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

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Abstract— **This research explored the potential of an innovative mitigation strategy to combat the aircraft-produced ultrafine particle (UFP) concentrations at the airport. 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. The system design component alternatives were analysed and a most optimal conceptual design for the airport was proposed, after which the feasibility, viability, and desirability were assessed.**

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. In 2021, the number of aircraft movements at AMS experienced a small growth in comparison with 2020 to 286 thousand (Royal Schiphol Group, 2022), where the expected growth for 2022 is more than 40 percent up to around 410 thousand flights (de Boer, 2022).

The resurrection of 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, such as CO_2, NO_x, SO_2 and particulate matter (PM), of which the large quantities of aircraft-produced PM primarily affect the air quality and are one of the most harmful pollutants to human health (Marcias et al., 2019). Ultrafine particles (UFP) are the smallest form of particulate matter, and have received increasing interest from the aviation industry and the academic community over the last few years.

UFP are generally defined as smaller than 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). At Amsterdam Airport Schiphol, high UFP concentrations were measured close to the terminals around the piers and platforms, as well as in the open field near the runways and taxiways (Stacey, 2019; Tromp 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, creating some sort of "washing" effect. Implementing this strategy to combat the UFP concentrations at the airport grounds is an interesting potential solution direction 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 ultrafine particles produced by aircraft 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. There is currently little to no academic knowledge on potential mitigation strategies to tackle the aircraft-produced UFP concentrations at airports, 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 ultrafine particle mitigation system at the airport, based on the deployment of

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water droplets to tackle the UFP concentrations. 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 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.

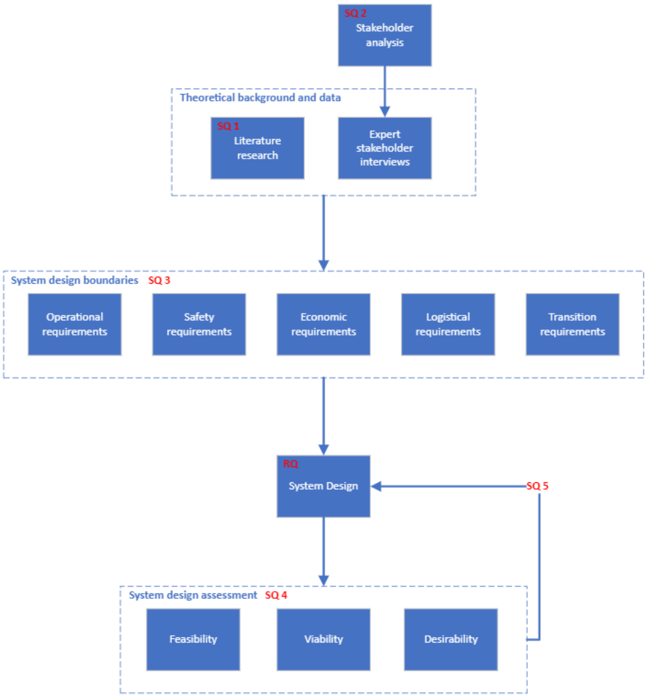

Fig. 1: Research structure

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. Data analysis

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.

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.

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

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). Most of these studies conducted the measurements at a certain distance from the runways, where the average background ultrafine particle concentrations could be registered. At all above-mentioned airports, high incidental peak UFP concentrations could be measured in between these average background observations. 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. For both CIA and LAX, UFP concentration peaks up to 2,000,000 $\#/cm^3$ were measured (Shirmohammadi et al., 2017; Stafoggia et al., 2016). 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 (Janicke et al., 2019).

The peaks can be associated with so-called 'jet blast events' of aircraft and are the consequence of starting air-

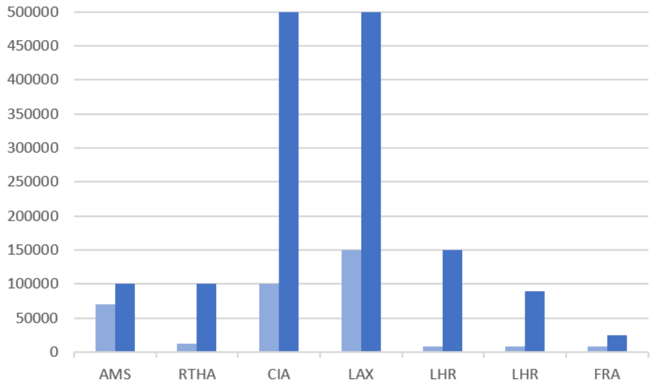

Fig. 2: Average and peak UFP concentrations [$\#/cm^3$]

craft 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. The studies that were conducted at the several airports mentioned in the previous section did not elaborate on the locations where the UFP concentration accumulations occurred throughout the day, with the exception of the study of Tromp et al. (2021). TNO conducted this research commissioned by RSG, The mobile measurements that were carried out on the Amsterdam Airport Schiphol grounds by TNO, as commissioned by RSG, 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. An overview of the measured UFP concentrations for the several different areas at Schiphol is presented in table II.

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 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.

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).

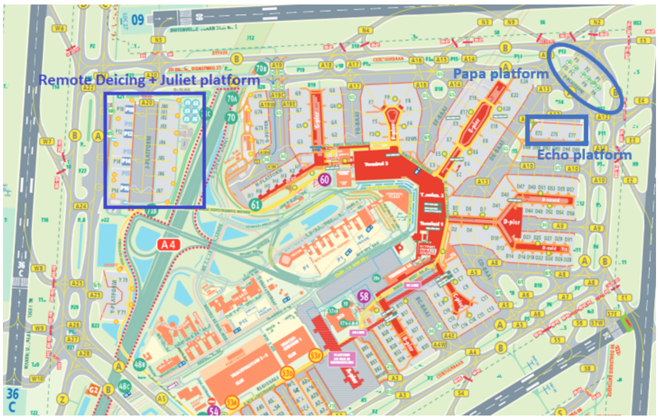

Fig. 3: Remote (semi-)central starting positions AMS

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 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.

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.

Fig. 4: Remote starting positions runways AMS

After the cold start of the aircraft, the ground idle procedures will start. The airport infrastructure that is dedicated for this part of the operation are the taxiways between the bay and the runways. Many airport, such as Schiphol, have 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. 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. An advisor in Stakeholder Strategy and Development 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).

After the ground idle procedure, the aircraft is positioned at the head of the dedicated runway. The collection of runways is the infrastructure that is dedicated to facilitate the LTO processes at the airport grounds. The runways are mainly surrounded by undeveloped infrastructure and lawns, which means that the jet blast during take-off is directed to the open field. 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. The mitigation strategy, based on combating the dispersion of UPF 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). 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 get out. 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). So-called “SprayCannons” and “SprayWalls” are examples of water droplet machines that are used to produce a curtain of micro water droplets (MB Dustcontrol, 2022b). 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’.

Royal Schiphol Group, Wageningen University & Research 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 fine-tuning this method, the hypothesis is that UFP produced by aircraft may exhibit the same behavior while interacting with water 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, 2022a). 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.

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. 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). An example of this device is displayed in figure 5, in which the turbo-fan is on the left-hand side of the cannon.

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

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 and even walls/ceilings. Another variation of the spraying cannon is 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.

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


Fig. 6: SprayWall (Scott Vickers, 2022)

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 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).

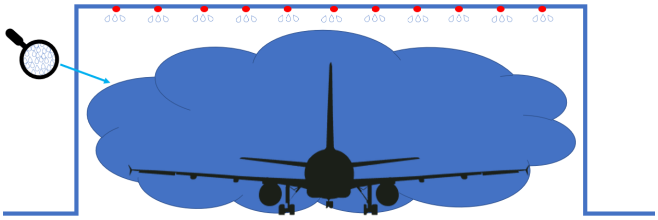
Fig. 7: System configuration of overhead SprayWall

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.

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.

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 requirements from table III are used for the analysis of the time-bound, geographical, and operational system design components, which are discussed in the following subsections.

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, 2022b). 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). 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, which incorporates the discussed components, will be assessed on its feasibility, viability and desirability. The assessment of the conceptual system design on these three criteria will be briefly discussed 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. 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 to confirm 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 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.

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, should also be analyzed. 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. This research provides a collection of knowledge, insights, ideas and opinions, from a wide variety of expert stakeholders from the aviation industry and the academic world, on combating the UFP concentrations produced by aircraft at the airport grounds by using water droplets. It is an overarching document 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. 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. 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. 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. 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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