During this interview, as well as during the interview with a professor in propulsion and flow physics from the faculty of Aerospace Engineering at TU Delft (appendix F.7), there was discussed that the vortex from the engines is very strong and relatively stable. This means that, even at a great distance from the aircraft, the emissions are still concentrated and extremely high UFP concentrations could still be mitigated by using water droplets. The vortex will further disperse with an increasing distance from the aircraft and the emissions will mix with air (appendix F.3), which results in diluted UFP concentrations, but the jet blast from the core of the engines will thus remain relatively stable and concentrated. Around the core of the vortex there are rotating components present, which create turbulence and result in complex air flows (appendices F.6 and F.7). The jet blast thus ensures that requirement 2 from table 7 is met, in order to guarantee the system performance.

The previously discussed aircraft vortex characteristics are used to determine the most effective and efficient water droplet cloud dimensions to facilitate as many UFP-droplet interaction opportunities as possible. First, the minimum width and height of the water droplet screen will be discussed. The overall consensus was that the width that the water droplets must cover should be at least up to the outside of the jet engines, with a buffer of x meters on the sides of both engines. The measurements of different types of aircraft should be taken into account while determining this minimum width. For narrow body aircraft, the minimum width can be calculated by using the above-mentioned measure. For wide body aircraft, the minimum width should cover up to the sides of the outside engines, while including a buffer of x meters on both sides. The minimum width of the water droplet cloud is visualised schematically for both a narrow body aircraft as well as a wide body aircraft in figures 29 and 30 respectively.

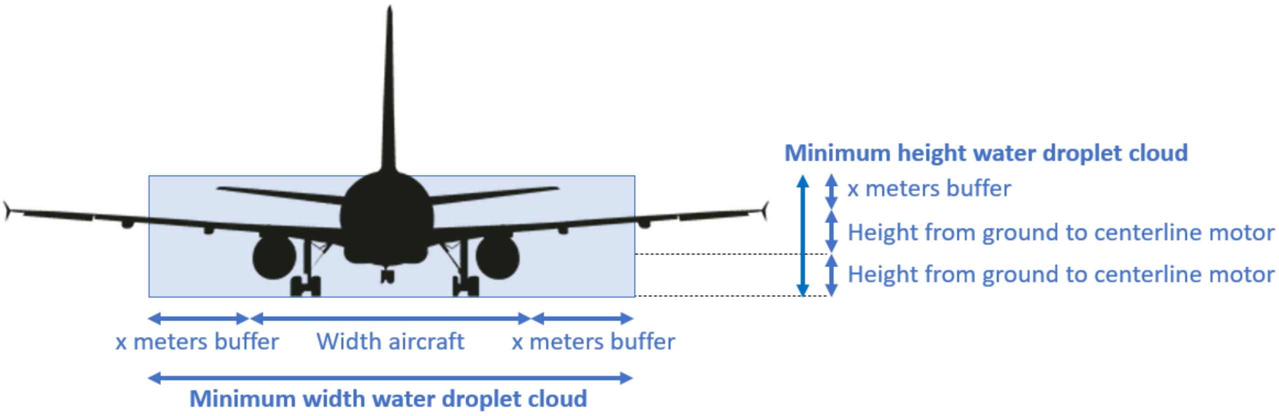

Figure 29: Dimensions of the water droplet screen (narrow body aircraft)

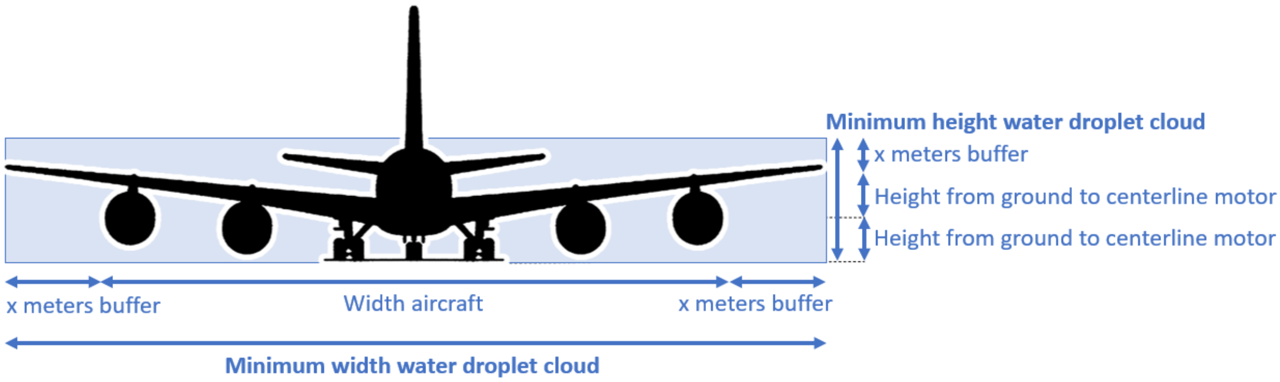

Figure 30: Dimensions of the water droplet screen (wide body aircraft)

In figures 29 and 30, the minimum height of the water droplet cloud for the mitigation of UFP is visualised schematically for both the narrow and wide body aircraft as well. The height that the, to be produced, water droplets should at least cover is determined as follows. For narrow body aircraft, the height from the ground to the center-line of the engine is taken, after which this same height is added to the height from the center-line of the engine up. A buffer is added to this height (twice the amount of meters from the ground to the center-line of the engine), which then results in the minimum height of a potential water droplet screen at the airport. For wide body aircraft, this minimum height is determined by using the same calculation. However, as wide body aircraft have two sets of jet engines, the height from the ground to the center-line of the highest pair of jet engines is taken into account while determining the minimum height of the water droplet screen.

When the depth of a water droplet screen is taken into account, the screen becomes three-dimensional, which makes it a water droplet cloud. The necessary depth of the cloud is dependent of how much time and space there is needed for the ultrafine particles to interact with the water droplets. It is still not completely clear how UFP goes through a water droplet screen/cloud and it is a wild guess to determine how many particles are captured by the present water droplets. It might be important to take the characteristics of the jet blast into accounting while investigating the necessary depth of the cloud, e.g. the wind speeds from the jet engines (vortex) and the behaviour of the emission concentrations behind the jet engines. A first sketch of the potential water droplet cloud behind an aircraft is provided in figure 31.

Figure 31: Depth of the water droplet cloud

To elaborate on the adjustment of the water droplet screen regarding the different type of aircraft at the stand, as mentioned in the previous section (6.1), the width of the cloud should thus be determined by whether a narrow or a wide body aircraft is positioned there. For a narrow body aircraft, the width that the water droplets cover can be narrowed, while the water droplet screen should be widened when a wide body aircraft is positioned at the stand.

6.2.2 Water usage of the system

Water supply source

Chapter 5.4.1 discussed the available, potential water supply sources for the UFP mitigation system, whereas table 8 provides an overview of the operational requirements with regard to the water supply sources. The most socio-economically accepted and sustainable source for the system's water supply is most likely collected rainwater, as it is the middle ground between the other potential sources. Using water from the Dutch drinking water network for this purpose is considered to be wasteful, is not sustainable, and will not be socio-economically accepted. The use of industrial water is more sustainable, but also requires extensive filtering before it can be used for the water droplet production. Besides this, airport employees and residents from neighbouring areas will not be supporting the use of this water source, due to its unhealthy and unsafe image. As mentioned in chapter 5.4.1, AMS is already planning to implement rainwater collection facilities for flushing the toilets at the new Pier A. The knowledge and insights regarding the collection of rainwater for that project could be used to implement these facilities for the UFP mitigation system at the airport.

Essential for the UFP mitigation system is that the used water is recollected in order to maintain a sustainable and circular water supply system (table 8). The system design thus needs to incorporate water collection facilities in (and on) the infrastructure, similar to the ones at the remote deicing platform of Amsterdam Airport Schiphol. As the used water droplets for the mitigation of ultrafine particles create some sort of haze and almost have the same characteristics as fine rain droplets, the collection of the used water should be relatively similar to the collection of rainwater. It might be necessary to first filter the collected (already used) rainwater before it can be used again, but this needs to be further investigated before the potential implementation of such a UFP mitigation system. For now, it is expected that new collected rainwater does not need filtering before being used for the mitigation, while already used water might contain some larger particles or potential harmful substances and thus needs filtering before reuse.

Evaporation time of the water droplets

Operational requirement 3 from table 7 states that the evaporation time of the water droplet should be as high as possible, which means that the droplets should remain a liquid once the ultrafine particles are captured and clumped together. A direct approach is to adjust the pressure on the nozzles of the UFP mitigation system in such a way that the water droplets are as big as possible, without directly descending to the ground. As long as the water droplets remain in haze-like conditions, they will have sufficient opportunities to interact with the ultrafine particles. The effective area size of the water droplet cloud (appendix F.3) will significantly decrease when the size of the droplets increases, but the longer evaporation time and the fact that the water droplets are still really small will (over)compensate this.

In addition to the adjustment to the water spraying nozzles of the system, the composition of the used water for the system could also be customized to increase the evaporation time of the water. A professor from the University of Twente, with expertise in the interaction between (nano) particles and droplets, addressed the potential of adding a small amount of salt (sodium chloride) to the water droplets, which ensures that the droplets remain a liquid for a significantly longer time. The sodium chloride slows down the evaporation process significantly, which is also the reason why respiratory aerosols in the human body remain in a liquid state for a long time. This solution direction meets the requirements with regard to health and safety hazards for (platform) employees (table 12), as these small amounts of salt are completely natural for the human body, which has the same pH-value. Large amounts of sodium chloride should probably not end up in the natural environment of the airport, which supports the reasoning from section 6.1 to implement the system at (unused) infrastructure and collect the used water.

6.3 Potential designs of a 'water droplet'-based UFP mitigation system

The functional and technical implementation of the conceptual system design have been discussed, which leaves us with filling in the potential design of the UFP mitigation system itself. This section will briefly discuss some alternatives that might be a good fit for the implementation of mitigation strategies at the airport.

Section 6.2.1 discussed the relevant water droplet cloud dimensions to implement an effective and efficient ultrafine particle mitigation strategy, and mentioned the potential of adjusting the droplet screen for each type of aircraft that is positioned at the dedicated area. It is interesting for the airport to implement a system where the water droplet production equipment can be placed in such a way that the created droplet cloud/screen is aimed at a specific aircraft stand. For instance, a system that is based on the use of water pipes with spraying nozzles mounted onto them (SprayWall) is divided into the number of aircraft stands, which makes it possible to create a dedicated water droplet screen/cloud for a specific type of aircraft that is positioned at that aircraft stand. A system that integrates this spraying strategy needs a dedicated (remote) location where the cold start of the aircraft could take place and where the water droplet production devices could be constructed. An example of such a potential platform configuration can be compared with the aircraft stands at the future A-pier at AMS (interview with Safety Consultant of KLM, appendix F.2). It is important that the platform, where the UFP mitigation strategy will take place, is compatible for all type of aircraft to be parked there and to be processed by the system. A complex lining pattern, indicated by led lights as well, is applied to indicate the correct position for each type of aircraft. A Visual Docking Guidance System (VDGS), can be implemented to assist the positioning of the aircraft. This system currently helps LVNL to determine which type of aircraft needs to be positioned at the stand, and it also may be a helpful tool for the implementation of the future UFP mitigation system at a remote starting location. The nozzles of the water droplet equipment could be adjusted and aimed to the right position for each type of aircraft (engine), which results in a better placed droplet cloud that covers the relevant dimensions of the jet blast. The trade-off that needs to be considered here is between the more efficient use of water by the system and the technical efforts that need to be made to enable this (interview with Advisor Stakeholder Strategy & Development of RSG, appendix F.11). As the providers of the water droplet production equipment state that the devices are able to direct the water droplets well (section 5.3), the technical feasibility of this system alternative should be relatively high. A schematic example of such an implementation is visualized in figure 32, which shows that the water droplet cloud is only produced at the position dedicated for narrow body aircraft, while the position dedicated for wide body aircraft is not covered by the droplets.

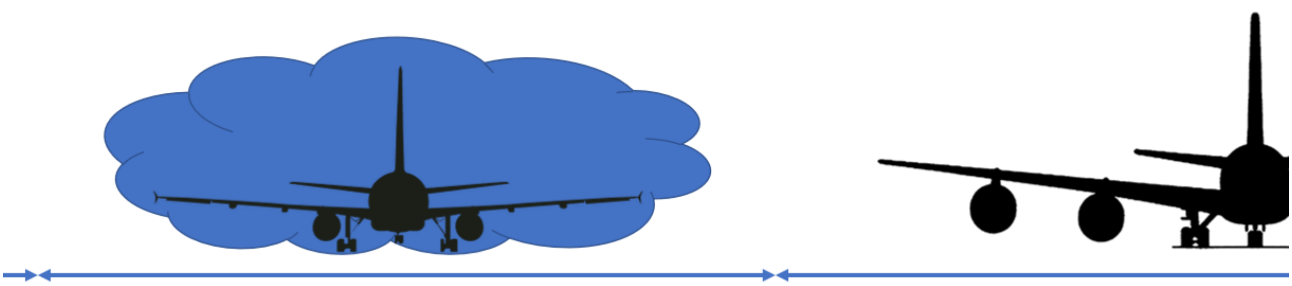

Figure 32: Mitigation strategy of spraying separate aircraft positions

Besides the discussion whether the (remote) platform for the cold start of the aircraft engines should be divided, the optimal distance between the outlet of the jet engines and the produced water droplet screen was also up for debate between the interviewed stakeholders. Several stakeholders state that the water droplets should be sprayed into the core of the engines to create as many droplet-UFP interaction opportunities as possible, while others mentioned that the high temperatures and wind velocities that close to the engines would evaporate and/or blow away the water droplets. Placing the water droplet production equipment too far away from the aircraft will also not result in the most effective situation, as the air will increasingly disperse when the distance from the engine outlets increases (interview with professor from WUR, appendix F.3). The distance from the jet engines should thus be determined in such a way that a significant share of the initially emitted UFP can be captured by the water droplets. As stated in chapter 3.2, the background concentrations of ultrafine particles at airports are usually already very high. This makes it imaginable that the water droplet cloud is also able to capture UFP, which is still present around the dedicated location, from other aircraft and other sources. A schematic example of a UFP mitigation strategy that is placed further away from the aircraft is shown in figure 33, of which the water spraying equipment alternative is the 'ground-bound SprayWall'.

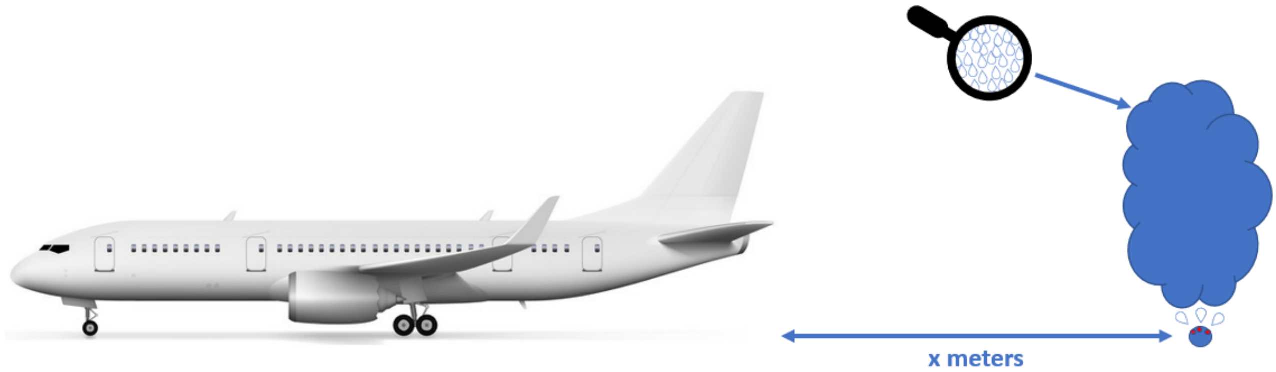

Figure 33: System configuration of SprayWall just outside 'safe zone'

Instead of a SprayWall that is placed on the ground and that sprays the water droplets upwards, the water pipes with spraying nozzles mounted onto them could also be fixed onto an overhead installation (section 5.3.2, figure 34). This might be a more suitable alternative for the mitigation strategies that are focusing on up-close UFP mitigation, since the construction of this system limits the spraying dimensions and it is thus of importance that the jet blast (vortex) does not disperse too much. Spraying cannons are a suitable alternative for this implementation and could provide a more flexible mitigation strategy.

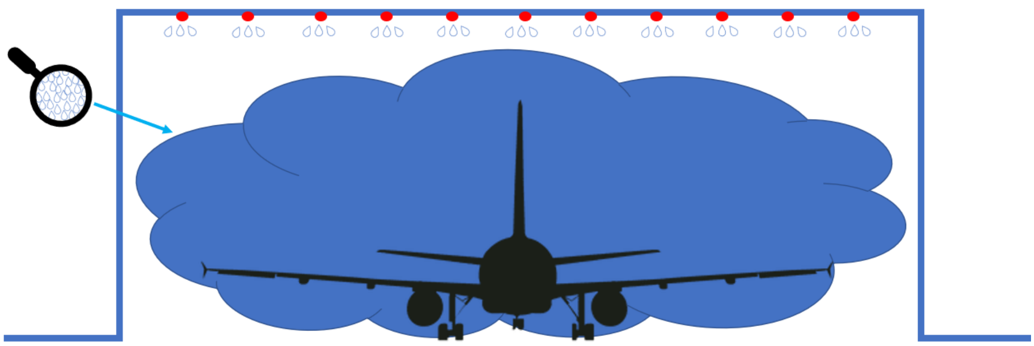

Figure 34: System configuration of overhead SprayWall

6.4 Feasibility

Now the conceptual system design for a 'water droplet'-based ultrafine particle mitigation system at the airport has been proposed, it is important to validate this design by assessing the discussed system components on whether they can be created with new or existing technology. A feasibility analysis is necessary to determine whether a system design can be implemented with the current knowledge, technology and other means, and to gain insight in which resources are still needed to make the potential implementation possible. A brief feasibility analysis is conducted for each of the relevant system design components, while taking the gathered knowledge and insights from the stakeholder interviews into account. These are discussed in the following subsections.

6.4.1 UFP mitigation during the cold start of the aircraft engines

The implementation of a system that combats the ultrafine particles that are produced by aircraft during the cold start of the jet engines seems the most feasible out of all the aircraft operation processes during which the system could be deployed. The aircraft is positioned at a dedicated position, which makes it a lot easier to produce the water droplet cloud across the desired dimensions. Instead of bringing the water droplets to the aircraft, the jet blast from the engines is directed to the already present water droplet screen. The devices for the production of the water droplets can be placed at a dedicated location at a certain distance from the position where the aircraft engines will be started, without disturbing other airport activities. These limited logistical challenges of UFP mitigation during the first process of the aircraft operation thus contribute to the operational feasibility of the implementation of a potential future system.

6.4.2 UFP mitigation at potential remote starting positions

Remote starting locations are an interesting alternative for the potential implementation of a UFP mitigation system at Amsterdam Airport Schiphol. It is important to analyze the currently available infrastructure and facilities for the construction of central starting positions to determine whether additional investments and constructions are necessary. The impact on the airport processes, by moving the cold start of the operation from the aircraft stand at the pier to a remote starting position, has been discussed extensively with stakeholders from Royal Schiphol Group, but also with other active stakeholders at the airport. The discussions with the two stakeholders from the Airport Operations department of RSG provide some useful insights regarding the current alternative locations at AMS for the potential implementation of remote starting positions (appendices F.10 and F.14).

The potentially available locations for the construction of remote starting positions have been extensively discussed in section 6.1. The Echo and Papa buffer (E- and P-platform) are both located between the D and E piers just outside the DE-bay, which is northeast of the airport building. The Juliet buffer (J-platform) is located next to the remote deicing platform, which is northwest of the airport building. From this set of alternatives, the P-platform and the remote deicing platform, including the J-platform, seem the most feasible to turn into remote starting locations, due to their geographical placement and their capacity. Using the aircraft positions at the E-platform is also possible, but many other positions of the D-platform have to be sacrificed for this purpose (interview Senior Process Advisor from RSG, appendix F.10). The capacity at the Papa buffer is fairly limited, but the available infrastructure is ideal, as aircraft have much space to make turns and many taxiways are adjacent to this platform. The Juliet buffer has more available capacity, but this platform is a bit more secluded and is less accessible for aircraft.

Several stakeholders addressed the potential benefits of turning the remote deicing platform into a remote starting location, during the warmer months of the year when it is not used for the deicing procedures. The available infrastructure at this platform offers a lot of capacity during the warmer months of the year, which makes high intensity use for remote starting activities possible. Besides the available space, the platform also has water collection, drainage and spraying facilities, which could be deployed for the production and (re)collection of water droplets for the UFP mitigation system after some necessary adjustments (interview with safety consultant of KLM, appendix F.2). Water drains are installed, so the water (with UFP) can flow away from the infrastructure after which it is collected in underground water tanks. Besides this, no employees are walking around there, so the safety hazards are fairly limited. Important to mention is that the remote deicing platform will have little to no capacity available for remote starting procedures during the Winter months, as aircraft will undergo the deicing procedures here. Not all positions will be used for this purpose throughout the whole day, but mixing these processes does not seem safe and efficient.

At first glance, it seems like there is sufficient capacity at Amsterdam Airport Schiphol to make the implementation of fully remote starting locations for the aircraft operation feasible. The discussed locations offer well-fitting infrastructure and facilities for this purpose, but an extensive analysis needs to be conducted in order to map the actual available capacity, as well as the necessary capacity for fully remote starting.

6.4.3 Use of water droplets for aircraft-produced UFP mitigation

The feasibility of the UFP mitigation strategy based on the use of water droplets is probably the most important criterion for the potential implementation of the system. The principle of encapsulating airborne particles in water droplets is relatively new and there is currently little to no (academic) research available that discusses this technique. The reasoning behind this mitigation strategy comes from the industrial sector, where water droplets are used for dust control in construction, mining and demolition projects (chapter 3.4). The use of these water droplets has been proven very effective to suppress the spreading of dust and thus prevents dust pollution and inhalation by people in neighboring areas. Providers of the spraying equipment also supply the devices to companies for the mitigation of fine particles, which is proven to be effective for this smaller form of dust (Erkho BV, 2022). MB Dustcontrol is a supplier of such water spraying equipment and was also the provider of the spraying devices for the experiments of Royal Schiphol Group and TNO in March 2022 (Schiphol, 2022b). This shows that the industry sees the potential of using water droplets to even combat the smallest forms of emissions, such as aircraft-produced ultrafine particles. Support from the industrial sector is of importance for the feasibility of the eventual deployment of water droplets to mitigate UFP, but acknowledgement from the academic community that this mitigation strategy could be effective is just as important. Professors and experts in the field of (nano) particles and meteorology confirm the theory that small water droplets are able to encapsulate ultrafine particles to prevent further dispersion of these airborne particles. A professor in meteorology and air quality from the department of Environmental Sciences of the WUR states that UFP moves in Brownian motion, which means that it might easily get trapped inside a larger particle, such as a water droplet (appendix F.3). He states that, once a particle is encapsulated by the water droplet, it is there to be washed out. This theory is affirmed by a stakeholder from the University of Twente, who is an associate professor/researcher with expertise in (nano) particle-droplet interactions and the drying of systems. He addresses that, as long as the relative humidity is high and the temperature is relatively low, the condensation of UFP (clumping together) and the absorption by water droplets will be possible and this mitigation strategy might be feasible at the airport. A researcher from TNO with expertise in (nano) particles and atmospheric composition also states the feasibility of deploying water droplets to effectively mitigate a significant share of aircraft-produced UFP from the air, while addressing the conducted water spraying experiments behind the aircraft (appendix F.6).

However, it is important to state that the spraying of water droplets behind the aircraft engines during the cold start is associated with extreme conditions. The use of water droplets might work very well for the mitigation of dust and fine particles in the construction and mining industries, but the air velocity and other external conditions in these industries are way less extreme than these are for the jet blast of an aircraft (interview with professor in meteorology and air quality of WUR, appendix F.3). A technical difficulty of this system might thus be the fundamental difference between the mitigation strategy at the airport and the solution that is found for other industries. It is of importance to determine at what wind speeds the ultrafine particles, coming from the jet engines, can still be encapsulated by the water droplets, without the droplet cloud being completely blown away by the jet blast. The discussed alternative of placing the water spraying devices inside the safe zone of the aircraft, but at a significant distance of the aircraft engines, might therefore be interesting in terms of feasibility. Mitigating at a certain distance from the outlets of the aircraft engines enables the wind currents to calm down (less turbulence and less strong vortex) and the temperature to drop (interview with research in (nano) particles from TNO, appendix F.6). Implementing the system at a distance from the location where the aircraft is positioned for the cold start, where the mitigation conditions in terms of water droplet and UFP interaction are more optimal, could thus increase the feasibility.

6.4.4 Implementation of a mitigation system at the AMS airport grounds

It is also of importance to determine whether the construction of the system at the airport grounds is feasible with the available resources, or whether investments are necessary and new technologies need to be incorporated for the implementation. As there are already companies that are specialized in supplying water spraying devices to various industries, the theory and technology behind the production of fine water droplets for the encapsulation of (ultra)fine particles is already available. The implementation of the water droplet production equipment at the airport infrastructure might be challenging, as a lot of accompanying systems need to be implemented as well. Facilities for water drainage, (re)collection and potential filtering all need to be incorporated in the infrastructure that is dedicated for the UFP mitigation system. Aligning all these systems is relatively complicated as there is no room for malfunctioning systems during the aircraft operation processes. However, these system components have already been implemented for other purposes at AMS (e.g., deicing and collecting rainwater), which means that a lot of resources and knowledge are already available for this system. This contributes to the feasibility of the potential implementation of the conceptual system design at the airport.

6.5 Viability

Analyzing whether the potential implementation of a system is viable for Amsterdam Airport Schiphol is also an important component of the conceptual system design validation. Determining the viability of a project or design is usually based on the results of executed quantification methods, with which the benefits and the costs are expressed in monetary terms. For businesses this provides insights regarding the profitability of a project and the return on investments, whereas societal projects are assessed in terms of the impact on society. For AMS and RSG, the viability of the implementation of the UFP mitigation strategy at the airport would be assessed by analyzing the impact on the health of employees and the quality of the living environment and determining whether these benefits would outweigh the initial investments and variable costs over a certain period of time. However, as this research was exploratory and qualitative methods were used, the viability of the proposed conceptual design for a UFP mitigation system at the airport was only assessed by insights and knowledge from the conducted stakeholder interviews.

6.5.1 The 'water droplet'-based UFP mitigation system itself

The viability of the potential system was mainly discussed with stakeholders from within the organization of Royal Schiphol Group. As they are often involved in the preparation and actual implementation of certain projects, they have insight into what is important, in terms of investments and benefits, for the eventual implementation of a project. First, the investments and expected variable costs that are associated with the implementation and eventual deployment of the UFP mitigation system will be discussed. The purchase of the water droplet production equipment, for multiple mitigation locations and for simultaneous use by a certain amount of aircraft, is an important part of the necessary investments that Schiphol needs to make for this system. However, the costs of these devices on the scale of the airport are not yet transparent. The costs of the spraying installations will be substantial, but an extensive cost analysis that incorporates the input of the potential suppliers needs to be conducted to retrieve insights in the order of magnitude of the costs. However, the aspects that are important for increasing the viability of the conceptual system design can already be analyzed. The degree of industrialization possibilities is an important characteristic of a viable system at the airport, which depends on whether the system is a widely applicable solution that can be reproduced well (interview with Sourcing Manager at RSG, appendix F.13). The department of Procurement & Contracting (PC) has a strong interest in the design of the final product/system, for which the following aspects are of importance: the use of standard components (no customization), sustainability, risk-free, and a reliable collective of development partners. The system should not only be implementable at Amsterdam Airport Schiphol, but also at other (Dutch) airports, which makes a reproducible system design according to the industry standard a necessity. The stakeholder from the PC department addressed that the system of water pipes is very valuable, but that the replaceable nozzles mounted onto this system makes it relatively easy to fix in case of a malfunction. Dividing the UFP mitigation system in such a way that it can spray water droplets at separate aircraft stands (section 6.3) results in a more efficient mitigation strategy, as well as in a more beneficial replacement strategy. These conceptual design aspects make the system more viable, as separate components of the system can be replaced instead of the complete system.

6.5.2 The impact on the airport capacity and available resources

A Process Owner Aircraft from the department of OPS at RSG mainly addressed the potential impact of fully remote starting on the airport capacity, as well as the necessary investments that are most likely associated with this conceptual system design component (appendix F.14). This stakeholder has the expectation that the number of employees and resources that will have to be deployed for the new operation, where the mitigation of UFP takes place during the cold start of the aircraft at a remote starting position, will have to be scaled up considerably. As all aircraft have to be towed from the stand at the pier to the remote starting position by a truck, the amount of truck movements will increase significantly, which results in the need for more aircraft tugs and a proportional increase in the number of drivers. This additional need for handling services requires investments, but the Process Owner Aircraft also predicts a non-desired impact on the starting capacity of AMS. When the implementation of an ultrafine particle mitigation strategy in combination with remote starting positions is not an option due to the current starting capacity of the airport, the balance between these two must be drawn up. Or accepting a lower starting capacity at AMS, which induces less aircraft movement per year but results in a more sustainable and healthy airport environment, or realizing a higher airport capacity by investing in the necessary resources and personnel. Another stakeholder from the OPS department argues that the current available infrastructure at AMS for potential remote starting locations is fairly close to meeting the required capacity that is needed for this fully remote starting system (interview with Senior Process Advisor at RSG, appendix F.10). For instance, Schiphol is planning to stop with inbound parking at the P-platform and the remote deicing platform offers a lot of capacity outside the Winter months, which provides opportunities for the implementation of remote starting locations. This stakeholder also addresses that aircraft tug drivers are often waiting for a significant amount of time before the operation in the current situation, which shows that there might be a potential to deploy these tow trucks for the pushback of the aircraft to the remote starting location. To conclude this section, the need for additional employees and resources needs to be analyzed extensively in order to make a prediction regarding the necessary investments, which in turn contributes to the better assessment of the proposed system design's viability.

6.5.3 Subsidies for the project implementation

An Advisor Stakeholder Strategy & Development of the S&AP department, who is also part of the 'task force UFP mitigation', addressed that the Dutch government grants subsidies to Schiphol for conducting research projects in sustainability and for the implementation of projects that contribute to a sustainable and future-proof airport (appendix F.11). A significant share of the needed investments for the potential implementation of a UFP mitigation strategy will thus be subsidized by the Dutch government. Besides this, Royal Schiphol Group is currently leading a broad European consortium called TULIPS, which is a collaboration of airports, airlines, knowledge institutes and industrial partners (Schiphol, 2022a). The objective of the consortium is to accelerate the implementation of sustainable technologies in aviation and aims to "significantly contribute towards the zero emissions and zero waste airports by 2030 and climate-neutral aviation by 2050". The European Commission has awarded 25 million in funding, which can be used to develop sustainable innovations such as for the mitigation of aircraft-produced UFP. These grants from government institutions and other investors partly meet Schiphol's own expenses.

6.6 Desirability

A system might be feasible and viable, but when a solution is not desired by Amsterdam Airport Schiphol and the involved stakeholders, the implementation will not take place. The system needs to be desirable from the organization's and industry's point of view, which shows the necessity of the solution and the amount of trust that the involved stakeholders have in the system. The desirability of a system can be determined by presenting the conceptual design to the involved stakeholders and gathering their insights and opinions on the implementation of the system and the separate components. The desirability assessment of the proposed conceptual design of the potential UFP mitigation system is based on the interviews with employees of Royal Schiphol and stakeholders from within the aviation industry, and is discussed in the following subsections.

6.6.1 Implementation of new systems/processes in the aviation industry in general

All new solutions and implementations in the aviation industry are usually not desired in advance by all parties involved in the operation of the aircraft (interview with Safety Consultant of KLM, appendix F.2). The zero alternative, which implies to keep the operation exactly the same, is generally the most interesting alternative for airlines, aircraft manufacturers and handling services. New systems, with sustainability as an objective, usually result in an increase in the turnaround time of the aircraft, which is associated with an inevitable increase in the ticket price for the passengers. Airlines want to maintain a profitable operation, but they also want to invest in a more sustainable image. The proposed system might result in a longer turnaround time of the aircraft and less revenue, but it might also contribute to the airlines' sustainability goals and their general image to potential passengers. For airlines and aircraft manufacturers it is also of importance that the mitigation of aircraft-produced UFP, by spraying water droplets into the highly concentrated areas, is not accompanied by additional risks for the aircraft. As long as the aircraft manufacturers confirm that the aircraft can operate in normal conditions in a situation where the proposed system is implemented, the airlines will not necessarily be against it.

Air Traffic Control the Netherlands (LVNL) also has their interest in the potential implementation of the discussed system, as they have to guide the aircraft from the aircraft stand at the pier up to the departure from the runway. Their guidance process becomes more complicated due to the additional phase of remote starting of the aircraft engines. LVNL probably won't be a big proponent of the new system, but the implementation will not result in drastic consequences for their operational responsibilities. Once the parties that are responsible for air traffic control are in favour of the new system, other stakeholders and parties in the aviation industry will have more trust in the implementation.

6.6.2 Necessity to tackle the UFP concentration accumulations at AMS

Royal Schiphol Group have started their research on the mitigation strategy of deploying water droplets to encapsulate UFP a few years ago, with the objective to explore potential systems to combat the aircraft-produced ultrafine particle concentrations at Amsterdam Airport Schiphol and analyze their performance. The fact that this is such an important item on the agenda of Amsterdam Airport Schiphol shows the urgent need of finding a solution to the UFP concentrations problem at the airport. The desirability of any conceptual system design is therefore already relatively high.

The Safety Consultant of KLM mentioned during the interview that the current starting capacity of AMS will most likely be compensated for in the situation where the UFP mitigation system, in combination with remote starting, is implemented at the airport (appendix F.2). However, it is necessary to combat the dispersion of ultrafine particles and the formation of concentration accumulations at the airport grounds as soon as possible, which justifies the potential impact on the airport operations to a certain extent. There are different categories of solutions that can be implemented at the airport: operational, innovative and source solutions (interview with Senior Process Advisor at RSG, appendix F.10). The use of a system that produces water droplets to capture the aircraft-produced UFP is an example of an innovative solution, just as the use of sustainable aviation fuels (SAF), while moving the cold start of the aircraft engines further away from the aircraft stand at the pier is an operational solution. An example of a source solution is the improvement of the aircraft engines to enable a more complete combustion of kerosene. Section 6.1 discussed that remote starting locations are probably the most optimal for the implementation of a mitigation system, in terms of the health and safety of people working on the airport grounds. By starting the aircraft engines from a central remote starting position, the production of aircraft emissions is moved further away from the piers and terminals where many (platform) employees are walking around. This is of substantial importance for the protection of the ground personnel's health (interview with Safety Consultant of KLM, appendix F.2). The stakeholders of the departments of Royal Schiphol Group, that are involved in the UFP mitigation project, discussed that a combination of operational and innovative solutions will most likely result in the most desirable system. By removing the production of large amounts of UFP during the cold start from the aircraft stands at the pier, a direct effect can be seen in the form of lower UFP concentrations at the densely populated airport areas. As the (platform) employees are working in those areas, this operational solution might already be very beneficial. By combining this with the innovative solution of deploying the water droplet system during the aircraft's cold start, a significant share of the produced ultrafine particles can also be captured and will not further disperse. At a relatively short term, the proposed conceptual system design can provide very desirable effects in terms of health and safety.

As the airlines operational at AMS are the actual emitters of the large concentrations of ultrafine particles at the airport grounds, they are strong supporters of the implementation of systems and solutions to make their operation more environmentally friendly, without affecting their profitability (interview with Advisor Stakeholder Strategy & Development at RSG, appendix F.11). For instance, KLM is the airline with by far the highest share of aircraft movements at Amsterdam Airport Schiphol, and is thus the biggest emitting airline at the airport. A strategy that combats the dispersion of UFP across the airport grounds is therefor a desired solution, as it may contribute to the image of KLM and aviation in general. Progressive airlines, such as EasyJet and TUI, are already investigating new solutions to make their operation more sustainable, and will probably be welcoming a system that mitigates the ultrafine particle concentrations produced by their aircraft.

Sub-question 4: *'What is the feasibility, viability and desirability of the 'water droplet'-based ultrafine particle mitigation system design at the airport?'*

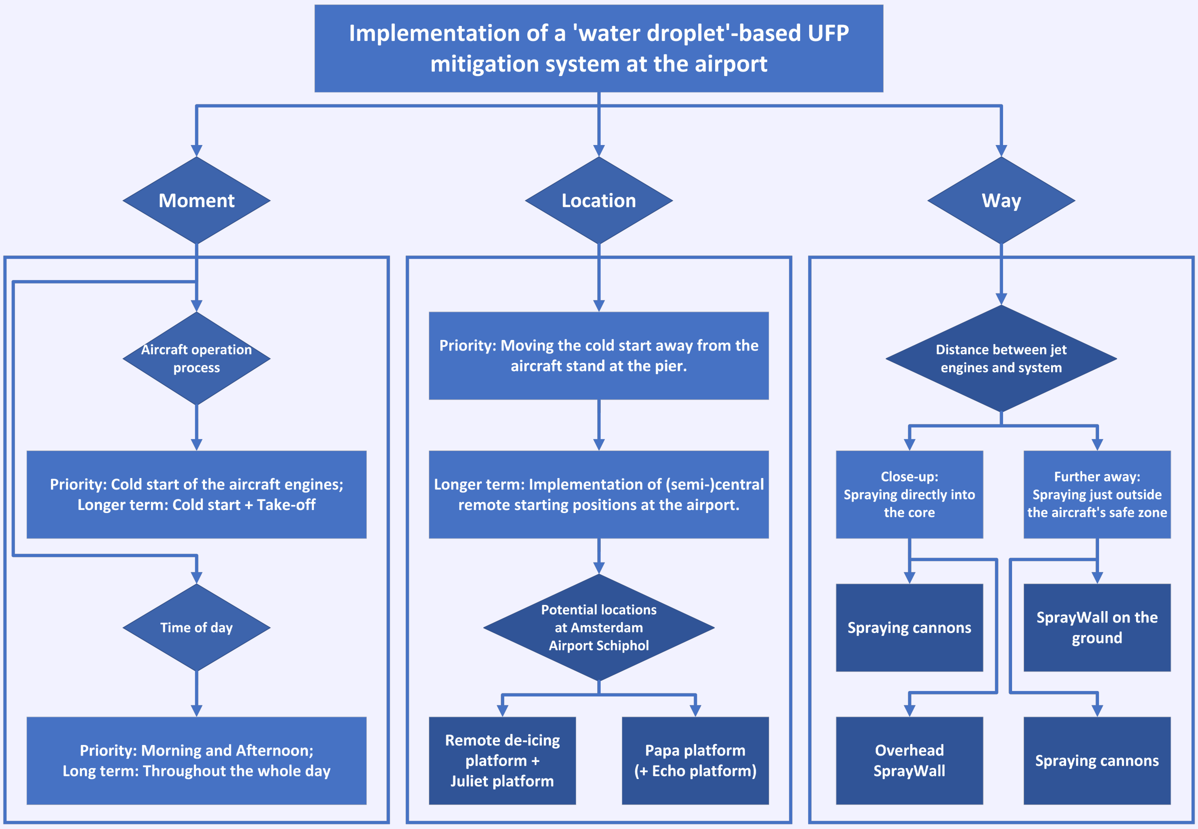

Figure 35: Conceptual system design of a potential UFP mitigation strategy at the airport

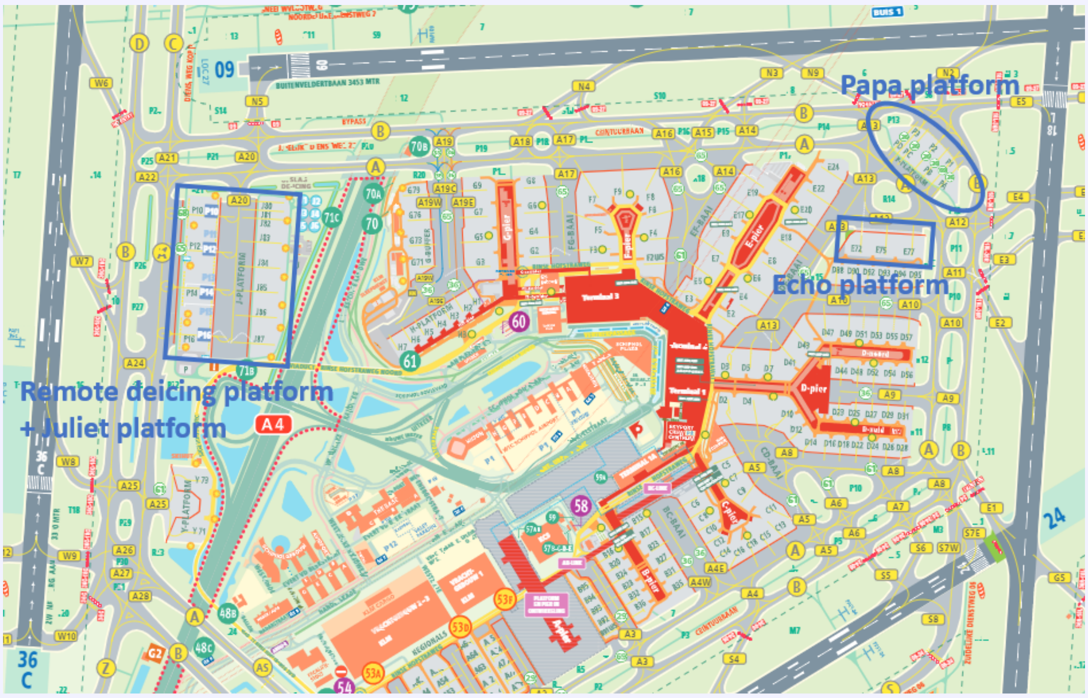

Figure 36: Potential remote starting locations at Amsterdam Airport Schiphol

Figure 35 shows a visualization of the conceptual system design of a potential mitigation strategy to combat aircraft-produced ultrafine particle concentrations at the airport. The diamonds in the framework represent the necessary decisions that should be made regarding the several system design components, as well as the potential decisions regarding the implementation of these components. The light blue rectangles in the three boxes show the proposed implementations, including a time horizon indication, while the dark blue rectangles show the most suitable alternatives that can be associated with the made decisions. Figure 36 shows the previously discussed potential remote starting locations at the airport grounds of AMS, which were introduced by several stakeholders of Royal Schiphol Group.

The proposed conceptual system design needs to be validated in order to indicate the expected potential of the system, before the implementation of the system at the airport can be further investigated. Assessing the feasibility, viability and desirability of the conceptual system design could provides insights whether the innovation is technically and financially achievable, as well as whether the system will be solving the right problem at the airport. These assessment criteria are used to determine whether the established system requirements are complied with by the conceptual system design. Chapter 5.4 provided an extensive requirements analysis, which resulted in an overview of all the operational, safety, economic, logistic and transition requirements that a potential UFP mitigation system needs to comply with before implementation at the airport. Table 19 provides an overview of all the established requirements and how the proposed conceptual system design scores on the feasibility, viability and desirability for each of them. Most requirements are not related to all three assessment criteria, which is why a share of the boxes is not marked to indicate that the criterion is not applicable for those requirements. A box is marked green in the 'feasibility', 'viability' and 'desirability' columns when the conceptual UFP mitigation system design complies with a requirement that is associated with the assessment criterion. A yellow-marked box indicates that it cannot yet be determined whether the system design meets the requirement, that is associated with the feasibility, viability and/or desirability. Normally, a box marked in red shows that a requirement is not complied with by the design, with no potential that this could be easily rectified. However, as this research is exploratory and the resources were not available to quantify the impact of the system implementation, the decision was made to indicate uncertainty about the system meeting a requirements with a yellow-marked box.

Operational requirements 5 and 6, which are associated with the water supply source of the system, show ambiguity with regard to the viability assessment. As there is currently no operating system at the airport grounds that requires the enormous amounts of water as a potential 'water droplet'-based UFP mitigation system, it is challenging to provide a useful estimation of the financial impact of the variable costs, as well as of the most viable water supply source. This also applies for the potential collection, filtering and reuse of the water (operational requirements 7 and 8), by which the feasibility and desirability of the system are also affected. Further analyses also need to be conducted in order to determine whether the potential system complies with operational requirements 11 and 12, which integrate the impact of the system on the turnaround time of the aircraft and the starting capacity of the airport. When this impact is not too substantial, the feasibility, viability and desirability of the system increases significantly.

Safety requirements 3 and 4 also discuss the use of large amounts of water for the operation of the system, but focus on the safety aspects that are associated with this water ending up on the airport infrastructure and in the environment. As it cannot yet be determined whether the used water can be fully collected during the operations, there cannot be affirmed that the conceptual system design meets these requirements in terms of feasibility. Safety requirement 10 integrates the importance of implementing the system as completely as possible, which is also related to the system transition requirements. Since there is no knowledge on the actual implementation process of the potential system, it is challenging to determine the feasibility of the complete system implementation. This also affects the related desirability of the system, as a partial UFP mitigation system will not result in an optimal situation at the airport.

The economic impact, in terms of the necessary investments for the implementation of the system, need to be quantified in order to determine whether the potential system is viable or not. This also significantly affects whether the system is desired by the airport and involved stakeholders. As the financial aspects of the system are not yet clear, there cannot be determined that the conceptual system design complies with the economic requirements.

Table 19: Assessment of the system requirements on feasibility, viability and desirability

1	Operational Requirements	Feasibility	Viability	Desirability
1	The water droplets should be sprayed in the area with the highest concentration of UFP.			
2	The air flows behind the aircraft should be complex and turbulent.			
3	The evaporation time of the water droplets should be as high as possible.			
4	The water droplet cloud should at least cover the complete cross section of the jet blast.			
5	The water supply must originate from a socio-economically accepted source.			
6	The water supply must originate from a sustainable source.			
7	The used water must be collected for reuse (as much as possible).			
8	The collected water should be filtered before reuse.			
9	The system shall not operate when the outside temperature at the airport grounds is below zero degrees Celsius (when using water without additives).			
10	The water droplets must not instantly evaporate when the outside temperature at the airport grounds is relatively high.			
11	The operation of the system should limit the increase in the turnaround time (as much as possible).			
12	The operation of the system should limit the decrease in the starting capacity (as much as possible).			
2	**Safety Requirements**			
1	The water droplets should not be sprayed into the inlet of the aircraft engines. / The water droplet production equipment should be installed behind the jet engines.			
2	The large amounts of water must not cause a significant impact on the decay of the aircraft.			
3	The large amounts of polluted water (with UFP and additives) must not end up in the environment.			
4	Large puddles of water should not arise at the used airport infrastructure.			
5	The water droplet cloud must not be created in the vicinity of airport employees.			
6	The water droplets should stay in liquid form for as long as possible.			
7	The system should not be implemented in the 'safe zone' of the aircraft, unless it is proven to be capable of enduring the jet blast.			
8	The first 40 meters on both sides of the middle of the runway must be obstacle-free.			
9	The construction of the system must be able to break down easily in the event of a colission.			
10	The system implementation and processes must be kept simple, unambiguous and uniform.			
3	**Economic Requirements**			
1	The fixed and variable construction costs of the system should be as low as possible.			
2	The available airport infrastructure and facilities should be optimally used by the system.			
4	**Logistic Requirements**			
1	The aircraft should be brought to the system, instead of the other way around.			
5	**Transition Requirements**			
1	The transition from the old situation into the new system should interfere with the aircraft operation and other processes as little as possible.			
2	The transition from the old situation into the new system should be implemented as completely as possible.			

7 Conclusion and discussion

This research explored the state-of-the-art of the concentrations of aircraft-produced ultrafine particles at the airport, with the focus on a potential mitigation strategy, based on the use of water droplets, to combat these UFP concentrations. A conceptual system design, which incorporates this 'water droplet'-based UFP mitigation strategy, was proposed for Amsterdam Airport Schiphol specifically. However, the gathered insights and knowledge are useful for case studies at other airports as well. The conclusion of this research is presented in section 7.1, after which the discussion is provided in section 7.2.

7.1 Conclusion

The conclusion of this research will first provide an answer to the main research question, after which the scientific and practical contributions that this research offers are identified.

7.1.1 Answer to the main research question

The aim of this research was to explore potential designs of an ultrafine particle mitigation system at airports, based on the deployment of water droplets to encapsulate the aircraft-produced airborne UFP and filter them from the air to prevent further dispersion across the airport grounds. The potential system designs consist of several components that integrate all the essential aspects of implementing a new innovation at the airport grounds. This research objective resulted in the following main research question:

'*What is the most suitable conceptual system design of a 'water droplet'-based mitigation strategy to combat aircraft-produced ultrafine particles at the airport?*'.

The potential system designs consist of several components that integrate all the essential aspects of implementing a new innovation at the airport grounds. Initial insights and knowledge regarding these system components were gathered by conducting a literature review and a case study at Amsterdam Airport Schiphol. To supplement these academic findings, 14 semi-structured interviews with stakeholders of several backgrounds, but all with expertise in the aviation industry and/or in the theory behind UFP-water droplet interaction, were conducted. Since it is a qualitative research that investigates an airport problem that has recently received more attention in the industry, as well as a completely new innovative technology, the input from involved stakeholders is of great importance for the determination of the conceptual system design implementation.

A current priority at AMS is to tackle the high ultrafine particle concentrations that accumulate at the densely populated areas close the airport terminals, such as the piers and platforms. Stakeholders from Royal Schiphol Group, as well as from other airport companies, mentioned the potential health risks for the platform employees and ground personnel who are walking around at these areas. The most direct benefits could be realized at these areas, which shows the importance of implementing UFP mitigation strategies that combat the concentration accumulations. Several studies at airports around the world analyzed conducted UFP measurements at and around the airport grounds, of which a research at Schiphol provided the most specific and complete insights. The highest concentrations that could be directly related to the aircraft operation were indeed measured at the airport terminals, piers and platforms, which could be linked to the nearby 'jet blast events': the cold start of the aircraft engines, ground idle procedures and the take-off on the runway. The cold start of the aircraft engines is associated with the production of large amounts of emissions, as the engines are turned on again after completely cooling down, which includes the combustion of additional waste in the jet engines. The cold start currently takes place at the aircraft stand at one of the piers of the airport building, which makes it the aircraft operation process that takes place the closest to the areas where (platform) employees are walking around. This aircraft operation process is therefore a suitable alternative for the conceptual system design component that integrates the moment of deploying the UFP mitigation strategy. The moment-bound design component also incorporates the time of the day during which the system should be deployed. Since the highest share of aircraft movements at AMS take place during the morning and the afternoon, the priority of combating ultrafine particle concentrations is the highest during these periods of the day. On the longer term, it is also interesting for the airport to investigate the potential of implementing a UFP mitigation strategy during the take-off on the runway and to extend the operating times of the system throughout the whole day (left side of figure 37).

The essence of moving the cold start of the engines further away from the piers elaborates on the previously discussed system design component. Quick benefits could be achieved by starting the aircraft engines at a certain distance from the original aircraft stand, as the employees are partly prevented from coming into contact with high UFP concentrations. On the short-term it is therefore beneficial to implement this partial solution, but in the long-term it is important for the airport to implement dedicated locations for this part of the aircraft operation, in order to create a more uniform and unambiguous system. The introduction of (semi-)central starting positions is an interesting alternative for the location where the cold start of the aircraft engines could take place. At Amsterdam Airport Schiphol, potential locations for the implementation of remote starting positions are the P-platform (Papa), E-platform (Echo), J-platform (Juliet), and the remote deicing platform (figure 36). A combination of these locations will be able to provide a substantial share of the starting capacity at AMS, whether or not the entire starting capacity, and are also able to offer sufficient space for the implementation of the facilities for the potential UFP mitigation system. Moving the production of ultrafine particles further away from the locations where many people are walking around on the short-term, in combination with the longer-term implementation of mitigation strategies to combat the formation of concentration accumulations, could lead to an effective and efficient solution to tackle this issue at the airport (center of figure 37).

The debate is still up whether the 'water droplet'-based UFP mitigation strategy needs to be implemented closer to the outlets of the aircraft engines, or whether the creation of a water droplet cloud/screen at a certain distance from the aircraft results in the most optimal mitigation strategy. Both strategies have their own benefits, which is why they are both integrated into the conceptual system design (right side of figure 37). The equipment that could be deployed for the production of water droplets to interact with the aircraft-produced UFP is available in several alternatives, of which the most suitable alternatives differ for the two different mitigation strategies. The spraying cannons are able to adjust the spraying angle and direction in such a way that the water droplets can be directed to the core of the aircraft engines, while a SprayWall on the ground is better able to efficiently create a water droplet screen against which the jet blast can be blown at from a greater distance. However, the overhead SprayWall and the spraying cannons could also be suitable alternatives for the close-up and further-away mitigation strategies respectively. The discussed equipment is able to produce a water droplet cloud that covers the cross-section of the jet blast (vortex) and reach the determined necessary width, height and depth. Besides this, these devices could make use of collected rainwater, after which the used water could be collected again and filtered before reuse.

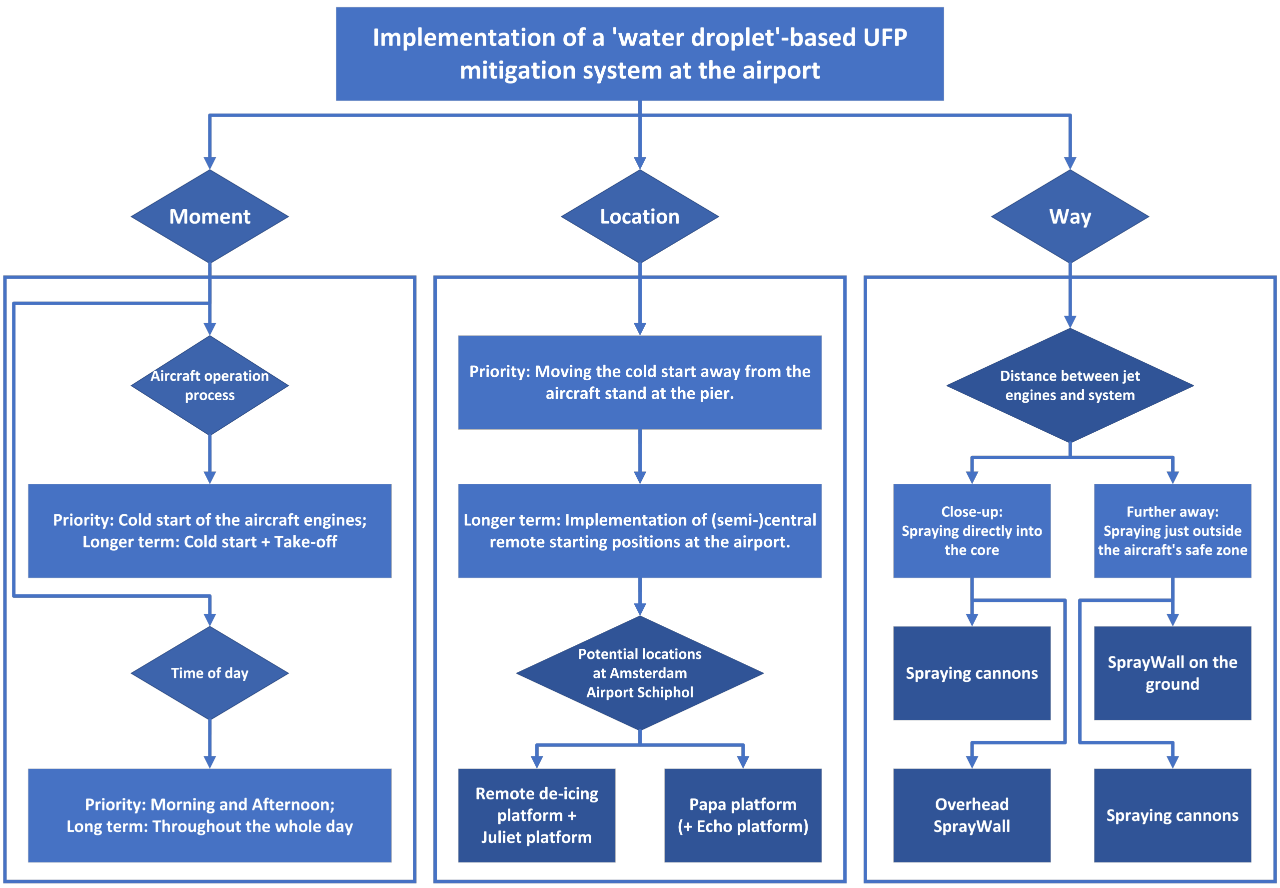

Figure 37: Conceptual system design of a potential UFP mitigation strategy at the airport

Figure 37 provides an answer to the main research question by presenting the most suitable and promising layout/implementation for each system design component, while also taking the feasibility, viability and desirability of the overall system design into account.

7.1.2 Scientific contributions

This study is one of the first to explore the ultrafine particle problem at the airport grounds, while associating the measured UFP concentrations at certain locations with the responsible sources. Previous studies on this topic mainly focused on the UFP measurements itself, as well as on the locations of concentration accumulations at the airports. This research supplemented the current state-of-the-art of academic research regarding aircraft-produced ultrafine particle mitigation at the airport, and thus (partly) filled the knowledge gap that was established after the conducted literature research. As there are currently little to no conducted (academic) studies about UFP mitigation available, this research provides new knowledge and insights about this topic that is still in its infancy. This study addresses the mitigation strategy of deploying water droplet production devices, which has not been incorporated in currently available academic work, and thus explores a completely new potential solution for this problem at the airport. This mitigation strategy could provide inspiration for airports around the world to think out of the box when searching for potential solution directions to tackle certain problems at the airport, which corresponds with the way of working of the Innovation Hub at Royal Schiphol Group.

The literature review and Amsterdam Airport Schiphol case study of this research elaborated on the ultrafine particle measurements at the several airport locations by providing an overview of the previously conducted studies, while also mapping the system of involved stakeholders within the UFP problem at the airport (AMS specifically). Involving a wide variety of experts to provide insights and knowledge regarding the ultrafine particle problem at the airport, as well as to provide input related to the potential mitigation strategies, is new within this research topic. An initial overview of the current state of the UFP problem at AMS within the aviation industry and the academic world could act as the foundation for follow-up research into the aircraft-produced ultrafine particle problem at the airport, as well as for future research into the exploration of potential strategies to combat the UFP concentrations at the airport grounds. The gathered insights and input are fairly subjective, as each involved stakeholder will have their own opinions and ideas regarding the topic, but they nevertheless show how certain organizations and experts within a certain field of expertise might position them self within the UFP mitigation problem.

The collection of the used methodologies could provide a useful structure for the design of innovative technologies at the airport in future research. This study addresses a significant share of all the relevant aspects and system components within the ultrafine particle problem at the airport, and thus provides a quite complete framework of all system dimensions that need to be determined. The conducted stakeholder analysis already provides quite a broad overview of all the actors that have a certain position within the system, while the requirements analysis provides a good basis of the set of requirements that the potential system design needs to comply with during future design analyses. This study could give an idea which system aspects and research directions could be taken into account while exploring the potential implementation of a new airport innovation.

7.1.3 Practical contributions

The discussed scientific contributions of this research resulted in a conceptual system design, which integrates the potential implementation of mitigation strategies to combat aircraft-produced ultrafine particle concentrations at the airport grounds. This conceptual design is substantiated by the gathered academic knowledge and the insights retrieved from the interviews with a wide variety of stakeholders from the aviation industry, as well as from research and knowledge institutes. It is an overarching study that discusses several aspects of the UFP concentration issue at airports and what might be potential strategies to tackle the problem, by taking a wide range of system components and requirements into account. First, a comprehensive overview is provided, which discusses the aircraft operation processes, relevant locations at the airport grounds, and currently available mitigation strategies that could be related to the potential implementation of an ultrafine particle mitigation system. This shows Amsterdam Airport Schiphol all the alternatives that are available, including the associated characteristics, benefits, and impediments, but could also serve as inspiration for analyses at other airports. The extensive requirements analysis that was conducted for this research gives an initial overview of all the system design boundaries that need to be established for the exploration of potential UFP mitigation system alternatives. This study is the first to analyze a wide variety of requirements that must be complied with by 'water droplet'-based mitigation strategies at the airport, while including insights and knowledge from experts within the airport community and from researchers/professors with expertise in the principles behind these strategies. Finally, a conceptual system design is proposed, which is deemed to be the most suitable for Amsterdam Airport Schiphol and the most interesting to further investigate by Royal Schiphol Group. The feasibility, viability and desirability of this design were assessed as well, which indicated the system aspects where the most improvement can still be achieved by conducting follow-up research and (quantitative) analyses. This document could be used by RSG and AMS, as well as by other airports, as a starting point and/or could provide feedback for future research (section 7.2) to recall system components and requirements.

Besides the practical contribution in terms of knowledge generation, this study has also taken the first steps towards gathering a group of interested and dedicated stakeholders from a wide variety of backgrounds for potential future brainstorm sessions and discussions about the ultrafine particle problem at the airport. The group of stakeholders involved in this research consisted out of the following experts:

- **Royal Schiphol Group:**
  - Department of Airport Operations:
    - Senior Process Advisor;
    - Process Owner Aircraft;
  - Department of Strategy & Airport Planning: Advisor Stakeholder Strategy & Development (Task force UFP mitigation);
  - Department of Safety, Security & Environment: Senior Environmental Advisor;
  - Department of Procurement & Contracting: Sourcing Manager;
- **Delft University of Technology - Faculty of Aerospace Engineering:**
  - Professor in Air Transport & Operations;
  - Assistant Professor in Aircraft Noise and Climate Effects, Air Quality and Air Pollution;
  - Professor in Flight Performance and Propulsion, Flow Physics and Technology;
- **KLM Royal Dutch Airlines:** Safety Consultant;
- **Wageningen University & Research - Department of Environmental Sciences:** Professor in Meteorology and Air Quality;
- **Copenhagen Airport:** Head of Sustainability Development;
- **TNO:** Researcher in (Nano) Particles, Atmospheric Composition, Air Quality Modelling;
- **Airbus Technology Bremen:** Senior Manager and Aircraft Architect, Head of R&T Plateau Bremen;
- **University of Twente - Faculty of Science and Technology, Physics of Fluid:** Associate Professor/Researcher in (Nano) Particle-Droplet Interactions and Drying of Systems.

This group of stakeholders thus consists of experts from several organizations within the aviation industry, both Dutch and international, as well as of professors and researchers from the academic community, all with their own interests in the ultrafine particle problem at the airport (AMS specifically). The transcriptions of the conducted semi-structured interviews provide Royal Schiphol Group, as well as other parties with interest in the system, with a brief overview of insights, knowledge, opinions and ideas from all the involved stakeholders. During the continuation of researching the aircraft-produced UFP concentrations at the airport and the potential strategies that can be implemented to combat the dispersion and formation of these concentrations, these gathered findings could be used as some sort of reference work, as they address a significant share of the currently available knowledge and discussions. This study could also be used as a starting point and/or could provide feedback for follow-up research to recall potential stakeholders. All the involved experts were very interested in the UFP problem at AMS, but even more in the progress of Royal Schiphol Group's project that explores the innovative technology based on the use of water droplets to combat the ultrafine particle concentrations at the airport. Most stakeholders, while not including those from RSG, indicated on their own initiative that they are interested in the continuation of the project and would be willing to contribute further when there is a demand for it in the future.

7.2 Discussion

This section of the final chapter will first discuss the limitations of this research, which are followed by the recommendations for future research in this area that can contribute to this research.

7.2.1 Limitations of this research

While evaluating this research, it is of great importance to also indicate the limitations of the deployed methodologies and the study itself. First of all, in consultation with Royal Schiphol Group, the decision was made to focus on the 'water droplet'-based UFP mitigation strategy in this research. As RSG was already investigating the potential of using water droplets for combating the aircraft-produced UFP concentrations at the airport, other potential mitigation strategies were not included in the scope of this research. Other strategies to mitigate the dispersion of aircraft-produced ultrafine particles across Amsterdam Airport Schiphol were briefly mentioned, but were not considered as alternatives in the composition of the conceptual system design. Therefore, the research does not provide the reader with a complete overview of potential UFP mitigation solutions and might give the idea that the potential use of a water droplet screen/cloud is the only interesting option.

It is also important to mention that this research tends to provide an overview of the currently available insights, knowledge and opinions on the mitigation of ultrafine particles at all airports in general, but that the proposed conceptual system design is compiled while keeping the potential implementation at Amsterdam Airport Schiphol in mind. The literature review, as well as the analyses of the system design components and requirements, could be useful for other airports around the world, but the case study and the actual conceptual system design are mainly directed to AMS and RSG. Besides this, a significant share of the involved stakeholders was also approached via contacts from Schiphol, which kept the international insights and knowledge relatively limited. Interviews with more stakeholders from other airports could have resulted in a broader overview of the UFP problem at airports, but this would have been accompanied by less insider knowledge regarding the situation at AMS. Additional interviews with representative stakeholders from several other important organizations in the aviation sector, as well as from other external parties, could have also contributed to the theoretical body of this research. However, the possibilities to include more important stakeholders in this research were limited by the available time and resources.

An important limitation of this research is the qualitative nature, which results in the composition and evaluation of the conceptual system design in a theoretical way. As the production of ultrafine particles has only been a research topic over the last decade and the potential mitigation of UFP (by using water droplets) is still in its infancy, the decision was made to keep the research exploratory. The goal was to incorporate a wide variety of stakeholders from the aviation industry, as well as several experts with knowledge in the field of aircraft emissions, propulsion and meteorology, within the semi-structured interviews, in order to provide a very broad overview on the research topic. Much knowledge and many insights were gathered, as well as a wide range of opinions and ideas on the potential implementation of a 'water droplet'-based system to mitigate aircraft-produced UFP. The semi-structured interviews were a convenient tool to start one-on-one discussions with each stakeholder and get a good idea of what their position is within the UFP mitigation debate. However, these findings were fairly subjective as all stakeholders have their own interests regarding the topic and do not have the same information on the mitigation strategy and aircraft-produced UFP in general. A method that could have probably resulted in more fruitful discussions is, for instance, organizing workshops and table discussions with a selection of the stakeholders. By providing the stakeholders all with the same information regarding the topic and the research, they can discuss their visions on UFP and potential mitigation strategies with each other in a fair and purposeful manner.

As the research is exploratory and not quantitative, the validation possibilities to assess the conceptual system design were very limited. The use of several design criteria and the evaluation of the scores of the proposed design on those criteria could have resulted in a more complete validation step. For instance, by expressing the components of the system design in monetary terms, the impact of the implementation of the system could have been determined more specifically by analyzing the various costs and benefits. Processing the system investments, the expansion of the remote starting capacity and the impact on the turnaround time of the aircraft as costs, while the impact on the health of the (platform) employees and the quality of the living environment are processed as benefits, could result in a helpful assessment of the system's impact. However, this assessment was not a part of the research scope, as the gap in the current academic body of knowledge first required an extensive analysis on the relevant aspects of the UFP problem at airports and a potential mitigation strategy. Once this area of research has been more explored, impact assessment and (societal) cost-benefit analyses of such systems become more relevant.

7.2.2 Recommendations for future research

As the discussion of the limitations of this research already showed, there are many interesting possibilities for follow-up research and sufficient knowledge gaps that can be addressed in adjacent studies. It is important to briefly mention these in case this research is consulted for future research.

Follow-up research in the field of ('water droplet'-based) UFP mitigation
A first field of study that requires extensive follow-up research before implementation at the airport is the potential deployment of ultrafine particle mitigation strategies that are based on the use of water droplet production equipment. As this study is currently one of the very few with 'aircraft-produced UFP mitigation, based on the use of water droplets, at airports' as the research topic, it is very important that more research will be conducted on this topic for strengthening the theoretical foundation and the academic body of work.

It is of substantial added value to further investigate the actual effectiveness of spraying water droplets in the areas with high concentrations of ultrafine particles to capture the UFP and lower the concentrations at the airport grounds. Royal Schiphol Group and TNO are currently busy with the preparation of the next round of UFP mitigation trials at the airport to follow-up the initial experiments carried out at the beginning of 2022. By adjusting the set-up of the aircraft and the spraying devices, as well as varying the settings of the equipment, the mitigation strategy can become more effective. After carrying out more experiments, it will become more clear whether this solution direction has actual potential of use under the extreme conditions during the aircraft operation. These analyses and measurements can then be incorporated into new studies.

Besides the effectiveness of the mitigation strategy itself, follow-up research on the separate system design components could also provide relevant insights for the potential future implementation. As the use of water is what the whole solution is built around, topics as the water supply source, the (re)collection of water and the need for filtering before reuse are all important to investigate extensively. According to the stakeholder interviews and by taking AMS's sustainability goals into account, rainwater seems like the most optimal water supply source for such a system. Before the rainwater can be turned into water droplets, it is important to determine how the rainwater can be collected at the airport grounds and whether filtering of this water is necessary prior to being used. The same goes for the recollection of this used rainwater, as it needs to made clear whether the "polluted" water can be reused by the system and whether filtering for the reuse is necessary.

Before a potential 'water droplet'-based UFP mitigation system can be implemented at the airport, a thorough analysis regarding the impact of large amounts of water on the aircraft, the environment and the health of (platform) employees needs to be conducted. The extent to which these factors are affected by the deployment of the system might be limited, but it is of importance to make sure that there are little to no safety and health risks associated with the system.

Exploring other UFP mitigation solution directions
This research focused on the exploration of the solution direction that is based on the potential of encapsulating ultrafine particles with water droplets to prevent further dispersion across the airport grounds. Other potential UFP mitigation strategies were briefly discussed, but were generally not investigated any further. Many involved stakeholders mentioned several other solution directions that might result in effective systems to combat the aircraft-produced UFP concentration accumulations at the airport grounds.

An example of an operational UFP mitigation solution has been discussed in more detail, which is the introduction of fully remote starting during the aircraft operation. Moving the cold start of the aircraft from the aircraft stand at the pier to a remote starting location at the airport grounds could already result in beneficial health effects for the employees that are working on the platforms. The aircraft emissions are produced further away which partially prevents the formation of high UFP concentration accumulations near the airport buildings. This strategy does not combat the dispersion of ultrafine particles and does not reduce the actual amount of UFP produced by the aircraft, but it is a mere in-between solution to obtain a direct health impact. As it could be beneficial for the health of the airport employees, it is interesting to further investigate the impact of the potential implementation of remote starting locations at the airport grounds. As discussed in this research, it is expected that this system might negatively impact the turnaround time of the aircraft and the starting capacity of Amsterdam Airport Schiphol. Impact analyses might provide insights regarding these effects.

RSG and AMS have been investigating the implementation of sustainable taxiing over the last years, which focuses on deploying sustainable aircraft tugs for ground idle instead of the aircraft taxiing themselves by running the jet engines. The fact that these projects in the field of sustainable taxiing are currently running within the organization of Royal Schiphol Group is one of the main reasons why UFP mitigation during ground idle is not considered as a priority. It is of value for future research in UFP mitigation solution directions to analyze the impact of sustainable taxiing on the produced concentrations of ultrafine particles and on the formation of concentration accumulations at the airport grounds. The combination of deploying a water droplet cloud at the cold start of the aircraft and implementing sustainable aircraft tugs for the ground idle procedures could result in a far more sustainable aircraft operation at AMS. Further research in the potential combination of these two sustainable projects might provide RSG and other stakeholders in the aviation industry with interesting and valuable results.

Another interesting solution for the realization of a lower production of ultrafine particle concentrations by aircraft is the use of sustainable aviation fuels (SAF). Several stakeholders, mainly from the academic community, discussed the interesting potential of these sustainable alternatives for kerosene, which should create less harmful aircraft emissions during the combustion in the jet engines. The carbon footprint of aircraft operating on SAF will be smaller in the life cycle context than the carbon footprint of an aircraft operating on kerosene, and might also have an impact on the amount of (ultra)fine particles produced during the combustion. The UFP concentrations at AMS are a local problem, while the use of SAF for the aircraft operation will probably be a global solution for sustainability. The switch to sustainable (sulfur-free) kerosene is therefore not the most obvious option, but analyzing the potential is still very interesting for tackling the UFP problem at airports around the world.

A final UFP mitigation solution direction that can be explored in future research is the use of more sustainable aircraft engines. These concern engines with a higher completed combustion and thus less residual products. The goal is to install jet engines that require less fuel for a more efficient aircraft operation that produces less emissions. Cars already have a catalytic converter, which contribute to the production of less polluting emissions. It is interesting to investigate the possibilities of improving aircraft engines by experimenting with potential built-in catalytic converters. More sustainable aircraft engines and the water droplet mitigation strategy could complement each other and might be able to combat the current UFP concentrations at the airport grounds.

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Appendix A   Scientific Paper

The scientific paper can be found on the following pages.

The Design of a 'Water Droplet'-based UFP Mitigation System at Airports - a Case Study at Amsterdam Airport Schiphol

R.B. Jebbink (4465059)

Abstract— **This research explored potential designs of an innovative mitigation strategy to combat the aircraft-produced ultrafine particle (UFP) concentrations at Amsterdam Airport Schiphol (AMS). This technique is based on the principle that fine water droplets are able to encapsulate dust and fine particles, which clump together and eventually descent to the ground. The reduction of airborne particle concentrations is expected to have a significant effect on the health of (platform) employees, which makes it an interesting strategy to further investigate. A wide variety of stakeholders, from both the aviation industry and the academic world, were interviewed about the important design components that need to be incorporated in a potential mitigation system, as well as essential requirements that the system needs to comply with. A system that integrated the cold start of the aircraft engines as the most suitable moment and the introduction of remote starting positions as the most optimal location for the implementation of UFP mitigation strategies, contributed to the proposed conceptual design for AMS. A system alternative in which the water droplets are directed into the jet engine outlets by spraying cannons was discussed for a close-up mitigation strategy, while an alternative in which a screen of water droplets is created to absorb the jet blast with emissions was established for the mitigation strategy at a further distance. The assessment of the conceptual system design, on its feasibility, viability and desirability, showed that the UFP mitigation system could have a desirable impact on Schiphol's environment on the short-term. However, the possibilities of implementing remote starting positions at AMS and the impact that the system has on the starting capacity and the turnaround time should be further investigated to increase the system's feasibility and viability.**

Keywords - Aviation, System Design, Aircraft emissions, Sustainability, Innovative technology

I. Introduction

The revival of the global aviation industry is in full swing, now that it seems that the peak of the COVID-19 pandemic is behind us. The number of flight movements is increasing again and airport companies and airlines are preparing to offer their services to returning and new customers at airports around the world. This is also the case for Amsterdam Airport Schiphol (AMS), which has been the main contributor to the growth of the Dutch aviation industry over the last decades. Aviation is associated with various advantages, such as a higher accessibility and the creation of many economic opportunities (Aguirre et al., 2019), but the enormous impact that air travel has on the environment has been overshadowing these benefits. Aircraft are known for producing large amounts of harmful emissions, of which particulate matter primarily affects the air quality and is one of the most harmful pollutants to human health (Marcias et al., 2019). Ultrafine particles (UFP) are the smallest form of particulate matter (< 100 nm) and research has indicated that these particles are generated in large amounts on airports by the jet engines used in commercial aircraft (Ungeheuer et al., 2021). Several studies on the impact of exposure to (aircraft-produced) UFP on human health have been conducted over the last decade. Findings showed that short-term exposure to high UFP levels near the Schiphol airport grounds were associated with prolonged re-polarization of the heart and decreased long function (Lammers et al., 2020). Prolonged exposure could result in adverse birth outcomes and can induce cell damage and release of pro-inflammatory markers (He et al., 2020).

With these potential risks on the health of the (platform) employees at AMS in mind, Royal Schiphol Group (RSG) initiated a UFP mitigation task force and started various research projects to investigate the potentials of tackling ultrafine particle concentrations at the airport. An innovative technology that is based on the use of a water droplet cloud to interact with the aircraft-produced ultrafine particles, is deemed to be a very interesting solution direction by RSG (Schiphol, 2021). The UFP is encapsulated and coagulates within these water droplets, which means that they clump together and are captured by the droplets. The water droplets with the clumps of UFP will eventually descent to the ground rather than disperse across the airport grounds. This could be an interesting strategy for airports to mitigate the impact of the aircraft operation on the health of employees and neighboring residents, as well as the air quality of the environment.

The state-of-the-art of research regarding aircraft-produced UFP mostly discusses the performed measurements at airports to analyze the concentration distribution, as well as the adverse health effects that are associated with exposure to ultrafine particles. There is currently little to no academic knowledge on potential mitigation strategies to tackle the concentrations, including the potential of deploying water droplets to prevent airborne distribution of these particles. This research aims to fill this knowledge gap, by exploring the relevant (conceptual) design components and requirements of a potential 'water droplet'-based UFP mitigation system at the airport. The objective of this research is to propose a conceptual system design, including the discussed components and requirements, which will be analyzed on its feasibility, viability and desirability.

The scope of this research is focused on UFP as the

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only emission, with aircraft engines as the only included source. Besides this, the mitigation strategy based on the use of water droplets is the only solution direction that has been investigated. The research has been conducted at Royal Schiphol Group, which is why Amsterdam Airport Schiphol is mainly used as a case study for a potential 'water droplet'-based UFP mitigation system. However, the findings from the conducted literature review and stakeholder interviews are also relevant for other airports around the world.

The research paper is structured as follows. Section II discusses the used methodology of this research. An overview of the findings from the conducted literature review and other data collection methods is provided in section III, after which the application of the methods is presented in more detail in section IV. The results from the system design study are mentioned in section V. Section IV contains the conclusions, as well as the recommendations for future research.

II. Methodology

The research methodology structure is visualized in figure 1, of which the several steps are briefly mentioned in the following subsections.

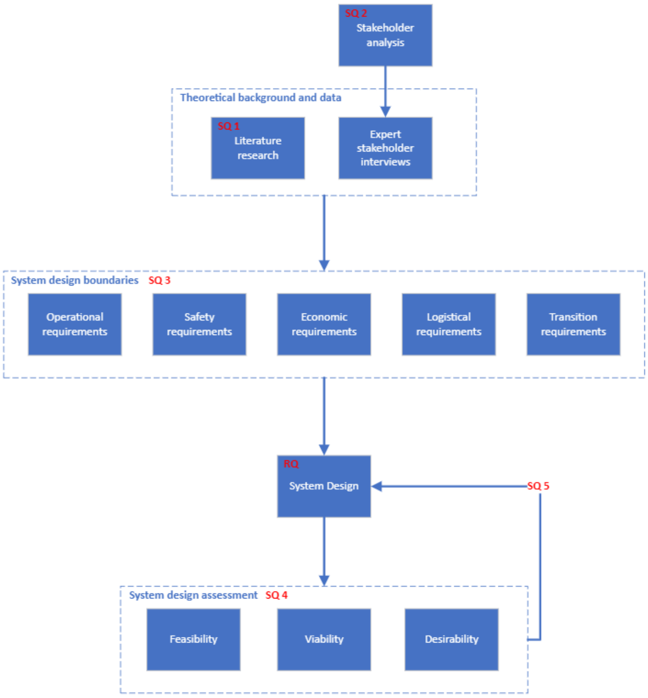

Fig. 1: Research structure

A. Literature research and data collection

A literature review is conducted to gather the state-of-the-art of academic research with regard to ultrafine particle production by aircraft, UFP dispersion across the airport grounds and potential UFP mitigation strategies at airports. The overview of current academic knowledge is an effective method to substantiate the conclusion that new research is of added value to the academic community: it identifies research questions and justifies future research in said area (Torres-Carrión et al., 2018).

As the current body of academic work regarding the research topic is fairly concise, it is of importance to retrieve more operational knowledge from the aviation sector and from the academic world with interest in the aircraft operation. In order to compose a shortlist of potential stakeholders to further include in this research, a stakeholder analysis is conducted. The implementation of a project in the airport context takes place in a multi-actor environment, which indicates that policy/organizational problems and processes involve multiple parties. All involved stakeholders have different interests, objectives and perspectives, which makes it important to map all these goals, as well as the inter-relationships between the relevant stakeholders (Bendahan et al., 2004). The eventual goal of the actor analysis is to create an overview of all the relevant stakeholders, whose interests and resources need to be considered when designing and implementing a 'water droplet'-based UFP mitigation system at AMS. Besides this, the actor analysis will be an important tool to create a shortlist of stakeholders for expert interviews, with which necessary information for the theoretical background and system design boundaries needs to be gathered.

Expert stakeholder involvement is an often used method in the academic world to obtain local knowledge regarding planning policies, technological limitations, environmental impacts, etc. (Berg et al., 2016). Suitable representatives, from the involved research institutes, aeronautical organizations and airport companies, were selected for semi-structured interviews. This interpretation was chosen to efficiently gather the stakeholders' knowledge and insights within their field of expertise and give them the opportunity to express their sincere opinions, expectations and concerns regarding the topic. Semi-structured interviews usually make better use of the "knowledge-producing potentials of dialogues" by letting the interviewer and interviewee elaborate on the angles that are deemed more important to discuss (Brinkmann, 2014).

B. Processing the analyzed data

The collected data from the stakeholder interviews - in the form of knowledge, insights, opinions, advises, quotes, etc. - is used throughout multiple parts of this research. The data is first analyzed for the formation of the theoretical and operational background of the potential UFP mitigation system at the airport, as various system components are of importance for the implementation of a conceptual design. The knowledge and insights of several stakeholders are processed in the content to consolidate the theoretical framework of this research, whereas opinions and advises are also used to a limited extent to provide a first indication of the potential configuration(s) of the system design.

After the data analysis for the system components, the analyzed data from the stakeholder interviews will serve as theoretical background for drawing up the requirements that a 'water droplet'-based UFP mitigation system at the airport must meet according to the interviewees. As the involved stakeholders are from various departments of Royal Schiphol Group, other organizations in the aviation industry and academics with knowledge in the operation of aircraft, they have a lot of knowledge and insights on which requirements are necessary for projects at the airport. The several requirement categories are associated with the operational, safety, economic, logistical and transition aspects of the potential UFP mitigation system at the airport.

C. Conceptual system design

The system design components will be incorporated into a conceptual system design, while taking all the system requirements into account. For each system design component, the most optimal configuration will be proposed, which will probably result in the most effective and efficient system at the airport. In this context, 'configuration' is used for the chosen option from the set of alternatives. The listed set of system requirements is used while determining the best fitting conceptual design of a ('water droplet'-based) UFP mitigation system during the aircraft operation, in order to comply with the operational, safety and economic standards, as well as to take the logistical and transition challenges into account.

D. System design assessment

The conceptual system design will be assessed on its feasibility, viability and desirability in order to determine whether the proposed design might be a well-fitting and effective solution to eventually implement. The system requirements are used to score these assessment criteria of the proposed conceptual system design.

III. Theory and data collection

This section of the report provides the most relevant findings from the conducted literature review, but mainly focuses on the data that was collected from the conducted stakeholder interviews. Fourteen stakeholders from several different business-oriented and academic backgrounds were selected from the proposed short list, which was the end result of the stakeholder analysis. These experts were interviewed in a semi-structured way about the aircraft-produced UFP issue at airports and the potential ways to tackle the UFP concentration accumulations. An overview of these stakeholders, with their function/expertise, the organization/institution for which they work and the specific department/faculty, is provided in table I.

TABLE I: Overview of conducted stakeholder interviews

	Function/Expertise	Organization/Institution	Department/Faculty
1	Air Transport & Operations	TU Delft	Aerospace Engineering
2	Safety Consultant	KLM Royal Dutch Airlines	-
3	Meteorology and Air Quality	WUR (Wageningen)	Environmental Sciences
4	Head of Sustainability Development	Copenhagen Airport	-
5	Air Quality and Pollution	TU Delft	Aerospace Engineering
6	Reseacher in (Nano) Particles	TNO	-
7	Flight Performance and Propulsion	TU Delft	Aerospace Engineering
8	Senior Manager & Aircraft Architect	Airbus Technology Bremen	-
9	(Nano) Particle-Droplet Interactions	University of Twente	Science and Technology
10	Senior Process Advisor	Royal Schiphol Group	Airport Operations
11	Stakeholder Strategy & Development	Royal Schiphol Group	Strategy & Airport Planning
12	Senior Environmental Advisor	Royal Schiphol Group	Safety, Security & Environment
13	Sourcing Manager	Royal Schiphol Group	Procurement & Contracting
14	Process Owner Aircraft	Royal Schiphol Group	Airport Operations

The reasoning behind the emerging interest from Amsterdam Airport Schiphol in the investigation of potential mitigation strategies, for the by aircraft produced UFP, has become clear from the conducted literature review, which indicated the high measured UFP concentrations at the airport grounds and the potential health hazards for (platform) employees. As the theory and reasoning regarding this 'Why?'-question has been academically substantiated, it is important to focus on answering the 'When?', 'Where?' and 'How?' questions regarding the mitigation of aircraft-produced ultrafine particles at the airport. These will be further discussed in the following subsections.

A. Moment of mitigating ultrafine particles

For the mitigation of ultrafine particles at the airport, there needs to be determined during which process(es) of the aircraft operation the system is deployed. The aircraft operation roughly consists of three separate processes: the cold start of the engines, the ground idle procedures (taxiing), and the landing and take-off processes (LTO). Besides relating the operating times of the UFP mitigation system to the aircraft operation processes, the system can also be operated during different periods throughout the day.

Over the last decade, aircraft-produced emissions measurements have been conducted on and around the airport grounds of various airports around the world (e.g., Los Angeles International Airport (LAX), Ciampino-G. B. Pastine International Airport (CIA), Heathrow Airport (LHR), Frankfurt Airport (FRA), Rotterdam The Hague Airport (RTHA), and Amsterdam Airport Schiphol). At all above-mentioned airports, high incidental peak UFP concentrations could be measured in between the average background concentrations. For instance at AMS, average peak concentrations higher than 100,000 $\#/cm^3$ were measured at a 200 meter distance from the taxiway, where the aircraft-related UFP concentrations at that location were generally 70,000 $\#/cm^3$ (Dinther et al., 2019). An overview of the measured average UFP concentrations (light blue) and the measured peak concentrations (dark blue) at that same airport is shown in figure 2, for AMS and all other mentioned airports.

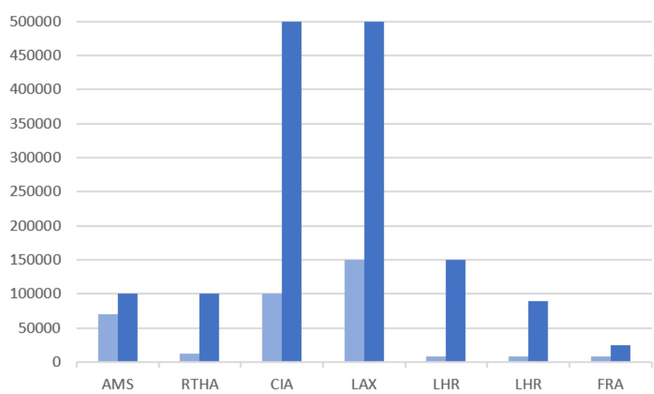

Fig. 2: Average and peak UFP concentrations [$\#/cm^3$]

The peaks can be associated with so-called 'jet blast events' of aircraft and are the consequence of starting aircraft engines near piers and terminals (cold start) and of taxiing and departing aircraft on and along runways (Tromp et al., 2021). A professor in meteorology and air quality (Wageningen University & Research) related 'cold starts' of aircraft engines to additional emissions, which mostly has to do with engine residuals that stick to the engines once they are switched off. Once the engines are turned back on, the aircraft produces some "bonus" emissions, which is basically the old emission residue that also gets burnt. The cold start takes place when the aircraft is positioned at a dedicated aircraft stand, which is close to the piers and terminals where most ground staff and platform employees are walking around.

Once the aircraft has left the aircraft stand at the pier, it continues its operation under 'idle' engine settings while taxiing over the apron and taxiways. The wide-spread layout of an airport, e.g. AMS, may result in relatively long taxi times from the aircraft stand to the runway for a share of aircraft. These distances, in combination with the lower operational engine settings, can cause the ground idle procedures to take much more time than the cold start of the engines. While the engine settings are relatively low in comparison with the cold start, the taxi times might result in a comparable production of UFP and other emissions. The ground idle procedures take place further away from the densely populated areas at the airport.

Arriving aircraft can usually return to the piers under low engine power settings as they land with sufficient thrust to taxi back for a certain distance, which thus requires a relatively limited amount of fuel and also results in lower emission concentrations production. This is another story for departing aircraft. The final step of the ground idle procedure is the positioning of the aircraft at the head of the designated runway, after taxiing from the aircraft stand at the pier over the taxiways. The jet engine settings are turned to full power once the departing procedure of the aircraft on the head of the runway has started. The runway is a demarcated area for the aircraft operation, but the aircraft operate at (or close to) full power for a relatively long distance.

B. Location of mitigating ultrafine particles

In order to mitigate the dispersion of aircraft-produced ultrafine particles, it is important to gain insight into where these UFP concentration accumulations are created and located at the airport. When this becomes clear, a UFP mitigation system can be implemented at the locations on the airport grounds where it can significantly reduce these emissions in the most effective and efficient way. Mobile measurements that were carried out on the Amsterdam Airport Schiphol grounds showed relatively high measured concentrations at the area (north)eastern of the airport building, especially at terminals 1 to 3 and piers B to G Tromp et al. (2021). An overview of the measured UFP concentrations for the several different areas at Schiphol is presented in table II.

The data in this table identifies certain 'hot spots' where high incidental (a few minutes) peak concentrations were measured, as well as high average concentrations. At multiple locations, higher measured UFP concentrations can be attributed to aircraft operations at AMS. Around the piers (especially C, D, E and F) and the terminals, increased concentrations are most likely caused by the cold start of the aircraft engines ('jet blast events') (Tromp et al., 2021). On and around the platforms (mainly A/B, H and S), the increased concentrations can very likely be linked to taxiing aircraft, but are potentially also caused by 'jet blast events'. On the runways, higher concentrations can be attributed to starting and landing aircraft. On taxiways along several runways higher UFP concentrations can be linked to taxiing aircraft, especially on intersections and at turns.

TABLE II: UFP concentrations for different areas at AMS

Areas	**UFP concentration ($\#/cm^3$)**		
	Mean	**Median**	**90 percentile**
Terminals and piers	100,000 - 120,000	44,000 - 68,000	210,000 - 270,000
Boulevard/Ceintuurbaan	62,000	42,000	130,000
Taxi- and runways	26,000 - 76,000	7,600 - 26,000	56,000 - 110,000
Platforms	36,000 - 140,000	13,000 - 36,000	37,000 - 200,000
Business parks	22,000 - 52,000	16,000 - 47,000	43,000 - 98,000
Motorway bypasses A4	54,000	30,000	110,000

The aircraft operation currently starts at the aircraft stand, located at one of the piers of one of the airport terminals. The aircraft stand is the location where the aircraft operation is closest to the airport building, which also makes it the most dense and hectic area at the airport grounds. Table II shows that the terminals, piers and platforms are the locations at the airport grounds where generally the highest mean UFP concentrations can be measured, which are also the locations where most ground personnel and platform employees are walking around and where many other processes and activities are taking place. Implementing a UFP mitigation system at this location can be a good start to combat the formation of emission concentration accumulations, but the employees still working so close to the aircraft operation might induce eventual health and safety hazards.

A Senior Process Advisor in the department of Airport Operations at RSG introduced the concept of 'remote starting positions' in the stakeholder interview, which is an alternative for the local start of the aircraft at the aircraft stand. The idea of introducing these new starting positions is based on the need to remove the production of aircraft emissions further away from the piers. From the interviews with experts within the organisation of Royal Schiphol Group, three categories of new potential remote starting positions can be proposed: the semi-central starting positions, the central starting positions and starting from the head of the runways. The category of semi-central starting positions consists of potential remote starting locations that are further away from the piers, but are still fairly close to the bay. A few interesting examples of semi-central starting locations at AMS are the Echo (E-) and Papa (P) platforms, which are located northeast of the airport building (figure 3).

While the semi-central starting locations are still located fairly close to several piers of the AMS terminals, the alternatives in the category 'central starting locations' are generally located further away from the piers. Stakeholders

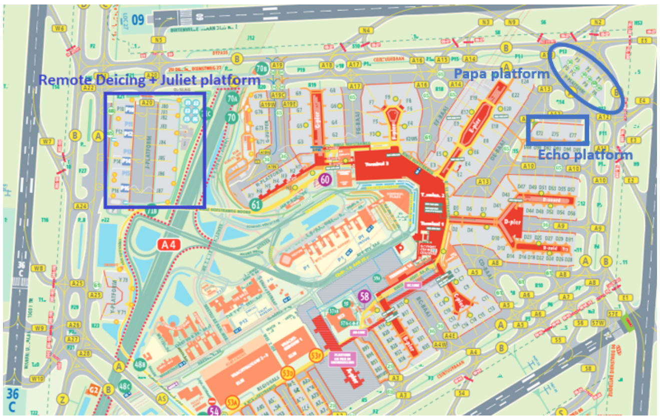

Fig. 3: Remote (semi-)central starting positions AMS

from different departments at Royal Schiphol Group suggested some locations at the airport grounds that might have potential to offer capacity for this starting strategy. Northwest of the airport building, the remote deicing platform (of KLM) and the Juliet (J) platform are located, which can be seen in figure 3. The last category of potential remote starting locations at AMS is starting the aircraft engines at the head of the dedicated runway. A remote starting position at the head of the runway where the aircraft will depart from means that the aircraft will be towed from the aircraft stand at the pier up to the runway. These potential remote starting positions for the AMS case are visualised for each runway, including the direction(s), in figure 4.

Fig. 4: Remote starting positions runways AMS

The involved stakeholders from several departments at RSG indicated that each category of remote starting locations, as well as the individual locations, all have their advantages and disadvantages. Important aspects to take into account while analyzing the potential of each location are: the available capacity, the accessibility by aircraft, the taxi distance, the applicable (EASA) rules, and the available facilities.

After the cold start of the aircraft, the ground idle procedures will start. The areas alongside the taxiways might be interesting locations for the implementation of mitigation strategies, as aircraft produce a significant amount of UFP over a substantial distance. However, this implies that the construction of such a UFP mitigation system must cover all ground idle infrastructure. It is also a logistical challenge to let the water droplet cloud move along with all the operating aircraft, as well as making sure that the right amount of water is available to spray at the right place and the right time.

After the ground idle procedure, the aircraft is positioned at the head of the dedicated runway. Implementing a 'water droplet'-based ultrafine particle mitigation system at the runways seems like an interesting configuration as it does not interfere with other airport processes and it does not seem to create any disturbances on the used airport infrastructure. Although there seems to be sufficient space for the introduction of UFP mitigation strategies at the runway, the aircraft operation takes place at full throttle and high velocities. This makes the efficient deployment of water droplets for the mitigation system much more complicated, as well as the stricter EASA regulations with regard to safety that are applicable at the runways.

C. Way of mitigating ultrafine particles

Besides determining the moment(s) and the location(s) of the deployment of the ultrafine particle mitigation system, the configuration and the operational aspects of the system need to be determined as well. As the creation of the water droplet screen/cloud is the pivot of the system, investigating the available production equipment alternatives is of great importance. After the ultrafine particles leave the jet engines as a product of the combustion process, their fate is controlled by several processes, i.e., coagulation, turbulent mixing, condensation-evaporation, and wet and dry deposition (Andronache et al., 2006). UFP as a product of the combustion process is airborne and will quickly disperse through the air above the airport grounds. Ultrafine particles and clumps of UFP (conglomerates) can be captured in tiny water droplets, wherein they might further interact with each other, and are not likely to leave that droplet. Water droplets that have interacted with (clumps of) UFP are initially airborne but will eventually descent to the ground, as long as the droplets do not evaporate. Wet deposition of UFP might thus lead to lower concentrations and implementing mitigation strategies that contribute to this process are interesting to investigate and potentially implement at airports.

Over the last few years, the implementation of water droplet production equipment has been introduced as a dust mitigation strategy in various industries (i.e., manufacturing, storage and demolition). Several companies have specialized in the field of dust control in construction: combating the produced dust at construction sites by atomizing water at high pressure. These companies, e.g. MB Dustcontrol and Erkho, address that the very fine water droplets can be used well for the suppression of dust and (ultra)fine particles and that their equipment can be placed for many different applications (Erkho BV, 2022). Most providers in the dust control sector offer relatively similar products, which can be subdivided into two main equipment categories: water spraying cannons and water pipes with spraying nozzles mounted onto them, which are also available in alternative configurations (MB Dustcontrol, 2022b).

The operation of so-called 'water spraying cannons' is based on the technique of guiding the water supply through a powerful turbo-fan, which produces a turbulent airflow containing fine water droplets. An example of this device is displayed in figure 5, in which the turbo-fan is on the left-hand side of the cannon. There are many alternatives of the spraying cannon available, mainly varying in the spraying distance potential of the cannons, as well as in water usage, the spraying surface, the number of nozzles, etc. The spraying distance of the cannons can be varied by adjusting the pressure on the nozzles, the water supply, the rotation speed of the fan, etc. Besides the technical aspects of the equipment, the mounting construction of the spraying cannons also widely varies. The cannons can stand-alone by themselves, but they can also be mounted onto trucks, (moving) platforms, hydraulic masts, and even walls/ceilings. These variations increase the versatility of the spraying cannons as the spraying angle and direction can be adjusted in multiple dimensions.

Fig. 5: Example of spraying cannon (MB Dustcontrol, 2022a)

The alternatives in the other equipment category are based on water pipes with spraying nozzles mounted onto them. The water pipes are similar to fire hoses that can differ in diameter and have special exchangeable nozzles and supports that make it possible for the produced water droplets to reach every corner of the dedicated spraying area (Environmental XPRT, 2022). On the left side of the figure it is visible that the SprayWall is attached to a normal water hose, which in turn is connected to a water supply point. The maximum pressure on the hose can result in a water droplet "wall" up to ten meters high and the separate hoses, with a length of 20 meters, can be attached to each other so a wide droplet screen can be created. MB Dustcontrol offers this type of equipment as the so-called 'SprayWall NM20', which is shown in figure 6 (MB Dustcontrol, 2022c). The black blocks underneath the hose are the supports that help position the SprayWall.

A configuration of the system where the SprayWall is mounted onto a construction above the ground has also been discussed during several stakeholder interviews. The idea of these overhead SprayWalls is similar to the operation of

Fig. 6: SprayWall (Scott Vickers, 2022)

showers that spray the water droplets down, creating a slowly descending water droplet cloud. A potential configuration of such a system is shown schematically in figure 7. The angled line in blue represents the construction on which the water hose is mounted, with the red dots being the spraying nozzles. In comparison with the deployment of water hoses with spraying nozzles on the ground, the pressure on the hose(s) and the nozzles that is required for the system operation is much lower. The water droplets do not have to be sprayed into the air, but can descent to the ground by means of gravity. The lower required pressure results in less energy consumption needed for pumping the water from the supply point through the hose(s), as well as significantly less water use needed for the creation of the droplet screen (interview with researcher from TNO).

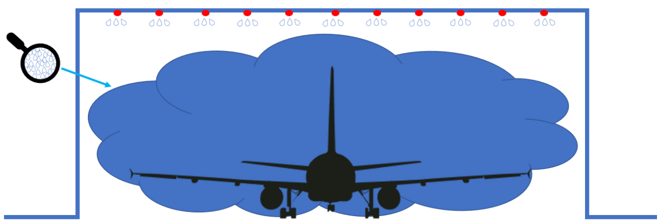

Fig. 7: System configuration of overhead SprayWall

IV. Application in more detail

A. *Ultrafine particle mitigation system design requirements*

It is of great importance to first establish the necessary design requirements prior to the development and implementation of a 'water droplet'-based UFP mitigation system at the airport. The interviews with stakeholders of Royal Schiphol Group, of other parties in the aviation industry, and of research/knowledge institutions consisted largely of discussions regarding the operational and safety aspects of aircraft-produced UFP mitigation strategies at the airport. Operational requirements related to efficiency, water supply, meteorology and the aircraft operation itself were established, while the safety requirements incorporated the potential risks regarding the use of water and regarding the system implementation itself. An overview of these requirements is shown in table III. A limited selection of additional requirements, related to investments, logistical challenges and transition into the new system, could be established as well (table IV).

The economic requirements are taken into account while assessing the viability of the potential conceptual system design, while the logistical challenges and the transition requirements are incorporated into the feasibility assessment. All requirements are used for the analysis of the time-bound, geographical, and operational system design components, which are discussed in the following subsections.

TABLE III: Operational and safety requirements

Category	1	Operational Constraints
Constraint	1	The system must create as many opportunities for the UFP to interact with the water droplets as possible.
Requirement	1	The water droplets should be sprayed in the area with the highest concentration of UFP.
Requirement	2	The air flows behind the aircraft should be complex and turbulent.
Requirement	3	The evaporation time of the water droplets should be as high as possible.
Requirement	4	The water droplet cloud should at least cover the complete cross section of the jet blast.
Constraint	2	The water supply source must result in the most optimal system, in terms of filtering, health and investments.
Requirement	1	The water supply must originate from a socio-economically accepted source.
Requirement	2	The water supply must originate from a sustainable source.
Requirement	3	The used water must be collected for reuse (as much as possible).
Requirement	4	The collected water should be filtered before reuse.
Constraint	3	The system must take meteorology and weather conditions into account for the operation.
Requirement	1	The system shall not operate when the outside temperature at the airport grounds is below zero degrees Celsius (when using water without additives).
Requirement	2	The water droplets must not instantly evaporate when the outside temperature at the airport grounds is relatively high.
Constraint	4	The system must not negatively affect the aircraft operation.
Requirement	1	The operation of the system should limit the increase in the turnaround time (as much as possible).
Requirement	2	The operation of the system should limit the decrease in the starting capacity (as much as possible).
Category	2	Safety Constraints
Constraint	1	The use of water must not cause damage to the airport, aircraft and environment in any form.
Requirement	1	The water droplets should not be sprayed into the inlet of the aircraft engines. / The water droplet production equipment should be installed behind the jet engines.
Requirement	2	The large amounts of water must not cause a significant impact on the decay of the aircraft.
Requirement	3	The large amounts of polluted water (with UFP and additives) must not end up in the environment.
Requirement	4	Large puddles of water should not arise at the used airport infrastructure.
Constraint	2	The use of water must not cause health risks and safety hazards for the (platform) employees.
Requirement	1	The water droplet cloud must not be created in the vicinity of airport employees.
Requirement	2	The water droplets should stay in liquid form for as long as possible.
Constraint	3	The system implementation must not cause safety risks during the aircraft operation.
Requirement	1	The system should not be implemented in the 'safe zone' of the aircraft, unless it is proven to be capable of enduring the jet blast.
Requirement	2	The first 40 meters on both sides of the middle of the runway must be obstacle-free.
Requirement	3	The construction of the system must be able to break down easily in the event of a colission.
Requirement	4	The system implementation and processes must be kept simple, unambiguous and uniform.

B. *Time-bound system design component*

From an operational point of view and according to the interviews with stakeholders within RSG, the aviation sector and the academic world, implementing UFP mitigation strategies during the cold start of the aircraft engines seems the most efficient and effective. One of the initial reasons to explore UFP mitigation strategies is the impact of the emissions concentrations near the platforms on the health of employees that are working there. As the cold start of the aircraft engines currently takes place at the aircraft stand next the pier, the produced emissions are blown in the direction of the terminals (interview with Senior Environmental Advisor from RSG). Concentration accumulations arise throughout the day, as the emissions remain located in wind-free areas and close to the buildings. It is a priority for airports to first tackle the problem in the areas where employees are the most affected by the aircraft operation, which supports the conceptual system design choice to implement the mitigation strategy during the cold start as it currently takes place in that area. A professor from the faculty of Aerospace Engineering at the TU Delft addressed that the cold start of the aircraft is associated with the production of large amounts of UFP and other emissions, due to the engines still containing clumped dirt from the previous operation(s). Mitigating the large share of ultrafine particles being produced during the cold start increases the efficiency of the system, which supports the conceptual design choice to begin with mitigation strategies at the cold start.

Several airports around the world, including AMS, are already investigating the potential of several ongoing projects that focus on the mitigation of aircraft emissions during the other processes. One of these solution directions is the deployment of so-called 'Taxibots', which are sustainable aircraft tugs that take the aircraft to and from the runway (Schiphol, 2022). As this mitigation strategy is focused on combating aircraft emissions during the ground idle procedures of the operation, investigating the potential implementation of a water droplet mitigation system for taxiing aircraft is fairly duplicitous. The time and resources that are available for the research on this solution can be better used while focusing on the potential implementation during the other processes.

The logistical challenge to implement the system during the cold start is also fairly limited, as this procedure of the operation takes place when the aircraft is positioned at a dedicated place and the water droplets do not have to move along with the aircraft (interview with professor from the faculty of Aerospace Engineering at TU Delft).

TABLE IV: Economic, logistic and transition requirements

Category	3	Economic requirements
Constraint	1	The system must be as cost-efficient as possible.
Requirement	1	The fixed and variable construction costs of the system should be as low as possible.
Requirement	2	The available airport infrastructure and facilities should be optimally used by the system.
Category	4	Logistic Requirements
Constraint	1	The logistical challenges associated with the system must be as limited as possible.
Requirement	1	The aircraft should be brought to the system, instead of the other way around.
Category	5	Transition Requirements
Constraint	1	The impact of the transition from the old situation into the new system must be limited as much as possible.
Requirement	1	The transition from the old situation into the new system should interfere with the aircraft operation and other processes as little as possible
Requirement	2	The transition from the old situation into the new system should be implemented as completely as possible.

The water droplet production equipment and other necessary facilities can be implemented at a few central locations, which is beneficial for the implementation costs, as well as the variable costs for operating the system. The conceptual design decision is thus supported by the previously stated system requirements, as the logistical challenges and the necessary investments seem to stay within limits the most during this part of the aircraft operation in comparison with both the ground idle and LTO procedures.

C. Geographical system design component

The location of the potential UFP mitigation system is strongly related to the determined aircraft operation process during which the system operates. Since the cold start of the engines has been selected as the aircraft operation process priority to focus on within the conceptual system design, the collection of potential mitigation locations has also become smaller. From the previously discussed potential locations, the aircraft stand at the pier and the remote starting positions are the main alternatives to consider for this component of the conceptual design of a 'water droplet'-based UFP mitigation system at Amsterdam Airport Schiphol.

As previously mentioned, the cold start of the aircraft operation currently takes place at the aircraft stand next to the pier of the airport terminal. A senior manager and aircraft architect at Airbus Technology Bremen stated that the water droplets should probably not be sprayed at the aircraft stand at the gate, as the large amounts of water could result in safety hazards for other operational systems and processes at the apron, as well as in safety risks for the platform employees that are working at these locations. This stakeholder mentioned that UFP mitigation by spraying water droplets at this level of locality is most likely not desirable. This point of attention was also raised during the interview with the safety consultant of KLM Royal Dutch Airlines, who stated that the use of water droplets during the cold start at a starting position located further away from the pier is a more desirable alternative than UFP mitigation at the aircraft stand. The possibility of creating a 'Legionella shower' at the locations where people are walking around is a risk that should be avoided at the airport grounds. Stakeholders from within Royal Schiphol Group and other interviewees also addressed their concerns regarding the production of large quantities of water close to the terminals, which were translated into several safety requirements (table III).

The safety consultant from KLM mentioned in the interview that the aircraft should be brought to the mitigation system, instead of bringing the system to the aircraft. Instead of implementing a mitigation system at every pier or aircraft stand, it is way more efficient to dedicate some airport infrastructure further away from the bay into remote starting locations where the mitigation strategy can be implemented. In the busiest and most dense area of Copenhagen Airport, aircraft are currently being towed away from the aircraft stand for 200-300 meters after which the engines are started. This is not considered to be fully remote starting, but the first analyses regarding the current system at CPH show some beneficial results. The concentration accumulations of UFP at the involved platforms and piers in the dense and busy area have decreased significantly and arriving aircraft had a better punctuality as inbound parking was not necessary anymore. This was only at the expense of a slight decrease in the starting capacity of departing aircraft. The head of sustainability development at CPH mentioned during the stakeholder interview that fully remote starting is currently not an interesting option for Copenhagen Airport, as the airport layout does not facilitate an optimal situation when that system is implemented. He mentioned that airports with an extensive layout, such as Amsterdam Airport Schiphol, might be a better fit for the fully remote starting system, as the pilot can stabilize the engines and execute the final checks during these longer taxi times prior to departure.

The majority of the interviewed stakeholders addressed the importance of moving the cold start of the engines, and thus the potential future UFP mitigation strategy, further away from the aircraft stand at the pier. Remote starting locations that consist of a to be determined number of aircraft positions currently seem like the most interesting location to further investigate for the potential implementation of a 'water droplet'-based UFP mitigation system at the airport.

D. Operational system design component

The final component of the functional implementation of the conceptual system design that needs to be determined is the way in which ultrafine particles will be mitigated at the airport. As exploring the use of water droplets to combat the aircraft-produced UFP is the initial essence of this research, the potential solution directions for the system were also analyzed by keeping this principle in mind. The main difference between the equipment categories is the way in which the produced water droplets are sprayed into the air, which determines how the water droplet cloud eventually is projected. A few stakeholders stated that the water spraying devices should be connected properly to the cores of the aircraft engines in order to spray the water droplets into the area of the engine where the largest amounts of UFP are produced. Water spraying cannons are probably the best alternative when the water droplets need to be sprayed into (the core of) the aircraft engines, as the devices can be adjusted in spraying angle and direction. However, the dissension between the stakeholders regarding this issue was clearly evident in the various interviews. A professor in meteorology and air quality from the department of Environmental Sciences at WUR stated that it is probably impractical to spray the water droplets into the core of the engine, as the thrust is the strongest there with therefore high wind velocities. The temperatures that close to the engine are also extremely high, which results in relatively fast evaporation of the water droplets in comparison with water droplets that are produced further away. The effectiveness of the UFP mitigation system is not high when the particles cannot be encapsulated by the water droplets due to the thrust and temperature of the aircraft engine core.

The other category of water production equipment consists of devices that are based on a construction of water pipes with spraying nozzles mounted onto them. These so-called 'SprayWall's project a relatively vertical water droplet cloud into the air and are not really able to adjust their spraying angle and direction due to their placement on the ground. This equipment seems like a good fit for a system that should be placed further away from the aircraft, as it is not able to spray the water droplets into the jet engines. Besides this, the necessary cloud dimensions that cover at least the cross-section of the aircraft vortex are generated more easily and straightforward by these water pipes with spraying nozzles mounted onto them, which results in a more efficient mitigation strategy. This meets one of the requirements from table III, from which the constraint from that table states that "the system must create as many opportunities for the UFP to interact with the water droplet as possible". During the conducted experiments from TNO there seemed to be a sufficient amount of water and enough time for UFP-droplet interaction opportunities, as the jet blast went through the water droplet cloud and the water even reached the measurement van, which was placed at a significant distance from the aircraft (interview with researcher from TNO).

In order to make a deliberate decision regarding this component of the conceptual system design, more experiments need to be executed for measurements of the performances of different device configurations from both water droplet production equipment categories. For now the water droplet production equipment based on the water pipes with spraying nozzles, placed on the ground, is linked to a slightly better performance.

V. Results

The proposed conceptual system design of a potential 'water droplet'-based UFP mitigation strategy is visualized in figure 8 and will be assessed on its feasibility, viability and desirability in the following subsections.

A. Feasibility

The implementation of a system that combats the ultrafine particles that are produced by aircraft during the cold start of the jet engines seems the most feasible out of all the aircraft operation processes during which the system could be deployed. The aircraft is positioned at a dedicated position, which makes it a lot easier to produce the water droplet cloud across the desired dimensions. Instead of bringing the water droplets to the aircraft, the jet blast from the engines is directed to the already present water droplet screen. The devices for the production of the water droplets can be placed at a dedicated location at a certain distance from the position where the aircraft engines will be started, without disturbing other airport activities. These limited logistical challenges of UFP mitigation during the first process of the aircraft operation thus contribute to the operational feasibility of the implementation of a potential future system.

Remote starting locations are an interesting alternative for the potential implementation of a UFP mitigation system. It is important to analyze the currently available infrastructure and facilities for the construction of central starting positions to determine whether additional investments and constructions are necessary. The impact on the airport processes, by moving the cold start of the operation from the aircraft stand at the pier to a remote starting position, is important to extensively analyze as well. The feasibility of implementing fully remote starting positions will differ for each airport, but overall it seems like there is sufficient capacity at Amsterdam Airport Schiphol to make the implementation of fully remote starting locations for the aircraft operation feasible as the discussed locations (section III.B) offer well-fitting infrastructure and facilities for this purpose.

Determining whether the technique of encapsulating airborne particles in water droplets is feasible as a mitigation strategy to combat the aircraft-produced UFP concentrations is also of severe importance. Confirmation from the industrial sector is of importance to determine the feasibility of this principle, but acknowledgement from the academic community that this mitigation strategy could be effective is just as important. Professors and experts in the field of (nano) particles and meteorology confirm the theory that small water droplets are able to encapsulate ultrafine particles to prevent further dispersion of these airborne particles. A professor in Meteorology and Air Quality states that UFP moves in Brownian motion, which means that it might easily get trapped inside a larger particle, such as a water droplet. He states that, once a particle is encapsulated by the water droplet, it is there to be washed out. This theory is affirmed by a stakeholder from the University of Twente and a researcher from TNO, both with expertise in (nano) particle-droplet interactions and the drying of systems. They address that, as long as the relative humidity is high and the temperature is relatively low, the condensation of UFP (clumping together) and the absorption by water droplets will be possible and this mitigation strategy might be feasible at the airport.

B. Viability

First, the investments and expected variable costs that are associated with the implementation and eventual deployment of the UFP mitigation system will be discussed. The costs of the spraying installations will be substantial, but an extensive cost analysis that incorporates the input of the potential suppliers needs to be conducted to retrieve insights in the order of magnitude of the costs. However, the aspects that are important for increasing the viability of the conceptual system design can already be analyzed. The degree of industrialization possibilities is an important characteristic of a viable system at the airport, which depends on whether the system is a widely applicable solution that can be reproduced well (interview with Sourcing Manager at RSG). The design of the final product/system should comply with the following aspects: the use of standard components (no customization), sustainability, risk-free, and a reliable collective of development partners. The system should be implementable at many airports, which makes a reproducible system design according to the industry standard a necessity. The system

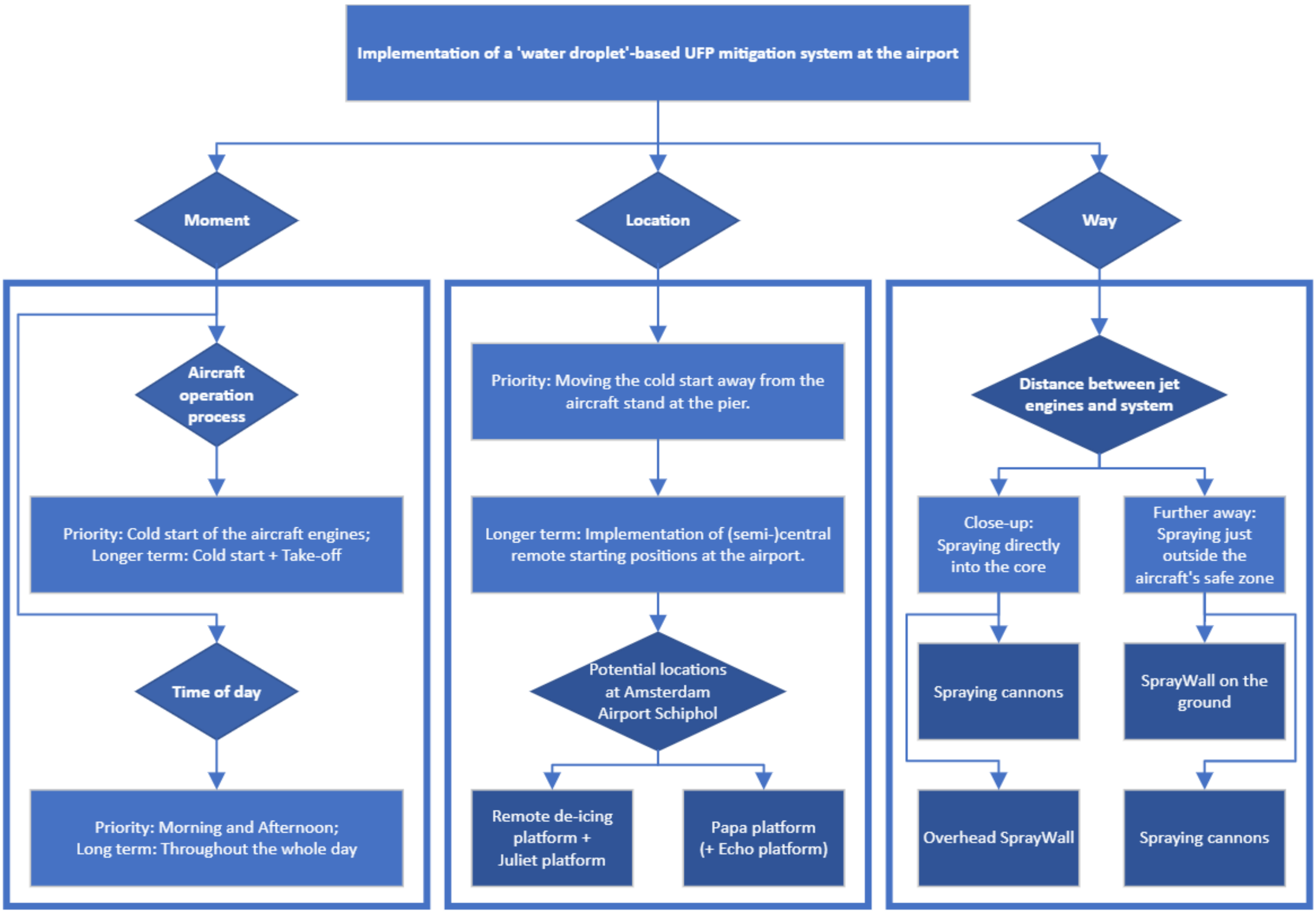

Fig. 8: Conceptual system design of a potential UFP mitigation strategy at the airport

of water pipes is very valuable, but the replaceable nozzles mounted onto this system makes it relatively easy to fix in case of a malfunction. Dividing the UFP mitigation system in such a way that it can spray water droplets at separate aircraft stands results in a more efficient mitigation strategy, as well as in a more beneficial replacement strategy. These conceptual design aspects make the system more viable, as separate components of the system can be replaced instead of the complete system.

Analyzing the potential impact of fully remote starting on the airport capacity, as well as the necessary investments that are most likely associated with this conceptual system design component, is also of importance while assessing the viability. It could be expected that the number of employees and resources that will have to be deployed for the new operation, where the mitigation of UFP takes place during the cold start of the aircraft at a remote starting position, will have to be scaled up considerably. As all aircraft have to be towed from the stand at the pier to the remote starting position by a truck, the amount of truck movements will increase significantly, which results in the need for more aircraft tugs and a proportional increase in the number of drivers. When the implementation of an ultrafine particle mitigation strategy in combination with remote starting positions is not an option due to the current starting capacity of the airport, the balance between these two must be drawn up. Or accepting a lower starting capacity, which induces less aircraft movement per year but results in a more sustainable and healthy airport environment, or realizing a higher airport capacity by investing in the necessary resources and personnel. In conclusion, the need for additional employees and resources needs to be analyzed extensively in order to make a prediction regarding the necessary investments, which in turn contributes to the better assessment of the proposed system design's viability.

Important to address is the potential of airports and airport companies to receive subsidies for conducting research projects in sustainability and for the implementation of projects that contribute to a sustainable and future-proof airport, which can be granted by (inter)national government institutions and other investors. These grants are beneficial for the viability of these projects, as they partially cover the expenses.

C. Desirability

All new solutions and implementations in the aviation industry are usually not desired in advance by all parties involved in the operation of the aircraft (interview with Safety Consultant of KLM). The zero alternative, which implies to keep the operation exactly the same, is generally the most interesting alternative for airlines, aircraft manufacturers and handling services. Airlines want to maintain a profitable operation, but they also want to invest in a more sustainable image. The proposed system might result in a longer turnaround time of the aircraft and less revenue, but it might also contribute to the airlines' sustainability goals and their general image to potential passengers. For airlines and aircraft manufacturers it is also of importance that the mitigation of aircraft-produced UFP, by spraying water droplets into the highly concentrated areas, is not accompanied by additional risks for the aircraft. As long as the aircraft manufacturers confirm that the aircraft can operate in normal conditions in a situation where the proposed system is implemented, the airlines will not necessarily be against it.

Research on the mitigation strategy of deploying water droplets to encapsulate UFP, with the objective to explore potential systems to combat the aircraft-produced ultrafine particle concentrations, has become a relevant sustainability goal at several airports (e.g., AMS). The fact that this is such an important item on the agenda of airports shows the urgent need of finding a solution to the UFP concentrations problem at the airport. The desirability of any conceptual system design is therefore already relatively high. A combination of operational and innovative solutions will most likely result in the most desirable system. By removing the production of large amounts of UFP during the cold start from the aircraft stands at the pier, a direct effect can be seen in the form of lower UFP concentrations at the densely populated airport areas. As the (platform) employees are working in those areas, this operational solution might already be very beneficial. By combining this with the innovative solution of deploying the water droplet system during the aircraft's cold start, a significant share of the produced ultrafine particles can also be captured and will not further disperse. At a relatively short term, the proposed conceptual system design can provide very desirable effects in terms of health and safety.

As the airlines are the actual emitters of the large concentrations of ultrafine particles at the airport grounds, they are strong supporters of the implementation of systems and solutions to make their operation more environmentally friendly, without affecting their profitability (interview with Advisor Stakeholder Strategy & Development at RSG). A strategy that combats the dispersion of UFP across the airport grounds is therefor a desired solution, as it may contribute to the image of airlines and aviation in general. Progressive airlines, such as EasyJet and TUI, are already investigating new solutions to make their operation more sustainable, and will probably be welcoming a system that mitigates the ultrafine particle concentrations produced by their aircraft.

VI. Conclusions and recommendations

The aim of this research was to supplement the current state-of-the-art of academic research regarding aircraft-produced ultrafine particle mitigation at the airport, and thus filling the knowledge gap that was established after the conducted literature research. The study discusses several aspects of the UFP concentration issue at airports and what might be potential strategies to tackle the problem, by taking a wide range of system components and requirements into account. A conceptual system design for a potential UFP mitigation strategy at the airport is proposed, which is substantiated by the gathered academic knowledge and the insights retrieved from the interviews with a wide variety of stakeholders from the aviation industry, as well as from research and knowledge institutes. Royal Schiphol Group and other stakeholders in the aviation industry could use this research as some sort of reference work, as it addresses a significant share of the current knowledge and discussions regarding aircraft-produced UFP mitigation. This document could be used as a starting point and/or could provide feedback for follow-up research to recall potential stakeholders, system components and requirements.

While evaluating this research, it is of importance to also indicate the limitations of the deployed methodologies and the study itself. As the decision was made to focus on the 'water droplet'-based UFP mitigation strategy in this research, it does not provide the reader with a complete overview of potential UFP mitigation solutions and might give the idea that the potential use of a water droplet screen/cloud is the only interesting option. Besides this, the possibilities to include more important stakeholders in this research were limited by the available time and resources. Additional interviews with representative stakeholders from several other important organizations in the aviation sector, as well as from other external parties, could have also contributed to the theoretical body of this research. As the research is exploratory and not quantitative, the validation possibilities to assess the conceptual system design were very limited. The use of several design criteria and the evaluation of the scores of the proposed design on those criteria could have resulted in a more complete validation step.

There are many interesting possibilities for follow-up research and sufficient knowledge gaps that can be addressed in adjacent studies. The actual effectiveness of spraying water droplets in the areas with high concentrations of ultrafine particles, to capture the UFP and lower the concentrations at the airport grounds, should be further investigated. As the use of water is what the whole solution is built around, topics as the water supply source, the (re)collection of water and the need for filtering before reuse are all important to explore comprehensively. Other potential UFP mitigation strategies were briefly discussed, but were generally not investigated any further. Many involved stakeholders mentioned several other solution directions that might result in effective systems to combat the aircraft-produced UFP concentration accumulations at the airport grounds, which are interesting topics for future research.

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Appendix B UFP concentration locations at Amsterdam Airport Schiphol

An overview of the measured average UFP concentrations on airport grounds can be visualized in a map, in this case for Amsterdam Airport Schiphol, such as shown in figure 38 (Tromp et al., 2021).

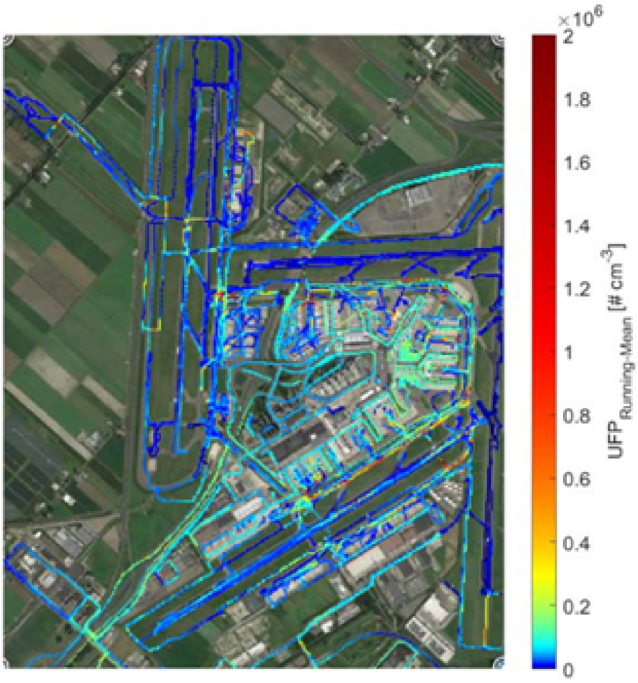


Figure 38: Overview of the average UFP concentrations at the Schiphol airport grounds

The areas marked in blue indicate relatively low measured UFP concentrations, where the areas marked in red indicate that high UFP concentrations were measured there. The green-turquoise areas identify that there were above-average UFP concentrations measured at these airport locations during the day. Figure 39 zooms in on figure 38 to better show the measured UFP concentrations surrounding the terminals and piers of the airport. The area (north)eastern of the airport building shows relatively high measured concentrations at terminals 1 to 3 and piers B to G of Amsterdam Airport Schiphol.

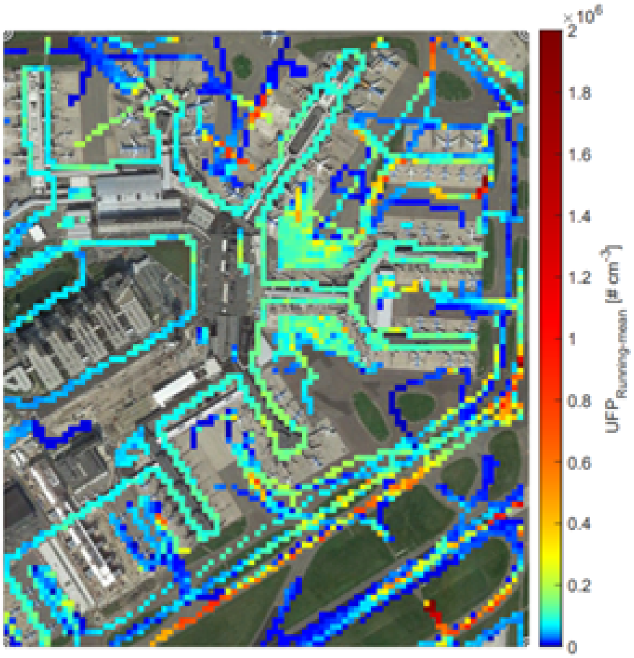


Figure 39: The average UFP concentrations surrounding terminals 1-3 and piers B-G

Figure 40 (Tromp et al., 2021) indicates the measured concentrations more specifically for the individual piers, (taxi)roads, runways, platforms and business parks.

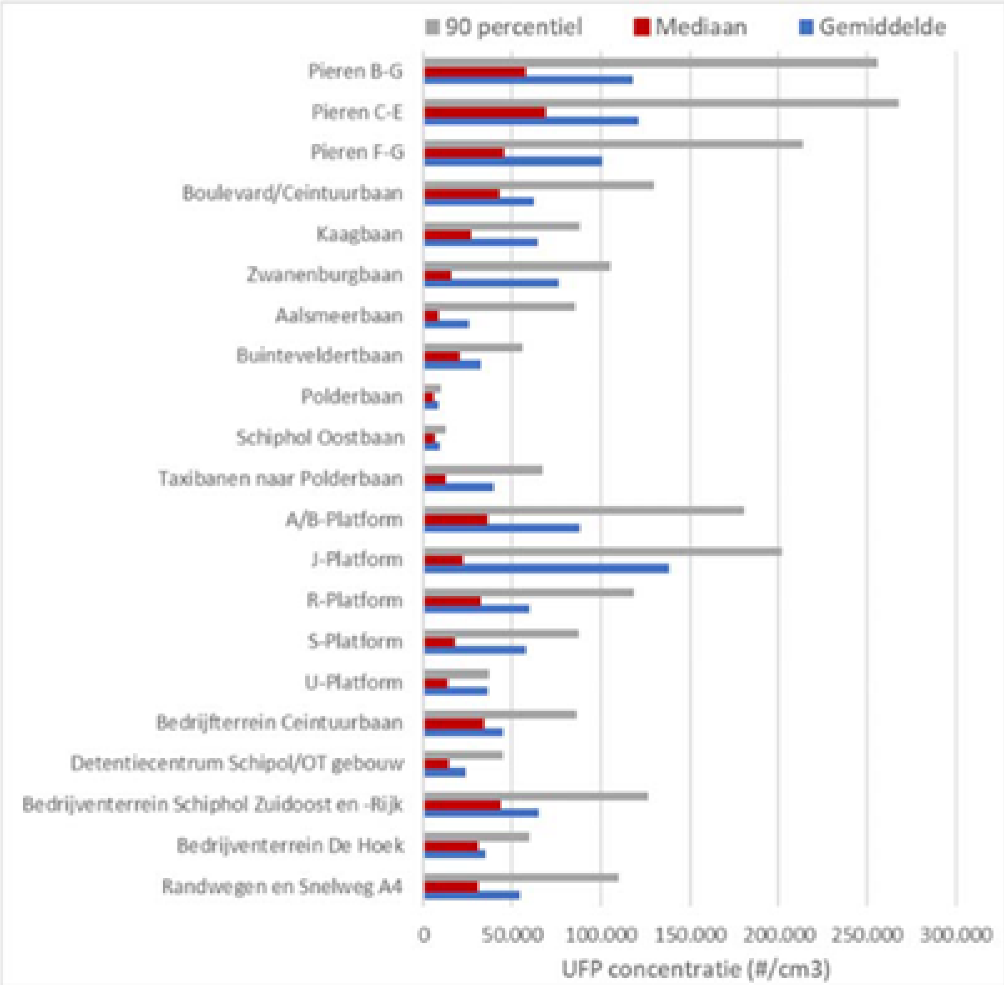


Figure 40: Average, median and 90 percentile UFP concentration values for the several locations at AMS

Appendix C Stakeholder analysis for the AMS case study

C.1 Stakeholder inventory list - descriptions

Royal Schiphol Group (RSG)
Royal Schiphol Group RSG is an airport company and the owner and operator of AMS, RTHA and Lelystad Airport, while also holding a majority stake in Eindhoven Airport (Schiphol, 2022a). RSG has an important socio-economic task: creating the world's most sustainable, high quality airport in order to allow trade, tourism and knowledge to flourish, with safety as a key enabler. The overall goal of RSG is to provide top-quality aviation infrastructure and air transport facilities for passengers and cargo. The company is divided into several departments, all with their own responsibilities, interests and objectives. The departments that are involved in the problem situation with regard to UFP mitigation are briefly mentioned below.

This research is carried out on behalf of the Innovation Hub, which is a team that is part of the department Strategy & Airport Planning (S&AP) at RSG. The objective of S&AP is to work on a future-proof Schiphol and they develop the medium/long term vision and strategy of Schiphol Group. S&AP explores innovative ideas with the ambition to create the worlds' most sustainable and high-quality airports. The focus is on the social interest, sustainability and maintaining the hub function of AMS. The Innovation Hub is working on the development of innovative solutions to make the airport more sustainable, as well as more efficient and future-proof. Within the family 'Healthy Environments' of the Innovation Hub, the project about 'UFP Mitigation' has emerged over the last few years.

Another department that may play an important role in the formation of the knowledge foundation of this research is Airport Operations (OPS). They are responsible for facilitating and directing all necessary processes for the airlines, i.e. landing and take-off of aircraft (LTO) and snow and slipperiness control. OPS makes sure that adequate safety requirements are complied with during the operation, and that the operation is structurally improved and input from the rest of the organization is being processed. Besides this, OPS is also responsible for the operation on the runways as a whole.

Within the department of Safety, Security and Environment (SSE), safe travel and a safe work environment for everyone is the guiding principle. SSE optimizes the safety and reduces the risks in the case of something happening, while also involving the surroundings of the airport. An important task of SSE is measuring, for instance, the noise and other emissions to make sure that these are below a certain benchmark. Within the department of SSE, the division 'Health, Safety and Environment (HSE)' supports the organisation in risk management in the fields of safety, health and the environment. A policy of the same name was drawn up by RSG to ensure that the company contributes to healthy and safe (working) environments and operational processes, with the key objective to prevent injury and damage. The starting principles, regulations and provisions in this area are all documented in a policy statement and an HSE Standard. The production of ultrafine particles as well as the exposure to UFP of (platform) employees and residents in surrounding areas also affects the environmental safety of the airport, which makes it a point of attention for HSE as well.

The department 'Asset Management' (ASM) is responsible for the planning, development, realization and management of all operational assets of AMS. These for instance include the runways, lanes and terminals, so in other words: the infrastructure of the airport. ASM creates the preconditions that guarantee the safe use of assets at the airport, but also ensures the availability of crucial data and information for innovative solutions. They also facilitate the development and renewal of assets for a future-proof and sustainable Schiphol.

Dutch government
The ministry of Infrastructure and Water Management is committed to an accessible, safe and sustainable the Netherlands. This also concerns the operations at AMS and the airport itself. The focus is also on the sustainability of the aviation industry, as well as on the quality of the air, water and soil on and around Schiphol. The ministry of Infrastructure and Water Management also grants subsidies to RSG for projects that may be able to contribute to a more sustainable airport and that ensure better compliance with environmental regulations. In the policy section of the ministry of Infrastructure and Water Management, four Directorates-General (DG) are concerned with developing policy, of which two are relevant for this research: the DG for Aviation and Maritime Affairs and the DG for the Environment and International Affairs. Of these DGs, policy development is especially interesting in the fields of aviation and air quality, respectively.

The ministry of Social Affairs and Employment strives for an honest, healthy and safe work environment in the Netherlands. In this context, the ministry of Social Affairs and Employment primarily stands up for the working conditions policy and the inspection thereof: a safe and healthy work environment for all (platform) employees at the airport grounds of AMS.

Knowledge institutes
Over the last four years, the National Institute for Public Health and the Environment (RIVM) has conducted some extensive research with regard to the health effects of UFP exposure and the potential impact on the health of platform employees at AMS. On the basis of these reports, the Dutch Health Council gives advice with regard to the mitigation approach of the UFP production at the airport. Both parties are primarily active as knowledge institutes and work as advisory bodies for the Dutch government.

TNO, the Netherlands Aerospace Centre (NLR) and Wageningen University & Research (WUR) are knowledge institutes with a lot of know-how within the area of UFP concentrations and dispersion at the airport grounds. They are appointed by RSG to conduct research regarding certain aspects of the UFP policies. These parties are financially rewarded for conducting the research and the arrangements concerning the intellectual knowledge after these projects need to be determined in advance.

The Delft University of Technology, also known as the TU Delft, can also be an important knowledge partner for projects at RSG. Students and professors at the TU Delft have a lot of know-how regarding the aviation industry and the technological developments that are happening in this field of study.

Air Traffic Control the Netherlands (LVNL)
Air Traffic Control the Netherlands manages the Dutch civil airspace and is therefore responsible for guaranteeing safe air traffic flows above and around AMS. For LVNL it is of great importance that they are able to optimally perform their tasks without too much hindrance from external effects, such as vision reducing circumstances.

FNV Schiphol + Platform employees, baggage handlers and other ground staff
FNV Schiphol is a trade union that represents the interests of all affiliated employees, including the platform employees at the airport grounds. They are employed by the companies that take care of the handling of the aircraft, e.g. the loading and unloading of aircraft, under supervision of RSG. FNV Schiphol and the platform employees, baggage handlers and other ground staff demand a safe and healthy working environment at AMS, which cannot be sacrificed for the operation of the aircraft.

Aircraft Manufacturers
The aircraft manufacturers are the suppliers of the aircraft that are deployed during the operation at AMS and other airports all around the world. The design and construction of a certain type of aircraft is a very time-intensive process and can take a few decades when starting from scratch. For the operation at the airports, the aircraft need to be compatible with all the infrastructure and equipment that is needed for the processes. When future innovations are implemented at the airport, this compatibility needs to be taken into account. For instance, a future UFP mitigation system based on water droplets needs to be efficient and effective for all type of aircraft and the components of the system have to connect well with each other.

Airlines
The airlines that operate at an airport have to deal with all the regulations that apply there and will also be exposed to all innovations that the airport(s) will implement in the future. They demand a safe operating environment, without endangering passengers and employees. At AMS, KLM is the airline with the largest share in the entire operation and is therefore also the biggest "polluter". KLM and several other airlines that are progressive in the field of sustainability, e.g. EasyJet and TUI, are searching for new solutions and innovations to make their operation future-proof. Cooperation with the airports for future innovations in the field of UFP mitigation at the airport might be interesting for the airlines in order to strengthen their sustainable image.

Residents of the AMS surrounding areas
The residents of the areas surrounding AMS are involved in the operations at Schiphol as they experience the produced noise, other emissions and visual hindrance created by the aircraft. They should be able to enjoy living in their neighborhood without potential harm for their health, and thus require as little nuisance caused by noise and air pollution as possible, as well as by visual hindrance.

Investors
Investors in RSG projects, e.g. TULIPS for the UFP mitigation project, expect their investments to be used for the right purposes and hope to see results. TULIPS is part of the European Green Deal and provides, among other things, subsidies for RSG, KLM, NLR and TNO. Without financial resources, studies and projects cannot be carried out, so these partners are of great importance for RSG and the knowledge institutes.

Water droplet production equipment providers
The water droplet production equipment providers, such as MB Dustcontrol and Erkho, are specialized in the production, distribution and installation of water spray equipment. These machines produce a water droplet screen or cloud, initially for dust control purposes for open terrain. This equipment is based on the principle that the water droplets agglomerate with the dust particles in the air, after which they precipitate by means of gravity. The used technology fights dust in an efficient and sustainable way and the equipment can produce the water droplet screen completely autonomous. Applying this technique for the mitigation of produced ultrafine particles at the airport is interesting to investigate and the providers of this kind of equipment are potentially important partners for AMS and other airports around the world.

C.2 Problem formulations stakeholders

	Interests	**Objectives**	**Important resources**
FNV Schiphol + employees	A safe and healthy working environment at AMS for all (platform) employees	The eventual implementation of a UFP mitigation project that is committed to a safer and healthier working environment at AMS	Involvement and media attention
Aircraft Manufacturers	Economic profit	Airport interventions that do not affect the economic profit in a negative way	Input and knowhow w.r.t. the design and construction of aircraft
Airlines	Economic profit	Airport interventions that do not affect the economic profit in a negative way	Input and knowhow w.r.t. a safe aircraft operation
Residents	A safe and healthy living environment around AMS for all residents	The eventual implementation of projects at AMS that do not cause nuisance in the fields of noise and air pollution, as well as visual hindrance	Expressing opinions w.r.t. the project
Investors	Use of investments for the right purposes with visible results	The eventual implementation of a project in which the investments are used for the right purposes and where results can be seen	Financial authority by making the research and implementation of studies and projects possible with the investments made
Equipment Providers	Economic profit	Partnering up with RSG as the dedicated water droplet production equipment provider	Knowledge and experience w.r.t. the use of water droplet production equipment

Table 20: Overview of problem formulations stakeholders

	Interests	**Objectives**	**Important resources**
RSG - Innovation Hub	Innovative aviation projects at AMS	The proposal of an innovative 'water droplet'-based UFP mitigation system design	Knowhow about UFP concentrations at AMS and innovative projects regarding the potential mitigation
RSG - S&AP	Creation of the world's most sustainable, high-quality airports	The design of a sustainable and efficient UFP mitigation system that will make AMS future-proof and more sustainable	Authority w.r.t. the implementation of sustainable and future-proof innovations due to knowhow about innovations
RSG - OPS	A safe and efficient handling of the operation, including structural improvements	The eventual implementation of structural improvements for the operation at AMS that comply with the adequate safety requirements	Operational authority and knowhow w.r.t. the entire operation at AMS
RSG - HSE	Optimal safety for everyone at AMS, with minimum risks of something happening	The eventual implementation of projects that mitigate the potential safety and health hazards at and around AMS with a minimum of risks	Authority w.r.t. the safety at AMS due to knowhow about measuring and maintaining the output of processes
RSG - ASM	Development and renewal of assets for a future-proof and sustainable AMS	The eventual implementation of sustainable and future-proof operational assets with a safe-use guarantee	Operational authority and knowhow w.r.t. the possible implementation of innovations and the making available of data and information
DG for Aviation and Maritime Affairs	Policy development in the fields of aviation and maritime affairs	The eventual implementation of a project that is of added value for the aviation industry as a whole	Formal authority in the form of laws and regulations
DG for the Environment and International Affairs	Policy development in the fields of a clean, safe, healthy and sustainable human environment; air quality; circular economy; sustainability; environmental security and risks	The eventual implementation of a project that is committed to tackling climate change and improving air quality	Formal authority in the form of laws and regulations
Ministry of Social Affairs and Employment	An honest, healthy and safe working environment in the Netherlands	The eventual implementation of a project that contributes to an honest, healthy and safe working environment in the Netherlands	Formal authority in the form of laws and regulations
RIVM and the Health Council of the Netherlands	Guarantee of a healthy population living in a healthy environment through research and advice, and by collecting and applying knowledge	The execution and publication of research that can contribute to a healthy population living in a healthy environment	Authority in the form of expertise and knowhow in the field of public health
TNO and NLR	Financial rewards for the conducted research and provided insights	The execution of research for RSG to generate funds	Authority in the form of expertise and knowhow w.r.t. conducting research in the aviation sector
TU Delft and WUR	Creation of intellectual property	The execution of research to create intellectual property	Authority in the form of expertise and knowhow w.r.t. conducting research in the aviation sector
LVNL	A safe and efficient handling of the air traffic flows by managing the Dutch civil airspace	Guarantee of a safe and efficient handling of the air traffic flows by at AMS	Input and knowhow about the safe handling of air traffic flows at AMS

C.3 Initial expert stakeholder shortlist

Table 21: Expert stakeholder shortlist

Stakeholder	Role in this problem	Needed knowledge for theoretical background
RSG - OPS	Assuring that the potential UFP mitigation system design(s) comply with the adequate safety requirements needed for the operation and that, after implementation, the operation can take place undisturbed.	Knowledge on the introduction of new starting positions of aircraft; knowledge on the various alternatives to mitigate UFP; knowledge on the eventual implementation (location, time and way) of a UFP mitigation system.
RSG - S&AP	Assuring that the potential UFP mitigation system design(s) are verified by all departments and external partners.	More knowledge on the involved stakeholders within the UFP mitigation problem situation; knowledge from the Taskforce UFP Mitigation about the synergy between departments.
RSG - HSE	Assuring that the potential UFP mitigation system design(s) comply with the adequate safety and health requirements on the airport grounds with a minimum of risks.	Knowledge on the environmental and worker-related safety restrictions that the system must comply with; knowledge on the EASA regulations that apply on the airport grounds.
RSG - ASM	Assuring that the potential UFP mitigation system design(s) may result in a sustainable and future-proof operational asset with a safe-use guarantee.	Knowledge on the management of operational assets at AMS.
TU Delft and WUR	Knowledge partner.	Scientific knowledge on the effect of weather conditions on the dispersion of UFP, as well as on the potential mitigation of UFP.
RIVM	Knowledge partner.	Knowledge on the UFP concentration accumulation sources and locations at AMS and the potential health impact on (platform) employees.
Equipment Providers	Knowledge partner.	Knowledge on equipment and strategies to potentially mitigate UFP.
Knowledge institutes (TNO, NLR, To70)	Knowledge partner.	(Scientific) knowledge on the UFP concentration production, dispersion and potential mitigation at the airport grounds.

Appendix D Aircraft engine characteristics

During the stakeholder interviews with professors from the faculty of Aerospace Engineering at TU Delft (appendices F.1 and F.7), discussions regarding the potential impact of the aircraft engines on the effectiveness of the 'water droplet'-based UFP mitigation system arose. Some general knowledge on the performance and characteristics of jet engines was therefore provided by these stakeholders to complement the theoretical background.

The engines of an aircraft produce one beam of wind/air, which includes some sort of rotating components in the engine outlet (swirls). The engine consists of two parts: the core and the bypass duct, which are clearly visible in figure 41.

Figure 41: Back view of an aircraft engine

The core of the engine (over the cone) is the warm part of the engine, through which the polluted air with emissions from the combustion process flows. The bypass duct is the cold part of the engine, which is placed around the core, through which "clean", compressed and accelerated air flows. For a Boeing-787, the volume of air that passes through the bypass duct is ten times bigger than the volume of air that flows through the engine's core. The cross-section of a modern-day (turbofan) jet engine is shown in figure 42, in which the air that flows through the bypass duct is indicated by the purple arrows ('Cold Nozzle').

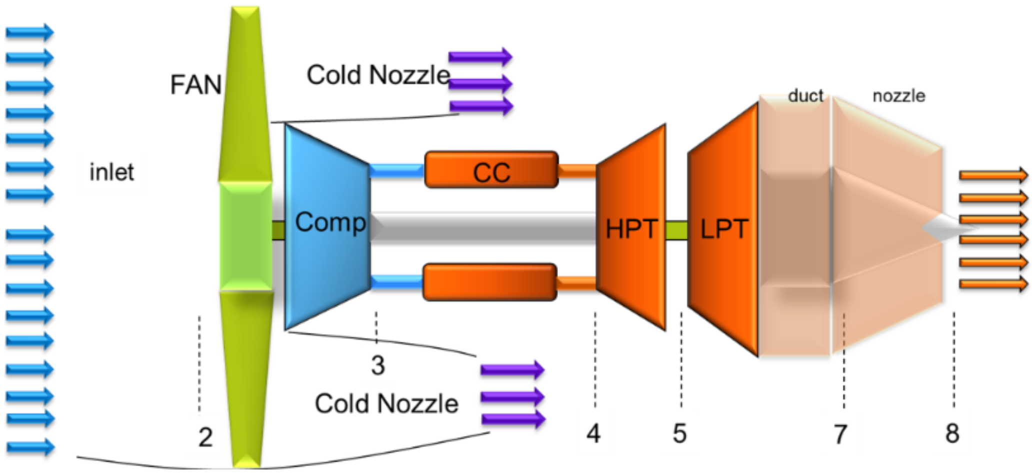


Figure 42: Cross-section of a modern-day turbofan jet engine

The air (blue arrows) enters the inlet of the engine, after which it will go through the FAN. The air will then enter the compressor (Comp), after which the compressed air will flow into the combustion chamber (CC). In this combustion chamber the jet fuel is added and, after ignition, a warm gas flow is created. This gas flow is a combination of all the emissions and will first go through the high pressure turbine (HPT), which is connected to the same rotary shaft as the compressor. The warm gas flow in combination with the HPT results in a rotating shaft and thus a rotating compressor. The gas flow will then proceed to the low pressure turbine (LPT), which is connected to the same rotary shaft as the FAN, and will thus let the FAN rotate. After the LPT, a small collection of warm air (energy) is left, which still contains all the emissions. This air with emissions will go through the duct and nozzle, and will eventually produce the thrust from the jet engine (orange arrows). Whilst the air flow is produced, a lot of energy is already used to make the compressor, as well as the FAN, rotate. The FAN is important for propulsion: a lot of (cold) air will not go through the core of the engine, but will flow through the bypass duct (cold nozzle) to provide more thrust. This cold air flow is responsible for around 80% of the thrust from the engines, while only 10% of the air actually goes through the engine's core. This share is the so-called bypass ratio: the ratio of air that goes around the core, so through the bypass duct, and the air that goes through the core. In conclusion, cold and warm air flows will mix inside and outside of the jet engines.

Appendix E Case study - Copenhagen Airport

For this research, a stakeholder interview was conducted with the Head of Sustainability Development at Copenhagen Airport (CPH) (appendix F.4), which is the biggest and busiest airport in Denmark. CPH was approached to be a stakeholder in this research, as this airport is relatively similar to AMS in terms of its geographical location and weather conditions, but mainly due to its involvement in projects to create a more sustainable and future-proof airport. Just like Amsterdam Airport Schiphol, CPH has conducted research and performed experiments regarding the potential implementation of remote starting positions and the deployment of water droplets to combat aircraft-produced ultrafine particles. CPH's visions on both studies will be discussed in sections E.1 and E.2 respectively.

E.1 Research on the implementation of (semi-)central starting positions at CPH

E.1.1 Analysis of fully remote starting at CPH

CPH conducted research on the potential implementation of remote starting positions at the airport, to move the production of emissions by aircraft further away from the piers, where most platform employees are walking around, without having a too significant impact on the starting capacity of the airport. In the current situation, aircraft at CPH will have a maximum taxi time of around six to eight minutes, which matches the necessary time frame for the pilots to do their last checks prior to departure. The minimum taxi time is normally around three to four minutes, which means that the pilots are relatively in a hurry to complete their final checks. In the situation where aircraft are towed by a truck to a remote starting position, the pilot has to wait with starting up the engines and finishing the final checks until the aircraft is positioned at the remote location. Besides this, an auxiliary power unit (APU) needs to be deployed in order to be able to start up the aircraft engines remotely. Normally, this would not be necessary as the final checks can be performed by the pilots before the engines are started.

The performed measurements showed that the use of an APU, which is a necessary additional power source for remote starting, resulted in an aircraft operation with a higher emission production than the current operation. The results indicated that more kilograms of fuel were used when the aircraft engines are started up at a remote starting locations than at the aircraft stand at the pier. This new system is partly beneficial, as the aircraft-produced emissions are moved further away from the busy airport areas where most of the (platform) employees are working, but overall it will have a bigger, negative environmental impact. As the pilots do not have sufficient time to stabilize the engines and perform the final checks during the remote start and the available time frame to get to the holding point, an average increase of the turnaround time with 19 to 20 seconds was calculated. However, the measurements showed no significant effect on the starting capacity of the airport, which means that the implementation of remote starting could very well be beneficial from an operational/practical perspective. The fact that the starting capacity of CPH was not affected by the system was not incorporated in the mathematical modelling. If the potential benefits were considered in this mathematical model, the outcome of the analysis would probably indicate that the implementation of remote starting of the aircraft engines would be more efficient and a higher potential benefit could be achieved. However, the Head of Sustainability Development stated that there were many uncertainties in the model, which would make it hard to incorporate the operational/practical aspect into the model (appendix F.4).

E.1.2 Intermediate solution at CPH

Even though the conducted research on fully remote starting at the airport did not show the most promising results, CPH has implemented an intermediate solution to reduce the accumulations of aircraft emission concentrations near the piers and platforms. In the very densely populated areas, where the most (platform) employees are walking around as well, the aircraft are being towed away for a few hundred meters to move the cold start further away. The main challenge and constraint of this intermediate solution is that the taxiways are used as a new starting point of the aircraft operation, so there must be made sure that the starting aircraft are not blocking the taxiways during regional and/or international departure peaks. During the off-peak hours, the deployed aircraft for international flights are also towed as far away from the terminal facilities as possible. Starting up the engines at the piers and aircraft stands in the busiest area of the airport has been banned at CPH and currently happens after a 200-300 meters pushback, once the aircraft has left the very narrow layout next to the terminal.

An analysis was carried out to provide insights in the operations, of both departing and arriving aircraft, on one taxiway between the two piers, after which this scenario, in which all starting points of the aircraft operation were moved further away from the aircraft stands at the pier, was modelled in relation to the baseline scenario. Results showed that arriving aircraft had a better punctuality, as they were able to directly taxi from the runway to the aircraft stand at the pier. Inbound parking was not necessary anymore, since the departing aircraft were moved 200-300 meters away from the aircraft stand at the pier, which made them available for arrivals. As the arriving aircraft could use their energy to return to the dedicated stand, there was no need to shut down the engines and restart them again to continue ground idle. A slight delay was calculated for the departing aircraft, because the additional pushback from the piers took one to two minutes extra. However, once the aircraft reached a cross way, the engines could be started before the ground idle procedure came to a hold. After decoupling from the pushback truck, the aircraft could continue with an efficient operation.

This intermediate solution thus has a positive effect on the arriving aircraft and a slightly negative effect on the operation of the departing aircraft. Besides this, the accumulation of UFP concentrations at the involved platforms and piers was reduced by at least 50%. Health hazards for (platform) employees with regard to aircraft emissions are therefore partially mitigated, as the employees are not working directly in the areas where the emissions from the aircraft engines are produced. In terms of investments, this partial solution fit in the current airport layout and no additional infrastructure, tow trucks and employees were necessary for the implementation. Starting locations that were used less in the previous situation are now used in this system, which resulted in maximized implementation of these positions. Overall, the new system is seen as a temporary solution by CPH as the slight negative impact on the operational procedures is compromised by the small beneficial impact on the aircraft emissions concentrations. Remote starting of the aircraft operation, in this case 200-300 meters away from the pier, could also be implemented at the less-congested areas of the airport where less employees are walking around. However, this would not really make sense in the current situation as there are less operational- and health-related problems here. In case of the expansion of this system across CPH, additional investments would eventually be necessary.

E.1.3 Potential of remote starting at AMS

During the interview with the Head of Sustainability Development of Copenhagen Airport (F.4), the potential of introducing remote starting locations at Amsterdam Airport Schiphol was also briefly discussed. The impact of the implementation of (fully) remote starting positions on the aircraft operation and the environment is highly dependent on the layout of the airport. Even though fully remote starting of the aircraft operation at CPH was not deemed to be significantly beneficial, this does not necessarily mean that the implementation of this system is also not efficient at all other airports.

Figures 43 and 44 show the graphical layout of Copenhagen Airport and Amsterdam Airport Schiphol respectively. By comparing these images, it is visible that the layout of AMS is very wide-scale, while CPH's layout is more compact and has three runways instead of six. The location of the runways at AMS results in longer taxi distances and longer taxi times, which might contribute to a successful implementation of remote starting locations. The longer taxi times might make it possible for the pilot to stabilize the engines and perform the final necessary checks during taxiing, and a potential limited increase in turnaround time is just a small share of the initial total time. Besides this, infrastructure for a few potential remote starting locations is already present at AMS, which limits the need for additional investments.

It is necessary to further analyse the potential of (fully) remote starting and determine whether this new system should be implemented for all aircraft operations. For instance, wide body aircraft emit much higher numbers of UFP than smaller aircraft, so it might be of importance to determine whether the system should initially be implemented for both aircraft classes. It is also interesting to compare this remote starting system with the use of the deicing facilities, as the deicing procedures might have a similar impact on the aircraft operation. At CPH, a remote deicing platform is in use, which results in longer taxi times and has a significant impact on the starting capacity of the airport. There is only one deicing slot available here, which is accompanied by lower departures due to longer delays. At AMS, there are multiple deicing slots available and the impact of these procedures on the starting capacity is less substantial. Using this remote deicing platform for starting up the aircraft remotely, outside of the Winter months, might thus be operationally feasible at Schiphol.

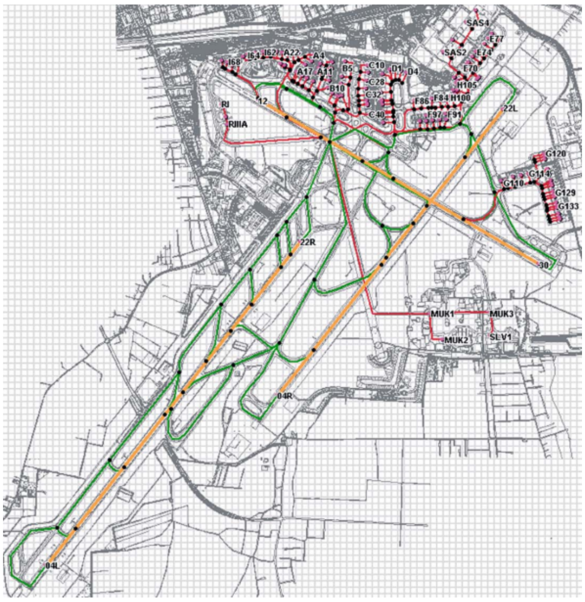


Figure 43: Layout CPH (Fenger et al., 2006)

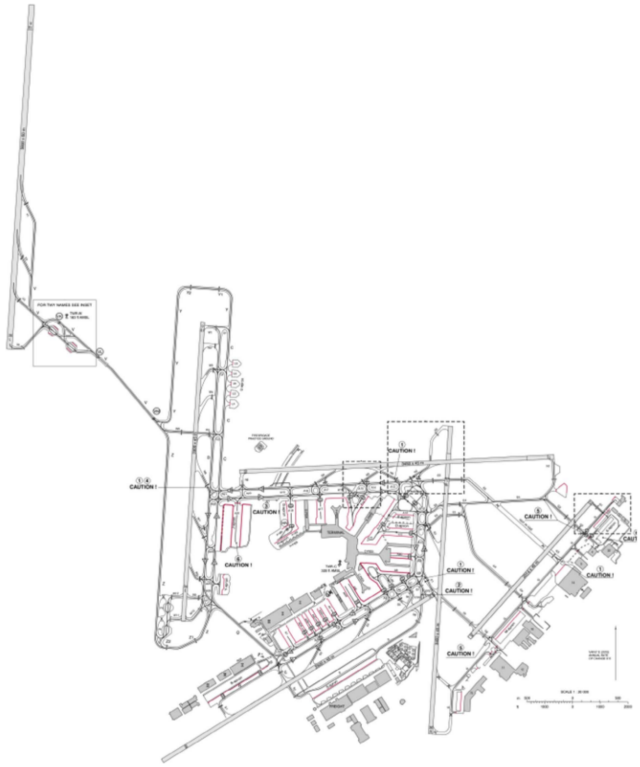


Figure 44: Layout AMS (Samà et al., 2018)

E.2 Experimenting with water droplets to combat aircraft-produced UFP

The interviewee mentioned that CPH is currently not active in the 'water droplet' project, due to a lack of valid evidence of effectiveness. They performed experiments in some sort of tube, in which a haze of water was created, after which they measured the UFP concentrations and compared them with the initially measured concentrations. The use of the water droplet haze resulted in lower ultrafine particle concentrations, but the concept of a system design and the design criteria for an actual system at the airport were not shown. A solution to tackle the UFP concentrations at the airport is important but, from a airport operator's point of view, this solution should not interfere with the airport operations. Currently, it is too big of a challenge to implement a water droplet cloud for the mitigation of ultrafine particles, especially during the Winter months. However, Copenhagen Airport is still interested in the developments of the UFP mitigation strategy that is based on the use of water droplets and is still playing a role in the advisory board of the Danish project that explores this potential solution. CPH would still like to investigate this solution direction once it is proven to be an interesting project for the airport.

Appendix F Stakeholder interview transcriptions

F.1 Interview A

Interview A (in Dutch)

Institution: Delft University of Technology
Faculty: Aerospace Engineering
Expertise: Air Transport & Operations
Date: 21-6-2022

Ultrafijnstof binnen de faculteit van Lucht- en Ruimtevaart

- Vooral focus op klimaatimpact binnen LR: UFP heeft vooral een lokale impact.
  - CO_2, NO_x en waterstof op grotere hoogte;
  - Niet heel erg bezig met (ultra-)fijnstof.
- NO_x is een product van rook, hoge verbrandingstemperaturen en hoge druk:
  - Nodig voor thermodynamische efficiëntie;
- De rest van de emissies moet eigenlijk volledig weg.

- KlimOp (Klimaat-ontzorgings-programma):
  - PM wordt meegenomen, maar zijn geen gegevens van in de database.
  - Wel unburnt hydrocarbons.
- Er kan niet echt aan UFP worden gemeten, dus heel lastig om mee te nemen momenteel.

Joris Melkert (verbranding en motoren) & Arvind Rao (propulsion)

- Onderzoek naar synthetische brandstof: gas-to-liquids;
- Kerosine maken van aardgas:
  - Veel schoner, minder restproducten.
- Propulsion.

Uitstoot van ultrafijnstof door vliegtuigen

- Bij de koude start van de motor veel partical emissions;
- Vooral op 'idle' heeft de motor veel onvolledige verbranding;
  - Koolmonoxide en koolwaterstoffen

- Verschil van UFP uitstoot tussen de soorten vliegtuigen en soorten motoren:
  - Generatie van de motoren;
  - Staat van de motoren;
  - Functioneren van de verbrandingskamer van de motor;

- Waar komt die ultrafijnstof vandaan? Vanwaar die onvolledige verbranding?

Verbranding in de motoren

- Door hoge temperatuurverschillen in de motor krijg je onvolledige verbranding.
- Bij de vlam heb je een heel hoge temperatuur, waar de brandstof langskomt, maar na de vlam koelt deze heel snel af, zonder dat de moleculen volledig zijn ontbonden in koolstofdioxide en water.
- Wanneer deze stoffen zijn afgekoeld reageren zij niet meer en krijg je (ultra)fijnstof als restproduct.

Inzet van waterdruppels voor het afvangen van UFP

- Motor zelf: de core en de bypass
  - Bypass duct:
    - Zit om de core heen;
    - Niks anders dan schone lucht: blaast waarschijnlijk al het water weg.
    - Water en lucht alleen gecomprimeerd en versneld erdoorheen.
  - Core (over de cone):
    - Lucht uit de core is door de verbrandingskamer heen geweest;
    - Daar zit het ultrafijnstof in;
    - Komen waarschijnlijk geen waterdruppels bij.
  - Bij een Boeing 787 is de hoeveelheid lucht die door de bypass heen gaat een factor 10 groter dan de hoeveelheid lucht die door de core heen gaat.
- Waterdruppels sproeien op de core van de motor:
  - Door de bypass heen in de core.
  - Soort sproeier over de cone heen.

  --> Logistieke uitdagingen: gaat rijdend moeilijk, stilstaan lijkt noodzakelijk.


- Op de kop van de baan niet ideaal, want daarvoor moet de motor al minstens 3-4 minuten aanstaan.
- Dus het sproeien van waterdruppels toch ergens halverwege in het proces.
- Lijkt vrij lastig in combinatie met duurzaam taxiën/ taxibots.

- Positie van vliegtuig van belang tijdens de mitigatie:
  - Met de achterkant richting het gras/ open veld;
  - Niet al het water blazen richtingen de taxibanen en andere infrastructuur.

- Verspreiden van de wolk waterdruppels van groot belang bij het afvangen.

- Veiligheidseisen, wet- en regelgeving:
  - Weinig te maken met EASA-regels: niet per se risico's voor het vliegtuig;
  - Meer te maken met Arboregels: veiligheid van de mensen eromheen.
  - Water aan de achterkant in de motoren blazen lijkt weinig gevaren met zich mee te brengen. Dit is een ander verhaal als er water aan de voorkant de motor wordt ingespoten: ook tegenovergesteld effect, wellicht neemt (ultra)fijnstof dan juist toe.

Toekomst van ultrafijnstof

- Kan je als vliegtuig-/motorontwerper of – bouwer iets doen aan die onvolledige verbranding en productie van ultrafijnstof?
- Zijn er dingen die verbeterd kunnen worden aan de motoren?

Oplossingsrichtingen

- Voorverwarmen van vliegtuigmotoren:
    - Tijdens het wegslepen van de kist;
    - Tijd die nodig is voor het warmdraaien verschilt per vliegtuig:
        - Minimaal 3 á 4 tot 7 minuten tot de motor gestart kan worden/ het vliegtuig kan opstijgen.
    - Starten van de motor in het veld in plaats van bij de terminal.

    - Al op 150-200 graden voordat deze überhaupt worden gestart.
    - Lager verbruik van brandstof --> minder uitstoot.
    - Mogelijke tijdswinst: motor starten tijdens rijden in plaats van hiervoor stilstaan, maar slepen gaat wel weer langzamer dan rijden door het vliegtuig zelf.
    - Wellicht al veel minder (ultra)fijnstof bij voorverwarmde verbrandingskamers.

    - Verbranding zal gelijkmatiger plaatsvinden;
    - Grote temperatuurverschillen zullen beperkt worden;
    - Verminderen van de opwarmtijd naar 2-3 minuten:
        - Gaat stuk efficiënter dan gelijk volledige start:
        - Hitte blijft in de motor in plaats van dat het naar buiten wordt geblazen.
        - Minder brandstofverbruik;

    - Op soortgelijke wijze als bij Formule 1 de motoren worden voorverwarmd.

- Remote starten:
    - Verplaatsen van het probleem: niet het grondpersoneel, maar de omwonenden de dupe.
    - Probleem dat de vliegtuigen op verschillende tijden moeten starten voor de verwarming van de motoren: de ideale plek om dit te doen is niet voor elk type vliegtuig hetzelfde.
        - Een vaste plek voor alle kisten is wellicht niet gewenst.
    - Bij implementatie veel verschillende plekken nog voor de verschillende type kisten.

    - Niet efficiënt voor brandstofverbruik om op het de-icingplatform de motoren te starten en dan helemaal naar de andere kant van de luchthaven te taxiën.

- Kan er worden gemeten of het effect heeft?
- Helpt het? Hoe kan het helpen? Wat voor opties zijn er?
- Hoe kan je het inrichten?
- Waar kan je het inrichten?

F.2 Interview B

Interview B (in Dutch)

Organization: KLM Royal Dutch Airlines
Function: Safety consultant, Safety & Compliance Organisation
Date: 23-6-2022

Techniek voor mitigeren van ultrafijnstof:

- Waterdruppels: gaat al decennia mee in verschillende industrieën;
  - Uitkijken voor een "Legionella douche" wanneer er mensen rondlopen.
- Filters: met een elektrostatisch effect plakt het UFP aan het filter;

Ultrafijnstof:

- Deeltjes kunnen geteld worden, maar het is nog niet zeker of ultrafijnstof daadwerkelijk de stof is die (het meest) schadelijk is voor de menselijke gezondheid;
- Bij andere emissies, zoals stikstof en koolstof(dioxide), is dit veel makkelijker aan te tonen;
  --> Deeltjesteller kan worden toegepast, maar de impact is nog onduidelijk.

- Er wordt onderzoek gedaan naar bepaalde gezondheidsparameters en de impact van ultrafijnstof, maar het werkelijke verband wordt hierdoor nog niet duidelijk.
- Eerst onderzoek doen naar de toxicologische onderliggende mechanismen: gezondheidsimpact van, e.g., zwaveldeeltjes en geluid voordat er een eenduidig verband kan worden aangetoond.
  - Verwachting dat dit nog wel 10 jaar zou kunnen duren.
  - Belangrijk om niet te laat beginnen met verder onderzoek en handelen.
- Zorg is er zeker, maar bewijs is er niet.

--> Wanneer ben ik klaar met mitigeren? Als de pieken zijn afgevlakt?
--> Hoe verplaatsen en gedragen de ultrafijnstofdeeltjes zich in het lichaam?
--> Na 5 jaar nog steeds de vraag: 'Hoe zit het nou precies?'

- Lastig om de gezondheidseffecten van UFP geproduceerd door vliegtuigen afzonderlijk te bepalen van andere emissies en andere bronnen, zoals wegverkeer en (diesel)apparaten.

Ultrafijnstof op de luchthaven

- Hoeveelheden ultrafijnstof die worden geproduceerd bij de 'koude start' moeten verplaatst worden van de pieren/terminals: gezondheid van het grondpersoneel en de platformmedewerkers hier het meest in gevaar.
- Ook veel UFP-productie tijdens het taxiën:
  - Door de Polderbaan wordt er momenteel ver getaxied door een hoop toestellen, waardoor er meer UFP wordt uitgestoten.
  - Lastig om waterdruppels in te zetten tijdens het taxiën.

Remote starten

- Centrale startposities per baai:
  - Niet effectief: one-size-fits-all implementatie in plaats van systeem per type toestel.
  - Niet efficiënt: wel 5-10 van deze remote startposities nodig om alle toestellen te kunnen afhandelen.

- Opstelplekken net buiten de baai nodig:
    - Weinig ruimte op het luchthaventerrein: er is niet zomaar een plek gevonden hiervoor;
    - Gaat redelijk wat tijd overheen: zijn niet zomaar in een (half)jaar aangelegd.
- Opstelplekken in de huidige infrastructuur:
    - De-icing platform ten noordwesten van het luchthavengebouw: in de zomer redelijk wat capaciteit, maar ver verwijderd van veel pieren --> ver rijden voor veel kisten.
        - Kost hoogstwaarschijnlijk veel meer tijd dan de vliegtuigen zelf laten taxiën vanaf de pier.
        - Heel ander proces in de omdraaitijd van het vliegtuig: niet erg, maar er moeten geen files ontstaan.
        - Op Amsterdam Airport Schiphol krap in de afstanden en tijd: sleeptruck van 10-20 km/h in plaats van een taxiënd vliegtuig op 40-50 km/h; sleeptruck moet ook weer terug naar de volgende pier.
    - Nood de-icing platform: bij rood-wit geblokte huisjes ter hoogte van de F-pier?
        - Wellicht geen ideale locatie.
    - P-platform:
- Inzet van waterdruppels op de remote opstelposities:
    - Voordeel van op één plek:
        - Hele platform wordt elke paar minuten volledig doorspoelt.
            - Kans op Legionella minimaal.
        - Installatie bij elke pier zorgt ervoor dat het vuile water soms tientallen minuten tot een uur stilstaat in de leidingen: wat gebeurt er met dit lauwe water?
    - Op een de-icing platform lijkt dat goed te kunnen passen:
        - Putten zijn al aanwezig, waardoor het (vuile) water eenvoudig kan wegstromen;
        - Niemand loopt er in de buurt, dus veiligheidsrisico's minimaal;

--> Het verder weg zetten van de processen moet passen in de infrastructuur en de tijd die hiervoor beschikbaar is, óf er moet meer infrastructuur en tijd worden vrijgemaakt.

--> Compenseren in capaciteit.

--> Er moet wat aan gebeuren, dus daarvoor moeten deze veranderingen plaats gaan vinden.

--> Combineren met taxibots: geen extra personeel nodig en ook een stuk schoner.

Waterstofdruppels inzetten voor UFP-mitigatie

- Tijdens koude start op een remote startpositie meer gewenst dan bij de VOP aan de pier, óf tijdens het taxiën: "vliegtuig naar het systeem brengen, in plaats van het systeem naar het vliegtuig".

- Invulling van het systeem zelf:
    - Moet goed aansluiten op de motoren per type vliegtuig:
        - Nevel niet van voren in de motoren;
        - Waterkanon moet goed aansluiten op de core van de motoren;
        - Elk type vliegtuig moet op de juiste positie staan om zo een gerichte waterstraal/-wolk in de core van de motoren te krijgen.

--> Vergelijkbaar met de A-pier: de "March Stands?"

- Elk type vliegtuig kunnen daar parkeren en afgehandeld worden;
- Ingewikkeld lijnenpatroon waar elk toestel moet staan;
- Die (led-)lijnen kunnen geïmplementeerd worden voor de juiste positie van elk toestel.
    - VDGS (Visual Docking Guidance System) in te zetten voor dit systeem:

        - LVNL weet welk type toestel het is;
        - Nozzles wellicht schuiven/richten naar de juiste plek per type motor/toestel.

- Veiligheid inzet waterdruppels:
    - Bevriezing tijdens de winter;
        - De-icing platform biedt daar mogelijkheden.
    - Grote plassen water wanneer het lokaal plaatsvindt.
        - Op remote/centrale startposities minder het geval.
    - Bij elke pier zo'n systeem zorgt voor een hoop installatie werkzaamheden en veel waterleidingen op en/of onder de grond:
        - Op enkele centrale startposities veel minder het geval.
    - Gevaar voor (platform)medewerkers wanneer dit dicht bij de pieren plaatsvindt:
        - Veel minder het geval wanneer dit op relatief afgelegen centrale startposities plaatsvindt.
    - Zijn er additieven nodig --> geen water meer, maar regen.

- Extra voordelen wanneer het water wordt opgevangen, vervolgens wordt gezuiverd/gefilterd en daarna weer wordt hergebruikt voor de waterdruppelproductie.

Stakeholders
Bij alle nieuwe ideeën/implementaties in de luchtvaartsector zullen alle betrokken partijen initieel niet enthousiast zijn: 1 op de miljard regel moet aan worden voldaan.

- Nul alternatief is primair het meest aantrekkelijke alternatief in de luchtvaart:
    - Bij nieuwe systemen en langere TAT is een verhoging van de ticketprijs bijna niet te voorkomen: niet gewenst voor de airlines en voor de passagiers.

- LVNL:
    - Die moet ondersteunen dat de vliegtuigen veel langer begeleid moeten worden in hun weg van de gate naar de remote startlocatie en vervolgens naar de kop van de baan: een extra fase wordt toegevoegd aan deze begeleiding.
    - Het proces wordt ingewikkelder: vliegtuigen van verschillende baaien naar één of enkele opstartplek(ken).
    - Voorkomen van files en botsingen, én ervoor zorgen dat de juiste kist op het juiste moment op de juiste plek staat.

- Airlines:
    - Erg zuinig op toestellen: elke verandering waar extra onderhoud of extra werkzaamheden bij te pas komen, zijn over het algemeen al gelijk niet gewenst.
        - Engineering & Maintenance (fleet services) moeten aangeven dat het goed is: groen licht door Boeing en Airbus dat nieuwe techniek geen kwaad kan voor de toestellen.
        - Kan het overtollige water op de grond en op de toestellen geen kwaad wanneer er bevriezing ontstaat?
    - Omdraaitijd (TAT) moet zo klein mogelijk blijven: momenteel 45-50 minuten:
        - 5 minuten extra taxiën is hier al een grote toename van de TAT: om en nabij een vlucht minder op een dag --> afweging tussen luchtkwaliteit en gezondheid en totale startcapaciteit.
    - KLM (50% vluchten); 25% EasyJet, Transavia, etc.; de rest minder geworteld in Schiphol:

    - Belangrijk om alle airlines mee te nemen in dit project.

- Aircraft manufacturers;
  - Blijven de toestellen door de implementatie van het systeem nog in de normale condities van opereren: ontstaan er problemen?
    - 1 op de miljard keren "mag" er een vliegtuig neerstorten: moet niet groter worden door de implementatie van de nieuwe techniek.
    - Geen invloed op de normale vlieguitoefening.

Implementatie: stapsgewijs/incrementeel of gelijk volledig?

- Voor beide wat te zeggen;
- In deze situatie kunnen remote starten, duurzaam taxiën en de inzet van waterdruppels elkaar versterken om uiteindelijk tot een effectiever en efficiënter systeem te komen.
- Incrementeel is wellicht beter te behappen voor alle betrokken partijen, maar de losse onderdelen van het systeem komen tot een minder goed systeem.
- Duurzaam taxiën en de inzet van waterdruppels kunnen een duwtje in de rug zijn om ook het remote starten in te gaan zetten op de luchthaven.

- Luchtvaart moet een stuk progressiever worden om zulk soort nieuwe ontwikkeling meer met open armen te ontvangen en niet tegen veranderingen op te kijken.

F.3 Interview C

Interview C

Institution: Wageningen University & Research
Faculty: Department of Environmental Sciences
Expertise: Meteorology and Air Quality
Date: 29-6-2022

- **What are the most ideal conditions to let the ultrafine particles clump together in the water droplets during the aircraft operation?**
- **While the aircraft is standing still, while taxiing, or while taking off on the runway?**

- Ultrafine particles are almost as small and thus almost as fast as a molecule;
- They move via Brownian Motion, so that it easily gets trapped into a large particle, such as a water droplet.
- Key principle behind the water droplet UFP mitigation technique: once a particle gets trapped inside a water droplet, it is there to be washed/rained out.
- The main issue: if the UFP comes out of the engine, they get an extra burst from the engine activity. This engine blast means that, not just the UFP, but the entire pocket of air might easily push away the produced water droplets. Once you "blow away" the water droplet cloud/screen, the capturing of the UFP by the droplets will be much less efficient.

--> The technical design of the solution will determine how efficient this system will be for the mitigation of UFP at the airport.

- It is possible that the engine should only run as softly as possible, which is impractical once you get to the runway, where you should increase the engine power by a lot.
- In taxiing it is possible and desirable to have the engines run at the lowest level possible while still going forward;
    - Or using a taxibot or sustainable taxi vehicle to tow the aircraft, which prevents turning on the engines for taxiing in the first place.
    - Prevents a lot of emissions close to the working environment of the (platform) employees.

- Remote starting positions:
    - Lower the exposure of employees to high concentrations of UFP

- **During which process(es) of the aircraft operation is UFP mitigation with water droplets the most efficient: 'the cold start', taxiing or the take-off on the runway?**

- There should be determined at what wind speeds, coming from the jet engines, can the ultrafine particles still be encapsulated by the water droplets, without the droplet screen to be blown away by the jet blast.
- With a water droplet screen produced too close to the engine the water droplets will probably be blown away, without too many ultrafine particles to be encapsulated by these droplets.

- The biggest UFP production problem for Schiphol is not at the cold start, but it is the general production of large concentrations of ultrafine particles at the airport.

    - Literature about the cold start of cars: the NO_x production in cold countries and in Winter months is a bit higher than in warmer countries and during the Summer, but not more than 5-10%.
    - “More UFP production at the cold start”, but the cold start only lasts a limited number of minutes, while the taxiing of the aircraft usually takes much longer. How much UFP per minute during the cold start and how much UFP per minute during the taxiing procedure? With what factor is this amount of UFP per minute higher for the cold start?
    - Limiting the operation time of the engines is the best way to reduce the emissions and thus the amount of produced UFP.

- The use of water droplets works very well for the mitigation of dust and fine particles in industries like construction and mining. However, in these industries the velocity of air coming from those industrial regions is way lower than that of the blast of a jet engine --> technical difficulty of the system: fundamental difference between the solution for this case and the solution that is found for the other systems (car, construction, mining).

- **During which weather conditions is UFP mitigation with water droplets possible? Is it dangerous under certain circumstances: humidity, precipitation, high or low temperatures, wind force, etc.?**

- Temperature:
    - Below zero: applying de-icing techniques, additives to the water for the UFP mitigation in order to lower the freezing point of the used water. Artificial water, which might make it toxic and less safe for the environment and employees.
    - High temperatures: the small water droplets will evaporate fairly quickly.
- Humidity:
    - High humidity: with fog, or being at the point of having fog, the UFP concentrations at the airport might already be much lower.
    - Low humidity: when the air is dry, the production and movement of water droplets is optimal.
- Wind:
    - Windless conditions are optimal to capture UFP in the water droplets, as the screen/cloud stays longer at the dedicated position. Strong winds can blow the UFP over, under or beside the water droplet cloud.
- Precipitation:
    - Rain: may help with capturing ultrafine particles. However, as rain droplets are much bigger than the water droplets produced for the UFP mitigation, the total volume of these droplets is much lower. Many small droplets create a much higher volume/area with which the ultrafine particles can interact --> bigger effective area size.
    - After rain, air pollution levels are generally much lower.

- **Is it necessary to blow the water droplets into the core of the jet engines, or is a water droplet cannon/screen at a certain distance behind the engines also a possibility?**

- Dispersion = something coming from an engine, like a plume, it travels into the vertical and horizontal directions: it slowly becomes wider, so the emissions are stored in a larger volume.
    - If you are far away from the source, you may not capture these emissions.

- Maybe impractical to blow the water droplets into the core, as the thrust of the engine and thus the wind velocity is the highest there.
- Besides this, when the water droplet screen/cloud is closer to the engine the water droplets might evaporate faster, which makes it more difficult to encapsulate the ultrafine particles.
- A lot of UFP comes out of the core, but also all the other emissions are produced there as well.
- When the water droplet screen is blown away by the thrust from the core, the effectiveness of the system is not high.
- From the point of view of an expert in the field of meteorology and air quality: blowing water droplets into the core of the engines does not seem like a good idea.

- When the water droplet screen is placed further away from the engines of the aircraft, the air will disperse between the exit of the engine and the water droplets so that not all the initially emitted ultrafine particles can be captured by the water droplets.
- However, the UFP from other aircraft and even other sources, which is still present around the dedicated location of the UFP mitigation system, can still be captured with this water droplet cloud. It is possible that not only the UFP produced by the present aircraft is captured.

- **Is the pressure of the nozzles that produce the water droplets of importance to better capture the ultrafine particles in the water droplets?**

- Higher pressure on the nozzles, so a higher speed of the coming together of the ultrafine particles with the water droplets, will not necessarily make a significant difference.
- Most of the work is being done by the high speed of the ultrafine particles themselves:
    - Wind velocity /air parcel is slowly moving in a certain direction;
    - The individual molecules that make up the air move at tremendous speeds and bump into each other, depending on the air pressure = Brownian Velocity/Motion.
    - Brownian Velocity is much higher, but also at a much shorter timescale, than the velocity and the timescale of the package of air moving in the direction of the wind.
    - This Brownian Motion ensures that the ultrafine particles also move at those speeds, maybe a bit slower, and because of that they will travel into the water droplets when they meet them. The water droplet itself will have a much slower speed, along with the wind, but because of the high velocity of the air and the ultrafine particles the UFP will be captured into the droplets.

- **Is the use of water droplets during the processes of an aircraft dangerous for (platform)employees in a certain vicinity?**

- Natural water is in principle harmless;
    - Only environmental risk is caused by the nitrogen deposition.
- Safety issues mainly related to the construction of the water droplet production equipment on or near the used infrastructure.
- At cold temperatures, the freezing of the water may create a problem. The temperature/weather condition are relevant in the application of this technique, especially around freezing levels.

- **Would pre-heating the jet engines have an impact on the production of UFP and how the particles will disperse and behave during this pre-heating process, but also during the actual start of the engines?**

- If you burn fuel to generate a certain amount of power, then the general law is: the more you burn / the higher the intensity you want to get out of your engine, the more emissions you have.
- At cold starts there are some additional emissions, this mostly has to do with engine residuals that stick to the engine once it is switched off. Once you switch the engines back on, the aircraft produces some “bonus” emissions, which is basically old junk that also gets burnt.
    - Does this make a difference for the production of ultrafine particles?

F.4 Interview D

Interview D

Organization: Copenhagen Airport (CPH)
Function: Head of Sustainability Development
Date: 4-7-2022

Vision on UFP mitigation

- Optimization of the operations is the main goal.
- Mitigating UFP production and dispersion by aircraft to limit the effect it has on people is important, but the climate crisis as a whole is of more importance.
- Looking for solutions that result in less fuel usage by the aircraft, as well as solutions that keep the health of employees and the environment in mind.
- Current tangible UFP mitigation efforts:
    - Having campaigns on APU usage at almost every aircraft;
    - Limiting the runtime of aircraft engines as much as possible;
    - Limiting the amount of diesel engines (aggregates and vehicles) at the airport.
        - Goal: complete substitution of diesel vehicles in 2030.

- It is much more difficult to make aircraft more sustainable, while substituting diesel vehicles at the airport with more sustainable variants is relatively easy.

Situation regarding UFP mitigation based on water droplets at Copenhagen Airport (CPH)

- CPH is currently not active in the 'water droplet' project, due to a lack of valid evidence of the system working;
- However, they are still playing a role in the advisory board of such a project, which is run under an innovation fund in Denmark.
- The Danish project did some testing (not in a climate chamber) with the creation of a haze of water and to see the effects of this haze on the UFP concentrations in comparison with the current concentrations. The experiment was performed in some sort of tube.
    - UFP concentrations were lower, but the design concept/criteria for an actual system at the airport were not shown.

- From the perspective of airport operators: a solution to tackle the UFP concentrations is important, but it must be a solution that does not interfere with airport operations.
- Too big of a challenge to implement a water haze for the mitigation of UFP, especially during the winter months.

- CPH is still very interested in the developments of the 'water droplet'-based UFP mitigation project and still would like to investigate this solution direction once it turns out to be an interesting project for CPH.

Vision on UFP mitigation based on water droplets at airports in general

- Requirement/design criterium: no part of the system should be able to damage the aircraft.
- Requirement/design criterium: polluted water (with UFP) should not end up in the environment (ground water, polders) --> make sure that the polluted water is collected and is filtered if necessary.

- Requirement/design criterium: the water should not freeze the run- and taxiways and disturb the operation.
- The weather aspect is of great importance:
    - The wind blows the water droplets across a large area, which is also already visible during the deicing procedures;
    - Humidity: lower concentrations of UFP were measured during high humidity conditions.

--> Does the system do what we expect it to do? Does it mitigate UFP?

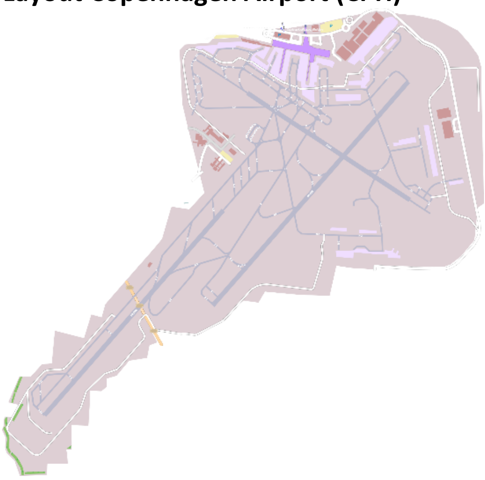
Vision on remote starting positions, (semi-)central starting of aircraft

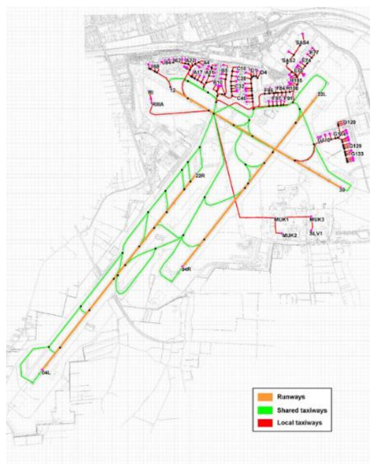
- CPH conducted research on the implementation of (semi-)central starting positions at the airport, but no clear benefits could be linked to starting the aircraft engines at a remote starting location. This was mostly due to the graphic layout of the airport:
    - The longest taxi time is between 6 and 8 minutes, which is in the necessary time frame for the pilots to do their check prior to leaving;
    - Normally the shortest taxi time is 3 to 4 minutes, which means that the pilots are in a hurry to complete their check.
- So, there has been chosen to not implement remote starting of the aircraft engines, as more emissions will be created since you must run the APU. Normally, this would not be necessary as the checks can be performed by the pilots before starting the engines.
- Pilots use the current taxi times to do all the necessary checks and stabilize the engines before take-off.
- No major positive impact of implementing remote starting positions.

- **Reasons to not implement remote starting positions at CPH just yet:**
    - A lot of necessary infrastructure changes;
    - Another necessary form of energy source for the aircraft: APU

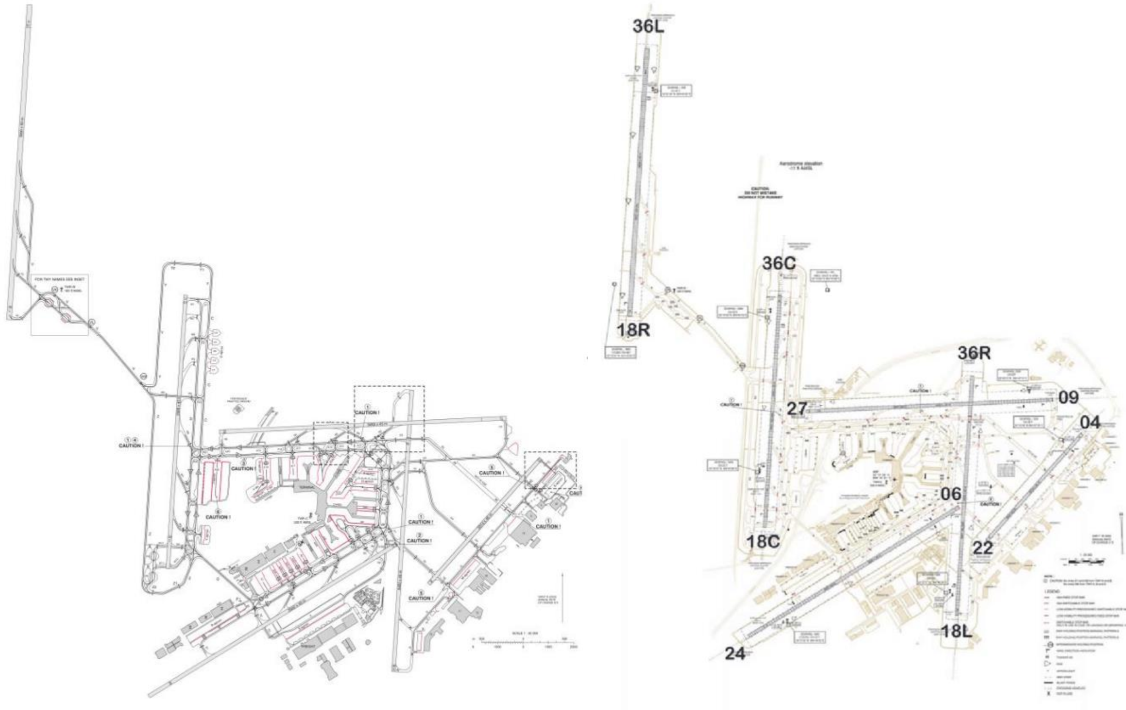
<u>--> More time needed for the operations, as well as longer runtime of APU;</u>
<u>--> More kilograms of fuel are used when aircraft taxi to a remote starting position;</u>
<u>--> Besides the fact that the emissions are moved further away from the busy areas where most (platform) employees are working, this system will have a bigger environmental impact.</u>

Layout Copenhagen Airport (CPH)





Layout Amsterdam Airport Schiphol (AMS)



--> Time needed to stabilize the engines and to do all the checks. With the current timeframe that the pilots have in order to get to the holding point, there is not enough time to do all the checks and stabilize the engines.

--> Increase of average turnaround time of around 19-20 seconds.

--> No effect on the starting capacity of the airport: from an operational/practical perspective, the benefits were significant. However, this was not incorporated into the mathematical modeling.

- If the operational/practical benefits were considered in the mathematical model, the outcome of the analysis would probably indicate that the implementation of remote starting positions would be more efficient, and a higher benefit would be achieved.
- However, as there are many uncertainties, it is hard to incorporate this aspect into the model.

Intermediate solution at CPH:

- However, CPH is currently towing/pushing the aircraft away from the very densely populated areas: where the most (platform) employees are walking around.
- In this area, mostly Type C aircraft are operated, as well as some Type B aicraft.
- Main challenge/constraint of this intermediate solution: taxiways are used as starting points, so there must be made sure that the taxiways are not blocked when they are in high usage.
- During off-peak hours, when regional and/or international departures are not peaking, the aircraft for the international flights are also pushed as far away from the terminal facilities as possible.
- This concerns only 200-300 meters pushback, after which the engines can start.
- Starting the engines at the piers/stands has been banned and is currently done when the aircraft has left the very narrow layout of Copenhagen Airport.

- <u>Analysis done at CPH:</u>

- Operations on one taxiway between the two piers were analyzed, both departures and arrivals, after which they were modelled with the baseline scenario and the scenario where all starting points were moved further away from the aircraft stands at the piers.

--> Arriving aircraft had a better punctuality, because they did not have to stop before taxiing from the runway to the aircraft stand at the pier. As departing aircraft were moved 200-300 meters away from the aircraft stand at the pier, arriving aircraft could use their energy all the way to the dedicated stand. They did not have to stop before continuing their way to the stand.
--> No inbound parking needed anymore;
--> No shutting down and restarting the aircraft engines anymore.
--> Slight delay for departing aircraft, because they had to be pushed away from the piers which cost 1-2 minutes extra. But as soon as they were on a crossway, they could start the engines before the taxi procedure came to a hold.
--> Efficient operation after the aircraft was decoupled from the pushback truck

--> Positive effect on the arriving aircraft and a small negative effect for the departing aircraft.

- This towing/pushing away of the aircraft for 200-300 meters has limited the UFP concentration by at least 50% in this area.
- The health hazards for (platform) employees are therefore partially mitigated, as the emissions of the aircraft engines are not directly "blown" in the faces of the employees.

- This partial solution fit in with the current layout of the airport and additional infrastructure and other investments were not necessary.
- Some less used starting points are now used for this partial solution, which resulted in the maximization of these starting points.
- Mathematical modelling was done to create more insights into the impact of this solution on the operational procedures: a small negative effect on the operation, as well as a small positive effect on the emissions production was found.
- These small effects weigh against each other, which makes it some sort of compromise solution.

- The partial solution could also be implemented all over the airport, so also in the less congested areas where not many employees are working. This would not really make sense in the current situation.
- Additional investments would be necessary once this partial solution is implemented all over the airport.

Remote starting at Amsterdam Airport Schiphol:

- There are no airports that have the exact same design, so whether the implementation of remote starting positions has a positive impact on the environment heavily depends on the layout of the airport.
- Might have a positive impact at AMS, as the taxi times of some aircraft are a lot higher than at CPH;

  --> The large-scale layout of Amsterdam Airport Schiphol, which results in longer taxi distances and higher taxi times, may assist the implementation of remote starting positions to be a success.
- If remote starting locations are already available at AMS, this solution would also be more attractive to implement.

- What do you want to achieve with the remote starting positions?

- Larger aircraft emit higher numbers of UFP concentrations than smaller aircraft;
- What are the shares of large aircraft and small aircraft in the total number of flight movements?

--> Analysis of importance.

- <u>De-icing platforms as a remote starting position:</u>
- At CPH, when the de-icing facilities are currently used, this already has a major impact on the operational procedure: lower number of departures, due to longer delays.
- The expectation is that, at least at CPH, when the remote starting positions are used in a situation similar to when all aircraft would need to be de-iced, this would not be operationally feasible.
- The de-icing spots at CPH are remote, so the aircraft must taxi there before it is able to take-off during the Winter months. One slot for one type E-F aircraft or two type C aircraft.

Sustainable taxiing – Taxibots

- Electric/Hybrid taxi trucks: very good solution for emission-free taxiing;
- Taxibots: depends on which one you are looking at, since there are several solutions already.
    - Mototruck??: small vehicle;
    - Taxibot: large vehicle;

--> At Copenhagen Airport, the Taxibot does impose some challenges once it is implemented, as the compact layout and current infrastructure of the airport does not really allow vehicles of that size to travel around the airport.

--> The smaller alternative of sustainable taxiing (Mototruck??) is a better match for CPH.

- However, just like remote starting, sustainable taxiing only partly solves the problem: aircraft engines still need to be stabilized before take-off, which takes 3-4 minutes and is usually done during the taxiing of the aircraft.

F.5 Interview E

Interview E

Institution: Delft University of Technology
Faculty: Aerospace Engineering
Expertise: Aircraft Noise and Climate Effects, Air Quality, Air Pollution
Date: 11-7-2022

Is the production of ultrafine particles by aircraft currently an important topic in your course 'Aircraft Emissions and Climate Effects' and at the faculty of Aerospace Engineering in general?

- Increasing scientific attention on aircraft produced ultrafine particles and the potential mitigation of UFP:
    - Health concern. It is necessary to better understand the health impact of UFP, as some research has already identified that the impact on health by UFP is bigger than the impact of, for instance, PM2.5 or PM10.
        - Due to size and the way these particles penetrate the human body;
    - Engineering aspect. Scientific interest in the formation of ultrafine particles, which is not just in jet engines or other combustion processes. When they form, they seem to vary a lot, which is caused by, for instance, meteorology and the different engines.

How does the UFP produced by aircraft spread behind the aircraft and across the airport grounds after leaving the engines?

- The behavior of aircraft produced UFP depends on the microphysical properties of the ultrafine particles.
- Depending on when, where and how, the ultrafine particles might grow/accumulate in the engines --> contrails in the sky: clouds with water/ice crystals.
- Ultrafine particles might have the same microphysical properties as the particles in contrails, that are created when water vapor condenses around small dust particles, which provide the vapor with sufficient energy to freeze (Airspace: Contrails (nasa.gov)).
- However, UFP is much smaller and lighter, which results in the fact that they stay in the air for longer. Besides that, the conditions of the operations near the ground are different of the conditions of the operations at a higher altitude.
- Global Civil Aviation Emissions Estimates for 2017–2020 Using ADS-B Data | Journal of Aircraft (aiaa.org)

- **During which process(es) of the aircraft operation are the most emissions, and thus also the most UFP, produced?**

- Several UFP properties that we (might) care about, e.g., numbers, sizes, mass, etc.
    - Trying to understand these different aspects is where we are at the moment.

Are there any UFP mitigation systems/solutions that you are already familiar with?

- Sustainable aviation fuels:

- In the lifecycle context, the carbon footprint of aircraft operating on sustainable aviation fuels will be smaller than the carbon footprint of aircraft operating on normal jet fuels.
  - No impact on the amount of NO_x produced, as the fuel is still burned at the same temperature;
  - Might have an impact on the amount of (ultrafine) particles produced, in the context of contrails.
  - The formation of contrails is one of the most warming(?) components of the climate impact of aviation.
- Depending on the SAF and how much it is blended, there might be less sulfur in the fuel and the (ultrafine) particles that will be emitted by burning SAF will have different properties.
  - From the perspective of contrails, but may be from the perspective of UFPs as well.
- Influence of Jet Fuel Composition on Aircraft Engine Emissions: A Synthesis of Aerosol Emissions Data from the NASA APEX, AAFEX, and ACCESS Missions | Energy & Fuels (acs.org)
- Impact of Alternative Jet Fuels on Engine Exhaust Composition During the 2015 ECLIF Ground-Based Measurements Campaign | Environmental Science & Technology (acs.org)

- Sustainable taxiing:
  - Pushback of the aircraft further away from the piers, almost up to the runway.

Could the implementation of a 'water droplet'-based UFP mitigation system at the airport be effective and efficient?
Under which circumstances can such a system operate? (Blowing water droplets into the core, instead of into the bypass of the engine)
During which weather conditions is UFP mitigation with water droplets possible? Is it dangerous under certain circumstances: humidity, precipitation, high or low temperatures, wind force, etc.?

- It is important to include KLM and other airlines in the system design requirements: aircraft should not be damaged by the water droplets and the system as a whole.

Is it efficient and effective to implement remote starting positions to move the production of UFP further away from the piers and the locations where most (platform) employees operate?

- Displacing the emissions further away from the piers, which makes it less of a problem for the (platform) employees that are working there.
- However, without other mitigation strategies, you will move this problem to the open field, which makes it a potential health hazard for people living in surrounding areas and the environment itself.
- Reducing the emissions, including UFP, is the main goal of mitigation strategies, but moving the emissions further away from the locations where the most (platform) employees are working could be a good starting point as well.

Pre-heating the engines? (Paul Roling)

- What does pre-heating the engines mean?
  - Turning on the engines earlier does not lower the number of emissions produced;

    - The engines will be on for a longer period of time.
- Where are the engines pre-heated?

F.6 Interview F

Interview F (in Dutch)

Organization: TNO
Expertise: Researcher in (Nano) Particles, Atmospheric Composition, Air Quality Modelling
Date: 14-7-2022

Waar heeft het volgens jou aan gelegen dat de eerste testen met de SprayCannons en –Walls qua resultaten tegenvielen en niet statistisch significant waren?

- Noodzakelijk voor een effectief experiment: voldoende tijd voor de ultrafijnstofdeeltjes en de waterdruppeltjes om in dezelfde omgeving met elkaar te kunnen verbinden.
- De tijd die de blast nodig had om de afstand van de vliegtuigmotoren naar de bus met meetapparatuur te overbruggen was 3-4 seconden, wat in principe voldoende zou moeten zijn.
- Van belang is dat de waterdruppels blijven bestaan:
  - De lucht die door de core van de motor gaat is 1200 graden;
  - De lucht die uit de motor komt is ongeveer 700 graden;
  - Water verdampen kost een hoop energie, dus er werd initieel gedacht dat de hoge temperaturen geen groot probleem zouden zijn.
- De waterdruppeltjes bereikten tijdens het experiment niet de core van de motoren: ook toen er met de SprayCannons werd gericht op de motoren was er te zien dat de waterdruppels vooral om de motoren heen vlogen en de wolk steeds breder werd.
  - Menging met een heel groot volume lucht, waardoor bijna al het water verdampte;
  - Het water kwam ook niet meer op de grond terecht, wat betekent dat er niet voldoende water kon worden gebruikt. Dit was ook het geval toen er met 2 SprayCannons in 1 motor werd gespoten.

- Onduidelijk waarom de experimenten met de SprayWalls niet gelukt zijn:
  - Voldoende water en voldoende tijd voor interactie.
  - Het water bereikte de bus en de jet blast ging door de waterdruppelwolk heen.
- Insignificant: is de manier van meten niet goed?
- Bij een vortex met een core is de concentratie van UFP het hoogste in het midden en heeft een Gauges(?) profiel --> de verhoging van de concentratie is een factor 10^5 tot 10^6 van de achtergrondconcentratie.
- Op het moment dat de wind die vortex een klein beetje opzij duwt, zullen de concentraties op een bepaalde afstand enorm verschillen.
- De variabiliteit in de metingen zorgde ervoor dat de situatie zonder water en de situatie met water niet te vergelijken waren, sinds deze golden voor andere metingen.
- Daarnaast duurde de terugval naar de achtergrondconcentratie extreem veel langer dan verwacht: veel last van recirculatie en de achtergrondconcentratie neemt gedurende de dag toe door het aantal vliegbewegingen op de luchthaven.
- Ook werden de experimenten uitgevoerd op een proefdraaiplaats (confined space), waar de jet blast aan drie kanten werd tegengehouden: de temperatuur bleef hierdoor langer hoog dan de normale situatie op een open locatie in de vrije lucht.

“Volledig geloof in dat de inzet van waterdruppeltjes effectief een significant deel van de ultrafijnstofdeeltjes, geproduceerd door vliegtuigen, uit de lucht kan halen.”

Zal het afvangen van UFP effectiever zijn als de waterdruppels gerichter in de core van de vliegtuigmotor worden geblazen? Is dit überhaupt mogelijk?

- Waarschijnlijk juist effectiever om de SprayCannons en –Walls in de “safe zone” van een vliegtuig te zetten, op een grotere afstand van de motoren: de luchtstroming is dan wat meer bedaard, minder turbulentie en de vortex is wat minder sterk.
- Net uit de motor waait het heel hard in de core van de vortex, maar verderop is dit een stuk minder.

- Niet té ver staan met de waterdruppel installatie.
- De vortex uit de motoren is vrij sterk en stabiel: zelfs op grote afstand achter de motoren worden de extreem hoge UFP-concentraties nog steeds gemeten, dus de emissies zijn nog steeds geconcentreerd. Op grotere afstand van het vliegtuig kunnen er nog steeds hoge concentraties UFP worden afgevangen.
- Relatief klein volume aan zwaar vervuilde lucht die je wilt “wassen”: op 100-200 meter afstand van een bulderend vliegtuig, net buiten de safe zone van het vliegtuig, kan de UFP in deze lucht nog steeds worden afgevangen.
- Belangrijk om te bepalen hoe groot de cross-sectie is van de vortex: net na de motor is dat ongeveer 1 m^2, maar op een grotere afstand zou dit wel eens significant kunnen toenemen.

"Je moet geheel af van het idee dat de UFP-mitigatie per se dicht bij de motoren moet plaatsvinden.”

“In een geheel afgesloten ruimte zullen SprayCannons in relatief weinig tijd alle UFP uit de lucht afvangen. Dat is bekend uit andere toepassingen en is ook hoe UFP uit de atmosfeer wordt verwijderd.”

- Opstarten/ Idle draaien van een vliegtuig in een soort tunnel, waar de lucht niet gelijk verdwijnt en waar de UFP-concentraties zich opbouwen. Zonder veel druk loopt de lucht er langzaam uit en wanneer aan beide uitgangen van de tunnel een (overhead) SprayWall geplaatst wordt, is er voldoende tijd en ruimte voor interactie tussen de UFP en de waterdruppeltjes.
- Vervolgens het taxiën: onduidelijk of UFP mitigatie hier een rol zou kunnen spelen.
- Vervolgens bij de blast op de kop van de baan op 100-200 meter afstand een SprayWall plaatsen.

Is een overhead installatie (ringleiding die de waterdruppels naar beneden spuit) wellicht effectiever dan de inzet van waterkanonnen of ringleidingen op de grond? Of een installatie die ervoor zorgt dat de waterdruppelwolk volledig achter en om de motoren heen wordt gecreëerd?

- De richting van de waterdruppels maakt in theorie (hypothetisch gezien) niet uit: of de waterdruppel omhoog of omlaag wordt gespoten zal niet uitmaken voor het systeem, indien de druppels hoog genoeg gesprayd kunnen worden.
- Het zou een betere configuratie kunnen zijn in het geval dat er veel lucht uit de motoren óver de SprayWall heen wordt geblazen. Er werd beweerd dat de SprayWall tot 6 meter hoogte zou komen, terwijl dit in de praktijk 4 meter bleek te zijn, ook al was er voldoende druk.
- Voordelen van een overhead SprayWall:
    - De lucht die normaal gesproken over een liggende SprayWall zou gaan en zou mengen met de "gefilterde” lucht, komt in deze configuratie wel in contact met de waterdruppeltjes;
    - Minder druk op de nozzles: minder energie en minder waterverbruik.
- Nadelen van een overhead SprayWall:

   - Hinderende constructies op de luchthaven;
   - Risico op botsing van vliegtuig met de constructie.

Kan een hogere druk op de nozzles ervoor zorgen dat de waterdruppels dichter bij de vliegtuigmotor komen en minder snel wegwaaien?

- Druk op de nozzles zal niet veel uitmaken: afhankelijk van de afstelling van de nozzle wordt er een kleinere of grotere waterdruppel geproduceerd.
   - Een grotere waterdruppel verdampt minder snel, maar een wolk die bestaat uit kleinere waterdruppels heeft een veel groter volume: effectieve gebiedsgrootte.

Zijn er nog andere technische eisen waar het systeem aan zou moeten voldoen?

<u>Hoeveelheid water die nodig is om het systeem effectief te kunnen laten werken:</u>

- Goede indicatie: de hoeveelheid water die werd gebruikt voor de experimenten met de SprayWalls op Schiphol. De waterdruppels bleven bestaan en het water kwam tot en met de bus met meetapparatuur.
   - Voldoende tijd voor de interactie tussen waterdruppeltjes en de UFP;
   - Voldoende water, wat dus ook nodig is voor de SprayCannons.

<u>Installatie van de SprayCannons en –Walls op grotere afstand:</u>

- In de "safe zone" van een vliegtuig zullen SprayCannons door de hoge windkrachten waarschijnlijk omwaaien.

<u>Veiligheidseisen gebruik van waterdruppels:</u>

- Niet veilig om waterdruppels in de voorkant van de motoren te spuiten.

- Het systeem zo ontwerpen dat de luchtstromen redelijk tot rust zijn gekomen (geen sprake meer van een vortex), maar dat de concentraties UFP zoveel mogelijk afnemen.
- Geen sprake van een vortex en geen hoge temperaturen, maar wel hoge concentraties UFP.

<u>Weersomstandigheden:</u>

- Temperatuur: een hogere buitentemperatuur zal weinig tot geen effect hebben op de snellere verdamping van de waterdruppels, aangezien hier veel meer energie voor nodig is.
- Wind: UFP en waterdruppels waaien allebei mee met de wind, waardoor zij alsnog genoeg mogelijkheden hebben om in interactie te komen met elkaar.

Is er literatuur op het gebied van het fundamentele idee/de wetenschap achter Brownian Motion? Dus hoe de ultrafijnstofdeeltjes, met een enorm hoge snelheid, in de waterdruppels worden gevangen, die zich met een veel lagere snelheid verplaatsen.

- Een ultrafijnstofdeeltje is "Browns", die beweegt zich bijna als een gas: legt een behoorlijke gemiddelde afstand af.
- Een waterdruppeltje valt langzaam naar beneden: de valsnelheid van een waterdruppeltje is vele malen langzamer dan de snelheid van een ultrafijnstofdeeltje, waardoor deze twee bij elkaar in de buurt kunnen komen (coagulatie).

F.7 Interview G

Interview G (in Dutch)

Institution: Delft University of Technology
Faculty: Aerospace Engineering
Expertise: Flight Performance and Propulsion, Flow Physics and Technology
Date: 15-7-2022

"Óf uitstoot van UFP voorkomen (duurzame vliegtuigbrandstoffen), óf het afvangen van ultrafijnstof nadat de concentraties zijn geproduceerd: waarschijnlijk een combinatie van beiden."

Is er in uw vakgebied al meer aandacht gekomen voor de productie en verspreiding van ultrafijnstof door vliegtuigen?

Focus binnen de luchtvaartsector ligt voornamelijk op het reduceren van door vliegtuigen geproduceerde CO2-emissies. Het reduceren van de non-CO2 emissies komen daarna pas ter sprake, waarvan UFP maar een klein onderdeel is van een grote verzameling aan emissies.

- Heeft te maken met de lokale luchtkwaliteit op een luchthaven: aangezien er nog geen normen zijn voor UFP, zijn de normen voor de andere vliegtuigemissies maatgevend.
- Normen voor meeste vliegtuigemissies zijn wereldwijd vastgelegd ('emission indices'), maar voor ultrafijnstof concentraties blijft het momenteel vooral bij adviezen.
- Uitvoeren van onderzoek >> Indicatie >> Norm.

Tijdens welke processen van de operatie van het vliegtuig worden de meeste emissies geproduceerd? Tijdens de koude start, ground idle of de take-off?

- Voornamelijk tijdens het opstarten van de motoren, waarbij de gasturbines enkele minuten moeten opwarmen.
- Nog onduidelijk of UFP voornamelijk wordt geproduceerd bij hoog vermogen of laag vermogen: is hier al literatuur over beschikbaar?
- <u>De grootste hoos emissies komt vrij bij de (koude) start van de motoren:</u>
    - Pushback/wegslepen van het vliegtuig naar de baan kan al het grootste gedeelte van de ground idle emissies reduceren;
    - Na het landen kan het vliegtuig meestal op laag vermogen of met behulp van een sleeptruck naar de pier worden gereden, waardoor hier ook relatief weinig emissies vrijkomen.

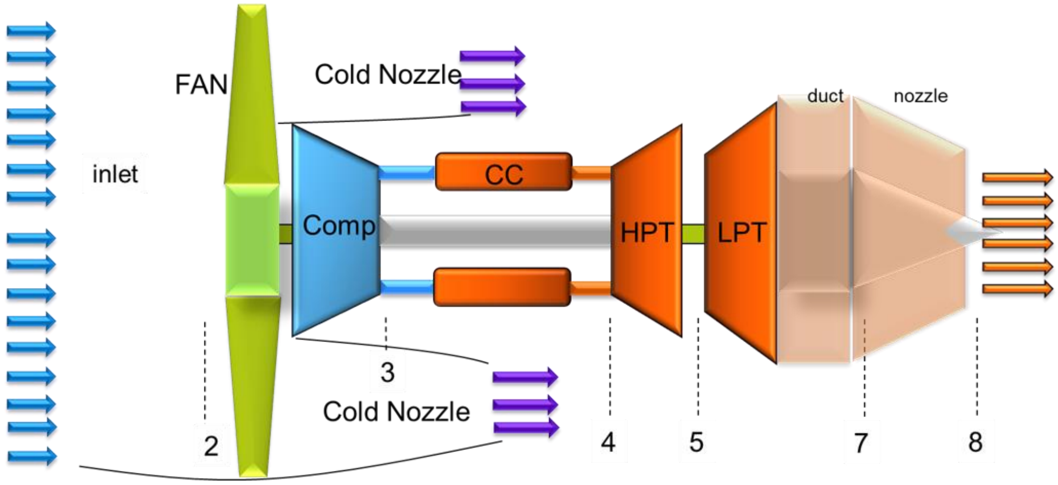
<u>Voorverwarmen van de motoren:</u>

- Heeft wellicht zin met zuigmotoren, maar heeft geen zin met straalmotoren.
- Is momenteel minutenwerk, dus dat zal te veel tijd kosten voor te weinig aandeel in de afname van emissies.

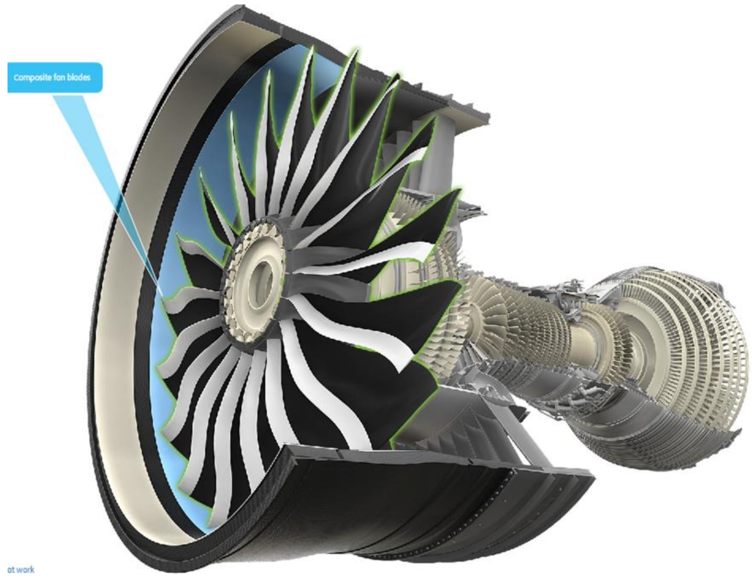
Hoe worden de emissies en ultrafijnstofdeeltjes door de motoren weggeblazen?

- De motoren van een vliegtuig produceren één straal lucht, waar wat "swirl" (draaiende componenten in de motor) inzit.
- Bypass ratio / Omloop verhouding:

Dwarsdoorsnede van een moderne straalmotor (turbofanmotor):



- Twee hoofddelen:
    - Kern (core): het hete gedeelte van de motor;
    - Bypass duct: het koude gedeelte van de motor, waar de lucht doorheen stroomt;
- De lucht komt binnen (blauwe pijltjes) de motor, waarna deze lucht door de FAN (de propeller) gaat; de lucht komt vervolgens in de compressor (Comp), waar deze wordt gecomprimeerd en vervolgens de Combustion Chamber (CC) wordt ingebracht; in deze verbrandingskamer wordt er brandstof bijgespoten, welke wordt ontstoken, waarna een hete gasstroom ontstaat; in deze hete gasstroom zitten alle emissies, welke eerst door de High Pressure Turbine (HPT) gaat; deze turbine/windmolen zit aan dezelfde as vast als de Compressor, dus de hete gasstroom zorgt er met de HPT voor dat de as en daardoor ook de Compressor gaan draaien; de hete gasstroom gaat daarna door de Low Pressure Turbine (LPT) welke vastzit aan een andere as (groen); deze groene as draait de FAN aan; na de LPT blijft er nog een beetje hete lucht (energie) over waar nog steeds alle emissies inzitten; deze lucht met emissies gaat door de straalpijp en zorgen uiteindelijk voor de stuwstraal.
- Bij het produceren van de luchtstroom is er al een hoop energie uitgehaald om de compressor te laten draaien en ook om de FAN te laten draaien.
- De FAN is belangrijk voor het voortstuwen van de motor: een hoop (koude) lucht gaat niet door de core van de motor, maar gaat via de bypass duct door de motor heen om het vliegtuig alsnog een zetje te geven = de koude luchtstroom, de cold nozzle.
    - Verantwoordelijk voor 80% van de stuwkracht van de motor.
    - Bypass ratio/ Omloopverhouding = verhouding van de lucht die om de kern heen gaat en de lucht die daadwerkelijk door de kern gaat: in moderne motoren al meer dan een factor 10.
    - 10% van de lucht gaat daadwerkelijk door de core van de motor heen, de rest is koude lucht die een zetje krijgt.



- Koude en warme stroom van de motor mengen binnen en buiten de motor.
- Naast turbulentie/”swirl” is het een vrij gerichte straal die uit de motor komt.

Op welke manier is het afvangen van deze deeltjes doormiddel van waterdruppels het meest effectief en efficiënt?

- **Ver weg of dichtbij?**
- **In de core van de motor?**

- Implementeren van een ultrafijnstof mitigatiesysteem bij de remote startposities:
    - Wat lost dit op?
    - Het probleem wordt dan opgelost op één locatie, tijdens één proces van de gehele operatie, maar vervolgens gaat het vliegtuig verder bewegen naar de taxibanen en de start- en landingsbaan.
- “Eigenlijk moet er een systeem worden geïmplementeerd waarbij de productie van waterdruppels met het vliegtuig meebeweegt, aangezien het vliegtuig gaat taxiën na de koude start en na 10-20 meter opnieuw emissies zal produceren.”
    - “Overhead SprayWall tunnels over alle taxibanen heen.”

<u>Wat een manier van mitigeren zou kunnen zijn:</u>

- Allereerst de vliegtuigen slepen van de VOP aan de pier naar een remote startpositie toe, weg van het platform;
- Tijdens de 2-5 minuten die nodig zijn voor het opwarmen van de motoren en het uitvoeren van de checks staat het vliegtuig bij de waterdruppel installatie, waar de uitstoot van UFP niet mee wordt voorkomen, maar waar de UFP mee wordt afgevangen;
- Na de start van de motoren taxiet het vliegtuig via de taxibanen naar de kop van de baan, waarbij er alsnog ultrafijnstof wordt geproduceerd en niet wordt afgevangen. Wel zullen de concentraties van deze emissies verder van de platformen verwijderd zijn, waardoor het probleem voor de gezondheid van de (platform) medewerkers kleiner is.

- Directe uitstoot op het platform en de uitstoot bij het opstarten van de motoren kan hiermee worden afgevangen, in combinatie met het (duurzaam) wegslepen van de vliegtuigen en het remote starten.

Ver weg of dichtbij mitigeren:

- De luchtstroom vanuit de motor komt ook relatief gericht bij een waterdruppelscherm dat op honderden meters van het vliegtuig is geplaatst.
- Spuiten van het water in de core van de motor is niet noodzakelijk, aangezien de luchtstroom niet snel weg zal waaien.
- Honderd kg lucht per seconde komt er uit de motor, dus heel veel kubieke meters lucht die moeten kunnen verbinden met de geproduceerde waterdruppels.

- Een heel lokaal probleem: wanneer het vliegtuig langer stilstaat op een vaste plek, om voor een bepaalde tijd de motoren op te warmen en de checks uit te voeren, kan een waterdruppel systeem een uitkomst bieden. Alleen hoeven vliegtuigmotoren niet meer dan 2-5 minuten op te warmen.
- Zodra de emissies verder zijn verwijderd van het platform zullen de problemen steeds kleiner worden, maar het is belangrijk om te achterhalen hoe groot het UFP-probleem op het platform zelf is.

Aan welke nieuwe technieken op het gebied van motoren met een volledigere verbranding wordt er momenteel gewerkt?

- Hier wordt continu aan gewerkt, maar het zijn hele geleidelijke stapjes;
- Op het niveau van de gehele vloot worden vliegtuigen per jaar 1-1,5% beter, en dus ook zuiniger: geen hele grote wijzigingen op korte termijn.
- Over 30 jaar genomen zullen motoren dan ongeveer 30% minder brandstof nodig hebben.

Aan welke nieuwe technieken op het gebied van duurzame vliegtuigbrandstoffen (SAFs) wordt er momenteel gewerkt?

- Groot deel van het probleem kan al worden opgelost door de introductie van synthetische-/bio-kerosine, met name door brandstoffen zonder zwavel (e.g., zwavelarme diesel bij vrachtwagens.
- Erg lastig om duurzame/zwavelvrije kerosine te introduceren op de markt, aangezien de wereldwijde kerosinemarkt relatief vrij klein is: de kosten voor het produceren van deze brandstoffen zullen veel te hoog zijn door de strenge kwaliteitseisen die er aan deze brandstoffen verbonden zijn.
- Staatssteun om het gebruik van duurzame vliegtuigbrandstoffen te introduceren zou de markt een zetje in de rug kunnen geven, maar aangezien de uitstoot van vliegtuigemissies een wereldwijd probleem is, zou dit op zijn minst Europees geregeld moeten worden.
- "Aangezien de ultrafijnstofconcentraties op Amsterdam Airport Schiphol een lokaal probleem is, zal de inzet van duurzame vliegtuigbrandstoffen niet de meest voor de hand liggende oplossing zijn."

Remote starten:

- Er zijn geen technische beperkingen voor het (heel) laat starten van de vliegtuigmotoren.
- 2-5 minuten nodig om straalmotoren op te warmen, waarna er vol vermogen mag worden gegeven.

- Dit kan allemaal worden gedaan na het taxiën: op een remote startlocatie of op de kop van de baan.
- Er zit een bepaalde separatietijd tussen de verschillende vliegtuigen: wanneer een vliegtuig naar een remote startlocatie of naar de kop van de baan wordt gesleept, zullen er meestal vliegtuigen voor staan. Dit biedt genoeg tijd en ruimte om de motoren op te warmen en de laatste checks uit te voeren.
- Belangrijk aandachtspunt: wanneer er iets mis is (technische problemen, problemen met de bemanning/passagiers), kan het vliegtuig dan nog makkelijk "uit de rij" om terug te keren naar de pier of wordt dan de hele stroom geblokkeerd?

- Aantal start- en landingsbanen op Schiphol liggen vrij dicht bij de pieren (Kaagbaan), wat sowieso al zorgt voor een vrij korte taxitijd voor de meeste vliegtuigen. Andere banen, zoals de Polderbaan, liggen erg ver van de meeste pieren, waardoor de taxitijden vrij lang zijn.
- Afhankelijk van welke baan het vliegtuig vertrekt, is het mogelijk om relatief laat de motoren te starten: het taxiën van een vliegtuig naar een baan verder weg gelegen van het platform, biedt mogelijkheden om de motoren later op te starten.

- E- en P-buffers als remote startlocatie:
  - Wanneer er iets mis gaat, kan het vliegtuig ook nog relatief eenvoudig terugkeren naar de VOP aan de pier, aangezien het vliegtuig niet meteen in de rij naar de baan toe staat.
- De-icing platform als remote startlocatie:
  - In Nederland staat er wel vaak een (zuid)westenwind, waardoor bij het opstarten van de motoren toch nog een hoop emissies naar de F-, G- en H-pier waaien.
  - Emissies produceren op grotere afstand van de pieren zorgt al voor een positief effect op het gebied van de gezondheid van de (platform)medewerkers, maar het liefst wil je het systeem zo implementeren dat de emissies helemaal niet het platform opwaaien.
    - Grotere afstand is sowieso al gewenst.

F.8 Interview H

Interview H (discussion via email)

Organization: Airbus Technology Bremen
Expertise: Airbus Technology; Senior Manager & Aircraft Architect; Head of R&T Plateau Bremen
Date: 26-8-2022

"In principle are of course watertight and designed for operation in adverse conditions (rain, snow, ice).

What comes into my mind for the operational dimension is that this spraying probably should rather not be applied at the aircraft gate stand to avoid water ingress (beyond the temporary rain) when all doors are open and people operating with the aircraft at the apron. This would impact maybe work safety and in the worst case of course also affect the aircraft when being in a more "vulnerable" position regarding corrosion and / or even impact on electrical circuits and / or operational systems.

In principle, however I have my doubts on how realistic a large-scale spraying really is ... (?)

Very local spraying (e.g., on selected aprons) may not help, and especially where most of the exhaust is generated (runways) it is not applicable."

"As alternative (easier?) approach a tug or a TaxiBot solution on the aircraft could pull the aircraft power off simply further away and the aircraft will start the engines somewhere on the taxiway far closer to the runway threshold (engine warm up time for takeoff of course to be considered)

Future alternative fuels -> SAF blends (and H2 in very long term) will also have a different particle emission .. maybe also to be considered, perhaps this relaxes the situation "for free"."

"As general "Airbus remarks" maybe take my comments ... in principle I no think on any issues to have the Aircraft in a spray curtain at engine start location, as its rather like a fine rainshower.

Only blocking issue which comes into my mind is:

- that in case deicing is required putting water spray after the deicing fluid is on (and has to stay on until the aircraft is in the air) is probably not acceptable
- that in case of icing conditions putting water spray on the aircraft which turns to ice of course is equally unacceptable."

F.9 Interview I

Interview I

Institution: University of Twente
Faculty: Science and Technology (TNW), Physics of Fluids (POF)
Expertise: Associate Professor/Researcher in (nano) particle-droplet interactions, drying of systems
Date: 30-9-2022

Background and expertise

- Working with particles, of all kinds, and droplets:
  - From particles of several (hundreds of) microhns, down to nano particles and droplets.
  - Especially tiny droplets.
- Research mainly focused on the drying of systems:
  - Looking at the behavior of the particles while the droplets are drying;
  - Creating particle structures during this process.

Ultrafine particles interacting with water droplets

- "Adsorption", as there is no chemical reaction between the particles and droplets.
- The essence of the system should be to create as many opportunities for the water droplets to interact with the ultrafine particles as possible.
- Once the ultrafine particle has made contact with a water droplet, it will stay inside that droplet as it is almost impossible for the particle to get out.
- You do not want to have them as a suspension in the air. However, as they are so small, you still might have them in the air. Even with the water droplets in the air, as they might evaporate.
- Even if multiple ultrafine particles are clumped together so that a particle the size of, for instance, a microhn is created, the water droplet still might evaporate, which makes the clump of particles still airborne.
- Effectiveness and efficiency of the system depends on the concentration of the aerosol particles in the air: the goal is to have as many ultrafine particles per water droplet as possible, which can be realized by spraying the water droplets in the area where the highest concentration of ultrafine particles is present.
  - The multiple ultrafine particles in the water droplet will clump together, so when the water droplet eventually evaporates you will end up with a (really) large particle clump that eventually descents to the ground due to gravity.
  - However, if the cluster is still as small as up to 100 microhns, it will still be airborne.

Difficulty of doing experiments:

- Different concentration ranges, so the parameter space is huge.
- Probably a very wide concentration range: from very high UFP concentrations after leaving the jet engines to very diluted concentrations in the air at a certain distance and/or after a certain time.
- The air circulation is of great importance: you want wind as you need motion for the ultrafine particles to reach and interact with the water droplets, but the wind will also dilute the concentration of particles in the air.
  - How to engineer the flow of the water droplets to collide more efficiently with the ultrafine particles --> you cannot leave it up to chance as the system is way too complex for that. You cannot assume a perfect mix in the open field.

- You have air currents that will not mix, unless you force them to. A challenge to mix the current with water droplets with the current with ultrafine particles, as this does not happen naturally.
- You need something to mix the currents, as the air flows in the open field are not complex enough --> creating turbulence.

- Dominik Krug (University of Twente) - expert in turbulence/flows and the mixing of currents:
  - (d.j.krug@utwente.nl)
  - Cleaning a tank of water in which small metal particles are present by letting produced water bubbles to collide with these particles: the bubbles that captured these metal particles will ascend to the water surface, where the particles can be easily scooped/removed.
  - Also using turbulence in this water tank to let the bubbles collide and eventually mix with the metal nano particles.
  - A lot of engineering is needed to create ideal mixing circumstances: in most situations there is no mixing.

Of importance for the effectiveness of the system:

- Larger water droplets will descent to the ground due to gravity. Since you want the water droplets to be airborne for as long as possible, the water droplets should be relatively small.
- The humidity in the Netherlands is usually very high, which means that the evaporation time of water droplets is relatively high, which is very convenient for a UFP mitigation system.
- The droplets need to stay liquid for as long as possible in order to encapsulate many particles.

Potential impact on health:

- After inhaling water droplets (with clumps of ultrafine particles encapsulated), they will typically be stopped in the upper respiratory system of the human body, so that the harmful particles do not get deeper into the respiratory system.
  - Already an impact on health by encapsulating the ultrafine particles within water droplets.

- Comparable situation: viruses in water droplets and how they stay in the human body.
- How long do respiratory aerosols remain in liquid state? --> respiratory aerosols and droplets with sizes up to 100 microhns remain airborne for a long time, especially in humid conditions.

- It is not true that there are no health risks with regard to ultrafine particles once they have reached the ground: when the water droplet evaporates, the clump of particles reduces in mass and size, which will let them remain airborne for a long time.

--> Beneficial for the health of platform employees by trapping the ultrafine particles in water droplets instead of just keeping them airborne as separate particles.

Delaying the evaporation of water droplets

- Adding a small amount of salt (sodium chloride) to the droplets helps to remain them as a liquid, so it slows down the evaporation time significantly.
  - The reason why respiratory aerosols remain in a liquid state in the human body for a long time.

- Completely natural as well (same pH value as human body), so no adverse impact on human health.
- In high humidity conditions (>75%), droplets do not evaporate anymore.
- --> Reducing the vapor pressure.
- You want to keep the ultrafine particles in the water droplets. Even for the human body, UFP in a liquid state is less hazardous than in a solid state: droplets will most likely be stopped by hairs in the upper part of the respiratory system, separate ultrafine particles will probably not.
  --> Keep the UFP in water droplets for as long as possible, you don't want them to dry too soon!

--> Make condensation (clumping together of particles) and absorption of water by themselves possible by keeping the relative humidity high and the temperature low.

F.10 Interview J

Interviews J (in Dutch)

Organization: Royal Schiphol Group
Department: Airport Operations
Function: Senior Process Advisor

Rol: link tussen de Innovation Hub en Operations.

Verschillende alternatieven voor UFP afvangen:

- Nevelproductie met waterkanonnen;
  - Kan ultrafijnstof ook worden afgevangen met zo'n nevelscherm?
  - Fietstunnel Schiphol project: indicatie van UFP metingen uit de fijnstofmetingen.
- Ioniseren van de mist, elektrisch veld creëren;

Drie soorten maatregelen:

- Innovatieve oplossing: Schonere verbranding in de motor, dus reductie van UFP bij starten, taxiën en LTO à alle oplossingen:
  - Waterscherm?
  - Gelijk warme lucht inblazen bij het starten van de motor;
  - Synthetische kerosine;
- Operationele oplossing: Personeel gerelateerd: niet starten in de baai/pier, maar op afstand à push-pull i.p.v. puur push;
  - Blast profiel
  - Uitstoot fijnstof en UFP
- Bron oplossing: motor zelf, volledige verbranding van kerosine
  - Hoe wordt deze schoner? Minder PM en UFP.

Vier mogelijke startplekken:

- Huidige situatie à niet gewenst, nieuwe locatie nodig;
- Semi-centraal:
  - Verder weg van de baai (Echo en Papa buffer)
  - à neerzetten en doorrijden
  - Efficiënt en minste risico, want dichtbij de pier/baai als er iets fout gaat:
    - Snel passagiers uitladen;
    - Apparatuur voor oplossen technische mankementen dichtbij.
- Centrale startpositie:
  - Eerst naar de-icing spot, veel ruimte om te draaien;
- Kop van de baan: kritische procestijden:
  - Veel risico, want erg ver van de baai/pier;
  - Duurt lang voordat het vliegtuig weer terug op de startlocatie is.

Uiteindelijke implementatie – locatie en manier van taxiën:

- Hybride model:
  - Narrow body vliegtuigen starten vanuit de centrale positie: de-icing spot;
  - Wide body vliegtuigen starten vanuit een semi-centrale positie:
    - Dichterbij, want deze vliegtuigen nemen meer risico's met zich mee:
      - Veel meer passagiers, dus veel meer logistiek en ingewikkeldere techniek van het vliegtuig zelf.

    - Capaciteits-technisch lastig om te verdelen.
- Inzet dieseltrucks voor taxiën/wegslepen:
    - Stuk minder uitstoot dan het vliegtuig zelf te laten taxiën;
        - Met dieseltrucks al vele maten beter (50x)
    - MAAR, alsnog niet heel schoon, en;
    - heel veel mensen en middelen nodig.

- Inzet elektrische trucks voor taxiën/wegslepen:
    - Nog minder uitstoot dan wegslepen met dieseltrucks;
    - Alsnog veel mensen en middel nodig:
        - Autonome voertuigen zouden dit kunnen verhelpen.

Uiteindelijke implementatie: manier van UFP afvangen

- Startscherm: in de buurt van de baai
    - Afvangen van vuile uitstoot als de motor nog koud is.
- Bulderscherm: UFP wordt de Haarlemmermeerpolder ingeblazen, echt op de runway zelf.
    - Blastprofiel in de eerste 200 meter, dan wordt alles afgevangen

Relevante dimensies:

- **Breedte van het nevelscherm**: minimaal even breed als de buitenste twee motoren aan de achterkant van het vliegtuig, inclusief een x aantal meters aan beide kanten.
- Mogelijkheid: brede leiding met nozzles implementeren die kan worden opgedeeld in het totale aantal opstelposities:
    - Narrow body vliegtuig met 2 motoren: waterscherm versmallen;
    - Wide body vliegtuig met 4 motoren: waterscherm verbreden.
    - Het type vliegtuig dat start bepaalt de breedte van het te creëren waterscherm!
- **Hoogte van het nevelscherm**: de hoogte die wordt gemeten van de centerline van de motor tot de grond ook moet er minimaal bij worden opgeteld voor de hoogte van de centerline van de motor de lucht in:
    - Centerline van de motor ongeveer in het midden van de hoogte van het nevelscherm;
    - Dus hoogte scherm = minimaal 2 * lengte centerline tot grond + x aantal meters
- **Diepte van het nevelscherm**: nog onduidelijk, wild guess:
    - Hangt er mogelijk vanaf hoe de deeltjes door het scherm gaan en of ze met een waterdruppel verbinden.
    - Luchtvochtigheid (90%) en mist vangt wellicht ook een hoop af, dus dan is een diep scherm minder noodzakelijk.
- Elke extra remote startlocatie betekent:
    - Meer leidingen met meer nozzles à meer waterverbruik door de nevelproductie.

Dimensies van het waterscherm visualiseren ten opzichte van achterkant vliegtuig!!

Impact op de capaciteit:

Qua startcapaciteit gaat de afhandeling er hoogstwaarschijnlijk op vooruit, in ieder geval gaat deze er niet op achteruit:

- **Huidige situatie:**
    - Vliegtuigen moeten achter elkaar vertrekken vanaf dezelfde opstelpositie bij de pier;
    - Sleeptruckchauffeur staat momenteel altijd langer te wachten dan de werkelijke duur van de pushback.
- Een pushback en dan naar het volgende vliegtuig: al gauw 10 tot 12 minuten wachttijd voor de sleeptruck.
- De separatietijd tussen de vliegtuigen is ruim genomen, dus veel reserves.
- **Nieuwe situatie:**
    - Vliegtuigen worden getaxied naar de (semi-)centrale startpositie, waarna de sleeptruck terugkeert naar de opstelpositie aan de pier;
    - Het volgende vliegtuig staat al klaar en kan vrij direct worden weggesleept naar de volgende opstelpositie.
- Je start later en hebt langere connectietijden (push en pull), maar
- Wachttijd is zeer dominant bij de pushback, dus het slepen kan deze tijd compenseren.
- De langere sleeptijd zou in principe moeten passen in de reservetijd die er beschikbaar is tussen de twee opeenvolgende vliegtuigen.

Op een dag wanneer de sleepdiensten achterlopen is de inhaalcapaciteit (tijd reserves) een stuk lager. Op een gemiddelde dag zou de nieuwe manier van afhandelen niet moeten zorgen voor capaciteitsproblemen!

Remote startposities

Momenteel ook vaak van een paar VOPs afhankelijk, dus de implementatie van 3 remote startposities prima mogelijk qua capaciteit:

- Oude startposities opnieuw gaan gebruiken;
- De neus van het vliegtuig kan beide kanten op worden gezet bij de Pappa buffer;
- Inbound buffering kan ook bij de Juliette buffer, wachten hoeft niet per se bij de P-buffer;
- Gezondheid van de medewerkers belangrijker dan wachtplaats van inbound kisten;
- UFP afvangen bij P-buffer kan aan beide kanten
- P-buffer voor D- en E pier voldoende qua capaciteit à verblijfstijd van kist op deze posities kan vrij kort zijn, dus moet kunnen passen.
- Reserveren van startpositie op de P-buffer minuten minder dan in de huidige situatie: capaciteitsverlies is niet zomaar gezegd, zeker een onderzoek waard.

- 6 remote startposities lijkt ideaal!
- In de winter: de-icing startposities voor de-icing, P-buffer voor remote starten;
- In de zomer: de-icing startposities voor remote starten, P-buffer als wachtplaats voor inbound kisten.
- Mogelijk om altijd 2 startposities te reserveren bij de de-icing spots voor remote starten.
- Voor Polder- en Zwanenburgbaan: startposities bij de remote de-icing spots voor kisten die naar één van deze start- en landingsbanen moeten.
- Voor Kaag-, Aalsmeer- en Buitenveldertbaan: P-buffer startposities voor kisten die naar één van deze start- en landingsbanen moeten.

- 2 + 2 baangebruik aan beide kanten van de luchthaven;
- P-buffer voor D-E baai, de-icing spots voor F-, G- en H-pier;

- Tijdens de zomer is de capaciteit bij de de-icings spots nog veel groter.

- Starten op de kop van de baan gaat niet passen qua capaciteit;
- Laten verdampen van water op Schiphol, te veel water aanwezig momenteel;

F.11 Interview K

Interview K (in Dutch)

Organization: Royal Schiphol Group
Department: Strategy & Airport Planning
Function: Advisor Stakeholder Strategy & Development, Taskforce UFP Mitigation

Stakeholders:

- Royal Schiphol Group:
  - Operations
  - Asset Management;
  - Strategy & Airport Planning sturing
    - Innovation Hub
    - Actieplan UFP (Sustainability)
    - Meer informatie per airline, bijvoorbeeld over vooruitstrevendheid.
  - Safety, Security & Environment:
    - Opdracht om onder bepaalde normen te zitten, te meten
  - Procurement & Contracting:
    - De opdracht, managen daarvan, de rechten die erbij komen kijken;
    - Wettelijke: wie de rechten heeft om bijvoorbeeld het product te verkopen.
  - Focus ligt voornamelijk op de gezondheid van de werknemers (Schiphol zelf, airlines, afhandelaren).

- Rijksoverheid:
  - Ministerie van Infrastructuur en Waterstaat: milieu regelgeving à politiek en publiek
    - Subsidies worden beschikbaar gesteld voor RSG.
  - Ministerie van Sociale Zaken en Werkgelegenheid: Schiphol en Intern
    - Voornamelijk inspectie en belangenbehartiger van de werknemers;
    - Niet per se bij het UFP Mitigation project betrokken.
  - RIVM: gezondheidseffecten UFP (2017-2021):
    - Gezondheidsimpact platformmedewerkers
  - Gezondheidsraad: advies UFP

- Kennisinstellingen:
  - TNO: UFP concentraties;
  - NLR: UFP mitigation;
  - Wageningen University & Research (WUR): UFP mitigation

- Luchtverkeersleiding Nederland (LVNL):
  - Van belang dat de operatie veilig en efficiënt uitgevoerd kan blijven worden!

- Airlines:
  - KLM;
  - Overige: TUI, EasyJet, Corendon, etc.
  - Informatie over ultrafijnstofproductie per airline kan gevoelig liggen!
    - KLM grote vervuiler, dus blij met een UFP Mitigation oplossing
    - Vooruitstrevende airlines, zoals EasyJet en TUI, zijn ook op zoek naar nieuwe oplossingen om hun operatie toekomstbestendiger te maken.

- <u>Afhandelaren operatie</u>;

- <u>Vakbonden</u>:
    - FNV;
    - Unie?

- <u>"Investeerders"</u>:
    - TULIPS: onderdeel van de European Green Deal
        - Subsidie voor onder andere RSG, KLM, NLR en TNO.

- Bij welke activiteit mitigeren zal niet te veel uitmaken, zolang je maar achter de pluim aanrijdt en nevel produceert.
- Het heeft wel zin om op één plek te mitigeren, maar dan zal je de maatregelen ook toepassen op momenten dat het niet heel erg nodig is.
- Er wordt al veel ingezet op duurzaam taxiën, dus nevelproductie tijdens deze activiteit lijkt onnodig en zonde van de middelen.
    - Focus op UFP mitigatie tijdens koude start en LTO processen!

- In dat onderzoek worden de ophopingen aangegeven!
- Op bepaalde plekken, de hotspots, mitigatie inzetten op korte termijn!
    - Zeker weten dat deze maatregelen effect hebben;
    - Waar de meeste platformmedewerkers rondlopen, gelijk een effect op de gezondheid;

- Momenteel erg gericht op het politieke momentum à gezondheid van de werknemers, maar kan komende maand omslaan naar de kwaliteit van de omgeving (onderzoek RIVM);
    - Kijken naar waar het grootste effect te behalen is, kan van werknemers omslaan naar omgeving.

- Perceptie van externen op het gebruik van bepaalde kwaliteit water:
    - Drinkwater: zonde;
    - Grondwater: vies;
    - Hoe komt het over op mensen?
- Hemelwater waarschijnlijk de beste optie;
    - Platformmedewerkers tegen industriewater, niet gezond;
    - De-icing, wat gebeurt er met het gebruikte water?

- Nevelscherm:
    - Is het noodzakelijk om deze op te delen in het aantal opstelposities en aan te passen aan het type vliegtuig dat er is opgesteld?
    - Wellicht efficiënter om de gehele dimensies te gebruiken van de nevelwolk?
    - Afweging tussen watergebruik en moeite van implementatie van de technologie.

F.12 Interview L

Interview L (in Dutch)

Organization: Royal Schiphol Group
Department: Safety, Security & Environment
Function: Senior Environmental Advisor within Health, Safety & Environment

De rol van de afdeling Safety, Security & Environment (SSE) binnen het UFP Mitigation project

- Health, Safety & Environment
  - Environmental safety;
  - Arbo kant

Restricties nevelschermen:

- Op locaties op de luchthaven:
  - Baai/pier?
  - Semi-centraal (Echo- en Pappa buffers)?
  - Centraal (de-icing)?
  - Op de kop van de baan?
- Watertoevoer?
- Afvoer van het vuile water?

Restricties fijnstofproductie:

- Op locaties op de luchthaven:
  - Baai/pier?
  - Semi-centraal (Echo- en Pappa buffers)?
  - Centraal (de-icing)?
  - Op de kop van de baan?

Safety aspect heel belangrijk bij deze projecten: waar in het systeem?

- Bij het starten: baai/pier of op de kop van de baan?
- Zowel voor het gebruik van water als van de machines.
- Risico's bij het vernevelen van water, maar ook de machines die worden geplaatst.
  - Op een veilige manier toepassen
- Landingsterrein veel EASA regelementen à veel beperkingen waar de installaties aan moeten voldoen om daar geplaatst te worden.
- 2 belangen die spelen:
  - Allereerste insteek: fijnstof reduceren, milieueffect rapportage (500k naar 550k)
    - Impact: geluid, maar ook emissies (CO_2 (globaal, niet lokaal), stikstof, (ultra)fijnstof à 10% meer opvangen om te compenseren voor de groei van de luchthaven.
  - Tweede insteek: gezondheid van de platformmedewerkers (bij de baai)
- Voordelen en nadelen opschrijven
- Installatie in de baai: al reduceren bij opstarten van vliegtuig
- Op het landingsterrein veel EASA regels, maar weinig overlast voor anderen;
  - Regels worden strenger hoe dichter je bij de baan komt, minder regels dichterbij de pier/baai: maar alsnog regels in dit gebied.
- Ultrafijnstof het meest reduceren waar de meeste mensen werken, dus dichtbij de pieren!

- Regelementen omtrent water ligt echt aan de toepassing: geen gladde plekken moeten er ontstaan. De waterverontreiniging is heel beperkt door de kleine UFP deeltjes.
- Op het landingsterrein zijn de regels te streng en veel gedoe/risico's met elektra en techniek, bijna niet in te plannen.
- Meest haalbaar bij de Echo- en Pappa buffers, nog steeds dichtbij maar verder weg.
    - Schetsjes maken van de scenario's: kwantificeren van de hoeveelheid water nodig, verhoudingen bekijken en de systemen visualiseren.

Twee kansrijke scenario's:

- Scenario 1: aandacht voor gezondheid van de platformmedewerkers:
    - Task force – ultrafijnstof concentraties in de baai.
    - De focus ligt hier voornamelijk op de ernst van de koude start, welke zorgt voor het blazen van ultrafijnstof richting de terminal.
        - Mogelijke oplossing: fixed start-up points in combinatie met electronic EAS
            - In Kopenhagen wordt dit al toegepast;
            - Op schiphol nog niet.
    - Introduceren van fixed start-up points ((semi-)centrale startposities) in combinatie met het produceren van nevelschermen bij de koude start:
        - Op korte termijn heel interessant;
        - Nevelproductieapparatuur in grasvelden naast de startposities;
        - Op deze manier kan Schiphol laten zien dat het serieus wordt genomen.

- Scenario 2: aandacht voor de gezondheid van de omwonenden:
    - Focus van ultrafijnstof mitigatie tijdens LTO-processen op de kop van de baan;
    - Meer EASA regels voor de veiligheid:
        - Vanaf de middenlijn van de start- en landingsbanen moet de eerste 40 meter aan beide kanten obstakelvrij zijn;
        - Installaties en apparatuur naast de start- en landingsbanen moet bij impact makkelijk kunnen afbreken om de schade van een collisie met een vliegtuig te minimaliseren.
    - Mogelijke oplossingen:
        - Nevelkanonnen in één serie, dus 1 voor 1 aanzetten met het vliegtuig mee;
        - Waterleidingen met nozzles naast de start- en landingsbanen, gericht op de vliegtuigen.

Semi-centrale startlocaties

Tussen de D-pier en de E-pier is een soort rotonde

- Aan het einde van de rijbaan vóór de E-pier is een buffer: daar alle vliegtuigen laten starten
    - Verplichte rijrichting, punt waar de vliegtuigen de baai verlaten;
    - Alle opstartpunten kunnen hier dan gebruik van maken.

P-platform:

- P-buffer wordt nu vooral gebruikt als wachtpositie, vanuit daar door taxiën;
    - 2 soorten stromen door elkaar: binnenkomende en vertrekkende vliegtuigen.

- Ook in het open veld, na meerdere starts na elkaar, grote UFP concentratie ophopingen.
    - Zeker bij windstille omstandigheden, concentraties blijven hangen;
    - Bij mooi weer: de concentratie wordt steeds hoger
- Terminalkant van de pier: windluwe vakken
- Tussen C en D pier de randweg, half overdekte straat à hoge concentraties UFP
- Dicht in de baai bij de terminal ophopingen

System Design:

- Scenario’s naast elkaar leggen en dan kijken
- Wat zijn de technische uitdagingen? Wat zijn de kosten?
- Toewerken naar één scenario om een prototype te kunnen opstellen!

Benevelingsinstallatie van bovenaf is hoogstwaarschijnlijk gewenster:

- Minder druk;
- Minder watergebruik;

F.13 Interview M

Interview M (in Dutch)

Organization: Royal Schiphol Group
Department: Procurement & Contracting
Function: Sourcing Manager

- De opdracht, managen daarvan, de rechten die erbij komen kijken;
- Wettelijke: wie de rechten heeft om bijvoorbeeld het product te verkopen.

Scope bij ontwerpen van System Design van groot belang!
- Welke factoren worden meegenomen en welke blijven buiten beschouwing?

<u>Uiteindelijke oplossing</u>
Industrialisatie van groot belang!

- Een breed toepasbare oplossing die goed geproduceerd kan worden;
- Belang van (vanuit Procurement & Contracting):
  - Standaardcomponenten à geen maatwerk;
  - Duurzaamheid;
  - Minder risico's (nozzles die verstopt raken);
  - Betrouwbare set van partners bij de ontwikkeling (niet per se MB Dustcontrol B.V.);
  - Goed reproduceerbaar design à Industriestandaard;
  - Uiteindelijk de rechten op het ontwerp.
- Dit binnen een bepaald budget: het moet aan de business case voldoen.
  - Zowel implementeerbaar op Schiphol Airport zelf, als op andere (Nederlandse) luchthavens;

Nevelwolkproductieapparatuur

- Sectorsproeier op de slangen zetten, een ringleiding met gaten erin:
  - Op elk van die gaten zit een sectorsproeier waardoor een nevelwolk ontstaat.
- Geconcentreerder sproeien op de piekpunten van de "blast" waar de meeste ultrafijnstof aanwezig is in de lucht à meer druppels op de hoogst geconcentreerde punten van de wolk.
- Schakelen van de sproeiers tussen narrow- en wide body vliegtuigen, zodat de nevelwolk zo efficiënt mogelijk gepositioneerd blijft.
- Ringleiding zeer kostbaar, dus een goede industriestandaard van de vaste leiding-infrastructuur nodig!
  - Nozzles makkelijker te vervangen.

Externe factoren

- Per luchthaven zijn er andere (weer)condities en -omstandigheden:
  - Luchtvochtigheid;
  - Windsterkte;
  - Temperatuur
  - Van belang voor de nevelproductieapparatuur: in extreme (weers-)omstandigheden moet deze ook kunnen worden toegepast en het blijven doen.

Watergebruik bij nevelproductie

- Welke kwaliteit water is er nodig voor de nevel?

    - Drinkwater, slootwater, opgevangen regenwater, grondwater?
- Kan het vernevelde water opnieuw worden verzameld en gebruikt?
    - Zonder filtering, of is eerst filteren nodig?
    - Rekening houden met verstopte nozzles door bijvoorbeeld zand, of water dat zo erg vervuild is met (ultra)fijnstof dat het niet opnieuw gebruikt kan worden voor het opvangen van nieuwe UFP.
- Welke hoeveelheid water is er nodig voor de werkzaamheden?
    - Wat voor pomp is hiervoor nodig?
    - Wat voor tank moet er gebruikt worden?

F.14 Interview N

Interview N (in Dutch)

Organization: Royal Schiphol Group
Department: Aircraft Operations
Function: Process Owner Aircraft

De impact op capaciteit:

- Wat is de impact van extra locatie in het proces waar motoren gestart worden?
  - Of hoe kan dit worden bepaald?
- Is er de verwachting dat er veel meer mensen en middelen moeten worden ingezet worden er gebruik wordt gemaakt van nieuwe startposities en duurzamer taxiën?
  - Extra voertuigbewegingen van pushback trucks?
  - Extra kosten voor afhandelaardiensten?
  - Wat is bijvoorbeeld de turnaround time van trucks ingezet voor het taxiën?

- Zijn de nieuwe maatregelen niet funest voor de capaciteit van de luchthaven?
  - Kunnen we door deze nieuwe maatregelen minder vluchten afhandelen per dag?

Capaciteit gaat drastisch omlaag (pushback procedure Kopenhagen)

- Starten vanuit semi-centrale positie
- Remote positie zou moeten kunnen
- Infrastructuur moet worden aangepast à nieuwe posities moeten worden gecreëerd;
- Voor een succesvol systeem moeten meerdere taxibots/sleeptrucks ingezet worden, er moeten geen toestellen wachten totdat zij kunnen worden weggesleept.
- Per baancombinatie kijken waar handige afkoppelpunten zijn
- Het één of het andere, geen hybride systemen à hoofddoel: proces moet eenvoudig, eenduidig, uniform zijn!! Geen verschillende vormen van systemen.
  - Draagt bij aan de veiligheid!
- 7 VOPS beschikbaar (de-icing, E- en P buffers) à soms zelfs 60 VOPS nodig
  - Qua capaciteit niet te doen
  - Hoeveel remote spots, 15 de-icing spots
- P-buffers worden nu gebruikt als wachtplaats voor inbound kisten
  - Kan P1 inbound en P3 outbound, maar niet ideaal
- Extra infrastructuur is nodig voor semi-centraal starten
- Zelfde inschatting voor volledig remote de-icen voor capaciteit
- Pushback trucks moeten flink worden opgeschaald: nu alleen op de VOP, maar bij de nieuwe situatie is de truck veel langer weg à nu zijn er soms al te weinig voor een goede operatie.
  - Ook het aantal chauffeurs moet evenredig worden uitgebreid
- Outbound en inbound plekken

Implementeren van (semi-)centrale startposities?

- Niet mogelijk met huidige capaciteit:
- Lagere capaciteit accepteren:
  - Minder vliegbewegingen per jaar, maar;
  - Duurzamer en voordelig voor de gezondheid van de (platform)medewerkers.

- Hogere capaciteit realiseren:
    - Meer infrastructuur voor centraal starten;
    - Meer sleeptrucks en personeel.
    - Qua benodigde capaciteit vergelijkbaar met de capaciteit die nodig is voor het volledig remote de-icen van toestellen.

- Gelijk volledig implementeren als hiervoor wordt gekozen, geen hybride systemen!
    - Eenvoudig, eenduidig en uniform systeem/proces is noodzakelijk voor de veiligheid.

Het watergebruik voor de productie van de nevelwolk:

- Waar kan dit water vandaan worden gehaald?
    - Waar wordt dit water opgeslagen?
- Onder welke omstandigheden kan de verneveling niet doorgaan?
    - Bij temperaturen onder 0? Extreme warmte, dus instant verdamping?
    - Bij harde wind, hagel/regen/sneeuw?

- Goede oplossing: centraal starten bij de de-icing spots à al gelijk genoeg watercapaciteit door de tanks die daar al staan.
    - Stukje zuivering (industriewater of oppervlaktewater) zou daar kunnen met voldoende capaciteit.
- Sprinklerkelders (grote capaciteit) kunnen ook mogelijk worden ingezet voor de buffers
    - Onder de grond water bewaren en aanvullen.

- Bij een bepaalde luchtvochtigheid (<<60%) werkt de verneveling een stuk minder goed.
- Temperatuur zal meevallen, echte oorzaak is de luchtvochtigheid!!
    - Nevel wordt sneller water met zuurstof
        - Minder afvangen dan normaal!
- Tegen de wind inblazen van nevelwolk bij hele harde wind.

Mogelijke locaties voor wateropslag en waterverzameling uitzoeken!!