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STRATEGY FOR SUSTAINABLE AIR TRAFFIC OF THE FUTURE

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ABSTRACT[*]

Air traffic enables the rapid worldwide transportation of persons and goods. It has increased over the last 20 years and will continue to grow in the medium term. However, this is associated with considerable environmental and health problems caused by greenhouse gases, air pollutants and noise. Therefore, an integrated approach is necessary. The German Environment Agency has developed a strategy for sustainable air traffic of the future. It contains ambitious goals to be reached by 2050, with an intermediate step by 2030. The strategy consists of eight modules that are coordinated and interlinked. They describe various instruments and measures at international, national, and local level. The key features of the strategy are presented. Moreover, the module on aircraft noise is explained in detail. It comprises instruments and measures to reduce aircraft noise. A significant reduction of aircraft noise in the vicinity of airports can be achieved through noise quotas during the day and strict flight restrictions at night. These instruments are also discussed. The strategy shows a realistic way to shape air traffic as environmentally as possible by 2050. Sustainable air traffic is characterised by the fact that it is both effectively reducing environmental impacts and meeting people's mobility needs.

Keywords: *aircraft noise, air traffic, sustainability*

1. INTRODUCTION

Air traffic enables the rapid worldwide transportation of persons and goods, but this benefit is accompanied by serious environmental and health impacts. Air traffic emits greenhouse gases, air pollutants and causes noise. According to the goals of the Paris Agreement on climate change, human greenhouse gas emissions must be almost completely reduced by 2050. Recent recommendations from the World Health Organisation (WHO) also show that noise levels at airports need to be significantly reduced to protect human health. In addition, the negative impact of air traffic on land use and resource consumption should be reduced. The impact of air traffic must therefore be considered in its entirety. The German Environment Agency has developed a comprehensive strategy for sustainable air traffic of the future [1-2]. The strategy consists of eight central modules that are coordinated and interlinked. The modules contain detailed packages of instruments and measures for environmentally friendly air traffic, which are to be implemented in a first step by 2030 and then by 2050. Air traffic can only achieve its climate, environmental and health objectives by 2050 if all the modules work together. The strategy's objectives and measures are presented below. The focus is on the aircraft noise module.

2. STRATEGY FOR SUSTAINABLE AIR TRAFFIC OF THE FUTURE

2.1 Modul 1: Noise reduction - protection of the population

2.1.1 Aircraft noise situation in Germany

Many people in Germany are affected by aircraft noise. The aircraft noise situation is characterised by different trends. One trend is that aircraft are becoming quieter than comparable older aircraft. On the other hand, the number of aircraft movements is increasing. The EU Environmental Noise Directive (2002/49/EC) provides information on the development of the noise situation in

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Europe. The results of the noise mapping for 2017 show that around 815,000 people are affected by aircraft noise with a L_{DEN} value above 55 dB(A) at the eleven major airports in Germany. About 240,000 people are exposed to L_{Night} levels above 50 dB(A) [3]. However, the EU Environmental Noise Directive only applies to Germany's busiest airports. Smaller airports, such as Bremen or Dresden, are not covered by the directive. Civil airfields are also not included. In addition, the figures do not include persons affected by aircraft noise at military airfields. The actual number of people affected by aircraft noise in Germany is therefore higher.

2.1.2 Noise effects

Noise has various effects on humans [4]. These include noise annoyance, cardiovascular disease, sleep disturbance and impaired cognitive development in children. Noise annoyance in Germany is investigated every two years. The survey is part of a representative survey on environmental awareness. According to the 2020 survey, 43 % of those questioned feel annoyed by aircraft noise in the vicinity of their homes [5]. But noise does not only affect subjective well-being and quality of life. It can also have serious health effects. Continuous exposure to noise can alter blood pressure and heart rate and lead to heart attacks. Moreover, noise impairs sleep. This manifests itself in an altered sleep structure, increased waking reactions and elevated cardiovascular risk factors. Furthermore, aircraft noise influences the cognitive performance of children. In particular, the acquisition of reading skills may be delayed by continuous exposure to aircraft noise. Due to the significant health effects of noise, the WHO published guidelines on environmental noise in 2018 [6]. In these guidelines, the WHO recommends that a L_{DEN} value of 45 dB(A) and a L_{night} value of 40 dB(A) should not be exceeded for aircraft noise in order to avoid adverse health effects. The German Environment Agency supports these recommendations.

2.1.3 Options to reduce aircraft noise

There are various instruments and measures available to reduce aircraft noise. Of these, measures at the source are the most effective. The permissible noise emissions of new aircraft types are regulated in Annex 16, Volume I, to the Convention on International Civil Aviation [7]. The noise limits are laid down in Chapter 14. They apply to subsonic jet aeroplanes and propeller-driven aeroplanes with a maximum take-off mass (MTOM) of more than 55 tonnes certified since 31 December 2017. For lighter aeroplanes, the limits of Chapter 14 apply to aircraft certified since 31 December 2020. The latest commercial aircraft such as the Boeing 787-9 or the Airbus A350-941, are already well below the Chapter 14 noise limits [8]. It is therefore necessary to further strengthen the noise limits in order to set ambitious targets for aircraft and engine manufacturers at an early stage. The Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organisation (ICAO) is currently investigating several options for reducing the Chapter 14 noise limits.

There are also several options for reducing aircraft noise at the operational level. These include the use of noise abatement flight procedures, the optimisation of flight tracks, the noise-optimised use of the runway system and the introduction of night flight restrictions. Flight operational measures have the advantage over technical measures that they can often be implemented more rapidly.

Another important instrument for noise reduction is land-use planning. This is included in the German Act on Protection against Aircraft Noise [9]. The act provides for the establishment of noise protection areas at airports, large civil airfields, and various military airfields. A noise protection area consists of two day-time protection zones and one night-time protection zone. The construction of noise-sensitive buildings (e.g., hospitals, schools) is generally prohibited in the entire noise protection area. The construction of new dwellings is also prohibited in both daytime protection zone 1 and night-time protection zone. These restrictions are intended to influence the development of settlements and to prevent potential noise conflicts.

For existing residential buildings in these zones, the Act on Protection against Aircraft Noise contains provisions that oblige the airport operator to bear the costs of constructional soundproofing measures. In addition, for buildings in the night-time protection zone, the airport operator must reimburse the costs of installing ventilation systems in rooms used primarily for sleeping. Expenses for constructional soundproofing measures including the ventilation systems are reimbursed up to 150 € per square metre of living space. In the case of the construction of new airports or the extension of existing ones, these regulations are supplemented by compensation regulations for the deterioration of the quality of outdoor living spaces (terraces, balconies, etc.) in the daytime protection zone 1. The compensation must be paid by the airport operator.

Economic measures are another instrument to reduce aircraft noise. For example, noise-related charges can be used to differentiate monetarily according to aircraft noise emissions. Low-noise aircraft pay lower charges than noisy ones. Such charges have been levied at German airports for decades. Extensive experience with these charging systems shows that they provide little incentive for airlines to use low-noise aircraft. Therefore, noise-based charging systems should be further developed. The noise-based charging systems at Frankfurt and Berlin airports can serve as a model [10-11]. Finally, there are regulatory measures to penalise violations of aviation law, such as unauthorised deviations from flight paths.

All these instruments and measures must be used to improve the aircraft noise situation. But this is not enough. What is missing is an overarching instrument that limits aircraft noise and thus provides an incentive to exhaust all possibilities for noise reduction. A noise quota system is a suitable instrument. It sets a specific noise protection target that can be achieved through various instruments and measures. It is important that the target is ambitious but realistically achievable. The noise quota can be designed in different ways. For instance, the maximum permissible noise exposure can be defined as an "upper noise limit". A noise rating index can also be defined: the product of the number of people affected in each noise class and a noise rating number per noise class. The noise quota is compared annually with the actual aircraft noise exposure. In principle, three cases are possible:

1. actual aircraft noise exposure ≤ target: No noise reduction measures are required
2. actual > target: If the target is only slightly exceeded, it may be agreed that it must be met in the following year
3. actual >> target: If the target cannot be achieved in the short term, a step-by-step approach towards the target is appropriate.

The noise objective can be monitored by the aviation authority or the airport operator. If it is not achieved, these institutions have the following options for action:

- Reduce the number of permitted flights
- Optimise the runway utilisation concept and flight procedures in cooperation with air traffic control
- Restrict night flights.

Airlines have the following choice:

- Use more low-noise aircraft
- Use noise abatement flight procedures
- Reschedule flights to less noise-sensitive times, especially from night to day
- Cancel flights and increase the load factor of the remaining flights.

A noise quota system gives residents of airports a clear perspective on noise because it guarantees that the noise target will be met. It is advantageous for the aviation industry because it has a free choice of instruments and measures and can apply the most effective ones first.

The German Environment Agency recommends the introduction of a noise quota at German airports between 6 a.m. and 10 p.m. to limit aircraft noise during the day. However, analyses by the German Environment Agency show that the WHO recommended value of L_{DEN} 45 dB(A) could not be achieved at all German airports by 2050 using proportionate means. Therefore, as a first step, noise quotas should be introduced at major German airports to limit aircraft noise exposure in residential areas to 63 dB(A) during the day. The noise protection target should then be tightened to 58 dB(A) by 2050.

Protecting people from aircraft noise at night is particularly important. Although there are individual differences in sleep behaviour, about eight hours of undisturbed sleep is necessary for mental and physical recovery. However, the night flight regulations in force at German airports provide operational restrictions at different times. At Frankfurt Airport, for example, flights are not permitted between 11 p.m. and 5 a.m. At Cologne and Leipzig/Halle airports, however, flights are allowed throughout the night. The German Environment Agency recommends that regular flights at densely populated airports should not take place between 10 p.m. and 6 a.m. Unavoidable night flights may be operated at one or a few airports. However, they must comply with the WHO objective that noise should not exceed a L_{night} of 40 dB(A) [6]. These airports should be located in sparsely populated areas. National airport planning, based on environmental criteria, should determine which airport locations in Germany are suitable for this purpose.

Tables 1 and 2 give an overview of all instruments and measures of the aircraft noise reduction strategy. A distinction is made between interim targets for 2030 and the final objectives for 2050. These are set at national and international level.

Table 1. Aircraft noise reduction measures at international level

Aircraft noise reduction measures at international level	Latest date of implementation
Strengthening of noise limits of subsonic jet aeroplanes and	2050

Aircraft noise reduction measures at international level	Latest date of implementation
propeller-driven aeroplanes by 28 EPNdB compared to ICAO Annex 16, Volume I, Chapter 14	
Civil supersonic aircraft must meet noise certification requirements comparable to those for subsonic aircraft	2030
Further development and application of noise abatement flight procedures	2030
Further development and application of technical and operational measures to reduce noise emissions from helicopters	2030
Establishment of noise certification requirements for drones and air taxis	2030

Source: German Environment Agency [1-2]

Table 2. Aircraft noise reduction measures at national level

Aircraft noise reduction measures at national level	Latest date of implementation
Noise quota at German airports from 6 a.m. to 10 p.m. with a limit of 63 dB(A)	2030
Noise quota at German airports from 6 a.m. to 10 p.m. with a limit of 58 dB(A)	2050
No regular flights from German airports close to town between 10 p.m. and 6 a.m.	2030
Relocation of unavoidable night flights to airports in sparsely populated areas	2050
Improving flight route planning, including regular environmental impact assessments and public participation	2030
Further development of noise charging systems at airports to improve their effectiveness	2030
Replacement of aircraft auxiliary power units (APU) by ground power units (GPU) at airports	2030
Electrification of all airport vehicles and ground handling equipment	2030
Engine testing should only take place in enclosed hush houses	2030
Promotion of the development and retrofitting of light propeller aircraft for noise reduction. This should include electrification where feasible.	2030
Ban night flights of drones over residential areas	2030

Source: German Environment Agency [1-2]

2.2 Module 2: Minimising climate-relevant emissions

Jet aircraft emit large amounts of carbon dioxide (CO_2), which is produced by the combustion of kerosene in the engines. They also emit particles, water vapour, sulphur, and nitrogen oxides. These affect the formation of aerosols and clouds and the concentrations of various atmospheric gases. Some of these so-called non-CO_2 effects contribute to the warming of the atmosphere, while others have a cooling effect. Overall, non-CO_2 effects are expected to have a warming effect [12]. The total climate impact of the non-CO_2 effects is about two to three times greater than that of CO_2 emissions alone. As these effects can only be mitigated by modern jet engines, it is not possible to fly climate-neutral in the long term.

In order to limit CO_2 emissions, aviation was included in the European Emissions Trading Scheme in 2012. Internationally, aviation is part of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) since 2021. However, these measures will not be sufficient to make aviation greenhouse gas neutral. The level of CO_2 emissions depends primarily on the traffic volume. Technological efficiency improvements will only slightly reduce this growth. In the future, electrically powered aircraft can make a small contribution to CO_2 reduction. However, the low energy density of current battery storage systems compared to kerosene makes these aircraft unsuitable for medium- and long-haul flights in the near future. A change in aviation fuel production is therefore necessary. Instead of fossil kerosene, synthetic kerosene should be used. This fuel is called Power-to-Liquids (PtL) [13]. It is important that only electricity from renewable energy sources is used to produce the fuel, because only then it is greenhouse gas neutral. Large quantities of PTL are required for aviation. However, there are currently no commercial PTL plants. Complete substitution of fossil kerosene with PTL is therefore only possible in the long term. For these reasons, commercial production of PTL must start now.

2.3 Module 3: External environmental costs charged to the polluter

Air traffic causes significant environmental and health costs [14]. The costs comprise the effects of aircraft noise and air pollution on human health, and the costs of the climate impact of aviation. These costs are not borne by the airlines, but by the public. It is therefore necessary to allocate the costs to the polluter, i.e. to internalise the external costs. This will reduce air traffic and improve the competitiveness of alternative modes of transport. The revenue from internalising external costs and the additional reduction in environmentally harmful subsidies should be used to promote environmental technologies in aviation [1].

2.4 Module 4: Ensuring clean air on site

Air quality around airports is mainly influenced by flight operations and feeder traffic. This produces air pollutants such as nitrogen oxides (NO_x) and hydrocarbons (HC). Most German airports have continuously operating measuring stations to record the air pollutant emissions. Comparisons of measurement results at the airport site with those in urban areas away from major roads show that the pollutant concentrations are in the same order of magnitude [1, 15-16]. EU limit and target values for air quality are therefore met. The values are currently being reviewed by the EU Commission because the WHO has further developed its air quality guidelines based on current scientific findings [17-18]. According to the WHO recommendations on air quality particulate matter pollution is problematic in Germany [19]. Particulate matter (PM) is divided into three categories according to size: particles with an aerodynamic diameter of up to 10 micrometres (µm) are called PM_{10}, while $PM_{2.5}$ comprises particles with a size of up to 2.5 µm. Ultrafine particles are even smaller, with a particle size of less than 0.1 µm ($PM_{0.1}$). Particulate matter is emitted from various sources (e. g. traffic, small combustion plants). Studies at various airports show increased exposure to ultrafine particles in the vicinity of airports [20-22].
Regarding the health effects of air pollution, nitrogen dioxide (NO_2) and particulate matter are of particular concern. NO_2 is produced by combustion processes and can damage the lungs due to its oxidising effect. Particulate matter also causes health problems. In general, the smaller the particles, the deeper they can penetrate the human respiratory tract [23]. PM_{10} can enter the bronchi and bronchioles during breathing and $PM_{2.5}$ can reach the alveoli of the lungs. The tiny ultrafine particles can be inhaled much deeper and even enter the blood circulation.
There are currently no limit values for ultrafine particles in the EU or Germany because the health risk cannot yet be sufficiently quantified and further research is necessary [24]. However, as a precautionary measure, particle emissions should be reduced as much as possible. To improve air quality at airports, the following measures should be taken by 2030

- Electrification of all airport vehicles and ground handling equipment
- Equipping ground power units (GPU) with particle filters
- Stricter emission limits for aircraft in accordance with ICAO Annex 16, Volume II [25], especially for NO_x
- Implementation of NO_x- and HC-based take-off and landing charges at all German airports
- Reduction of the sulphur content of kerosene.

2.5 Module 5: Designing sustainable infrastructure

There are around 900 airfields in Germany, ranging from helipads at hospitals and small general aviation airfields to international airports such as Frankfurt or Munich. The question is whether all these airports are necessary. To answer this question, a nationwide airport concept is required. The German Environment Agency therefore recommends that an overarching airport concept should be developed. This concept describes the necessity and function of the individual airports. It is based mainly on environmental criteria. This applies primarily to Germany, but it is also recommended for airports in the EU. The airport concept would ensure that each airport has a specific role in the air transport system.

2.6 Module 6: Shifting short-haul flights to rail

There are also short-haul flights in Germany. The German Environment Agency recommends that these flights should be shifted to rail for environmental reasons. Rail is often used instead of air if the destination can be reached within four hours [2]. However, this requires improved conditions for rail transport in

Germany. For example, all major airports should be connected to intercity rail networks. In this way, short-haul flights could be avoided. Attractive public transport connections are also important. Efficient rail and bus services create incentives to avoid car journeys. This saves parking space and reduces land use at airports.

2.7 Module 7: Conservation of resources, efficient use of raw materials

The protection of natural resources is vital. This also includes the protection of soil and water. This can lead to conflicts of objectives with the requirements of flight operations. An example is the de-icing of aircraft in winter. During this season, aircraft are sprayed with de-icing fluids before take-off to maintain the aerodynamics of the aircraft. The de-icing process takes place on special flight operations areas and lasts an average of 10 minutes. Significant quantities of de-icing fluid are used. For example, an average of 350 litres of de-icing fluid and 450 litres of hot water are used to de-ice an Airbus A 330 [26]. Wastewater contaminated with de-icing fluid is collected and then disposed of. Some airports have their own recycling facility. Munich Airport, for instance, has such a facility. This enables about 70 % of the de-icing fluid used to be reused [27]. This is not only environmental reasonable but is also economically advantageous.

Another environmental issue is the use of per- and polyfluoroalkyl substances (PFAS) in firefighting foams. These chemicals can get into surface water during firefighting, seep into the soil and contaminate groundwater. As the chemicals cannot be broken down by bacteria or other transformation processes, they remain in the environment and can be found in food (e.g. fish, eggs) [19]. It is therefore recommended that fluorinated firefighting foams should not be used unless absolutely necessary. Due to environmental concerns and current efforts by the European Chemicals Agency (ECHA) to restrict fluorinated firefighting foams, more and more airport fire brigades are replacing them with effective fluorine-free alternatives [28-29]. For example, the fire brigade at Stuttgart Airport in Germany uses fluorine-free firefighting foams.

Further important environmental issues are the use of raw materials and recycling management. The materials used in aircraft construction are mainly aluminium and titanium alloys and fibre composites. Raw materials are a valuable resource and should be used sparingly and efficiently. Recycling is also a significant aspect. In the future, an economic and material cycle should be considered in aircraft design. The aim should be to design aircraft by 2050 that are recyclable and can be returned to the economic and material cycle at the end of their life.

2.8 Module 8: Fewer flights

It will not be possible to completely avoid the environmental impact of air traffic. It is therefore advisable to consider changing consumer behaviour. Increasing ticket prices, replacing business flights with more efficient means of communication, buying regional products, and accepting longer travel times can reduce air traffic and its environmental impact.

3. CONCLUSION

Significant progress has been made in the past in aircraft design and engine technology. However, this is not enough to achieve the climate and environmental goals that have been set. The German Environment Agency's comprehensive strategy shows a realistic way to make air transport as environmentally friendly as possible by 2050. Sustainable air traffic is characterised by the fact that it is both effectively reducing environmental impacts and meeting people's mobility needs.

4. REFERENCES

[1] J. Bopst, R. Herbener, O. Hölzer-Schopohl et al.: *Umweltschonender Luftverkehr lokal - national - international*, Texte 130/2019, Umweltbundesamt, Dessau-Roßlau, 2019, https://www.umweltbundesamt.de/publikationen/umweltschonender-luftverkehr [Access 30.04.2023].

[2] J. Bopst, O. Hölzer-Schopohl, J. Lindmaier et al.: *Where are we going? The air traffic of the future: environmentally- and climate-friendly, greenhouse gas neutral, low-noise*, 2nd edition, German Environment Agency, Dessau-Roßlau, 2020, Where are we going? | Umweltbundesamt [Access 30.04.2023].

[3] Umweltbundesamt: *Belastung der Bevölkerung durch Fluglärm in der Umgebung der Großflughäfen nach Umgebungslärmrichtlinie, Tag-Abend-Nacht-Index (LDEN) und Nachtlärmindex (LNight)*, Umweltbundesamt, Dessau-Roßlau, 2018, Gesundheitsrisiken durch Umgebungslärm | Umweltbundesamt. [Access 30.04.2023].

[4] V. Sparrow, T. Gjestland, R. Guski et al., "Aviation Noise Impacts White Paper, State of the Science 2019: Aviation Noise Impacts", in *ICAO 2019 Environmental Report - Aviation and Environment*, pp. 44-61, 2019, ICAO-ENV-Report2019-F1-WEB (1).pdf [Access 30.04.2023].

[5] J. Belz, R. Follmer, J. Hölscher et al.: *Umweltbewusstsein in Deutschland 2020 - Ergebnisse einer repräsentativen Bevölkerungsumfrage*, Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz und Umweltbundesamt, Dessau-Roßlau, 2022, Umweltbewusstseinsstudie 2020 (umweltbundesamt.de) [Access 30.04.2023].

[6] World Health Organisation: *Environmental noise guidelines for the European Region*, World Health Organisation Regional Office for Europe, Copenhagen 2018, Environmental noise guidelines for the European Region (who.int) [Access 30.04.2023].

[7] International Civil Aviation Organisation: *Annex 16 to the Convention on International Civil Aviation, Environmental Protection, Vol. I - Aircraft Noise*, 8th edition, International Civil Aviation Organisation, Montreal, 2017.

[8] European Union Aviation Safety Agency: *EASA Certification Noise Levels - Jet aeroplanes noise database*, European Union Aviation Safety Agency, Cologne, 2023, EASA Certification Noise Levels | EASA (europa.eu) [Access 30.04.2023].

[9] *Gesetz zum Schutz gegen Fluglärm* of 31st Oktober 2007 (BGBl. I p. 2550).

[10] Fraport: A*irport Charges according to Art. 19b Air Traffic Act (LuftVG), Charges for Central Ground Handling Infrastructure,* Fraport, Frankfurt/Main, 2023.

[11] Flughafen Berlin Brandenburg: *Charges Regulation Berlin Brandenburg Airport*, Flughafen Berlin Brandenburg (FBB), Berlin, 2022.

[12] D.S. Lee, D.W. Fahey, A. Skowron et al.: "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", *Atmospheric Environment*, vol. 244, 2021, 117834, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018 - ScienceDirect [Access 30.04.2023].

[13] V. Batteiger, K. Ebner, A. Habersetzer et al.: *Power-to-Liquids, a scalable and sustainable fuel supply perspective for aviation*, background, German Environment Agency, Dessau-Roßlau, 2022, Power-to-Liquids | Umweltbundesamt [Access 30.04.2023].

[14] European Commission: *Handbook on the external costs of transport – Version 2019 – 1.1*, Publications Office, 2020, Handbook on the external costs of transport - Publications Office of the EU (europa.eu) [Access 30.04.2023].

[15] Fraport: *Lufthygienischer Jahresbericht 2021 - Bericht über die Ergebnisse der Luftqualitätsmessungen am Flughafen Frankfurt*, Fraport, Frankfurt/Main, 2022, Lufthygienischer Jahresbericht 2021 (fraport.com) [Access 30.04.2023].

[16] Flughafen Berlin Brandenburg: *Luftgütebericht 2021*, Flughafen Berlin Brandenburg (FBB), Berlin, 2022, Luftgütebericht 2021 (berlin-airport.de) [Access 30.04.2023].

[17] World Health Organisation: *WHO global air quality guidelines, particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*, World Health Organisation, 2021, WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide [Access 30.04.2023].

[18] European Commission: *Proposal for a directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (recast)*, COM/2022/542 final, European Commission, Brussels, 2022, EUR-Lex - 52022PC0542 - EN - EUR-Lex (europa.eu) [Access 30.04.2023].

[19] Sachverständigenrat für Umweltfragen: *Umwelt und Gesundheit konsequent zusammendenken*, Sachverständigenrat für Umweltfragen, Berlin, 2023 SRU Sondergutachten: Umwelt und Gesundheit konsequent zusammendenken (umweltrat.de) [Access 26.06.2023].

[20] B. Stacey: "Measurement of ultrafine particles at airports: A review", *Atmospheric Environment*, vol. 198, pp. 463-477, 2019, https://doi.org/10.1016/j.atmosenv.2018.10.041 [Access 30.04.2023].

[21] E. Fleuti, S. Maraini: *Ultrafine particles - study on volatile and non-volatile ultrafine particles at Zurich*

airport, Zurich Airport, Zurich 2022, v-/nv-UFP-Study (flughafen-zuerich.ch) [Access 30.04.2023].

[22] H. Lorentz, W. Schmidt, P. Hellebrandt et al.: *Einfluss eines Großflughafens auf zeitliche und räumliche Verteilungen der Außenluftkonzentrationen von Ultrafeinstaub < 100 nm, um die potentielle Belastung in der Nähe zu beschreiben - unter Einbeziehung weiterer Luftschadstoffe (Ruß, Stickoxide und Feinstaub (PM 2,5 und PM10))*, Texte 14/2021, Umweltbundesamt, Dessau-Roßlau, 2021, Einfluss eines Großflughafens auf zeitliche und räumliche Verteilungen der Außenluftkonzentrationen von Ultrafeinstaub < 100 nm, um die potentielle Belastung in der Nähe zu beschreiben - unter Einbeziehung weiterer Luftschadstoffe | Umweltbundesamt [Access 30.04.2023].

[23] German Environment Agency: Healthy Air, What Matters - Magazine of the German Environment Agency 1/2019, German Environment Agency, Dessau-Roßlau, 2019, What Matters 1-2019: Healthy Air | Umweltbundesamt [Access 30.04.2023].

[24] B. Hellack, W. Birmili, M. Elsasser et al.: *Ultrafeine Partikel - Verursacher, Messung und Wirkungsbewertung,* Texte 126/2022, Umweltbundesamt, Dessau-Roßlau, 2022, Ultrafeine Partikel | Umweltbundesamt [Access 30.04.2023].

[25] International Civil Aviation Organisation: *Annex 16 to the Convention on International Civil Aviation, Environmental Protection, Vol. II - Aircraft Engine Emissions*, 4th edition, International Civil Aviation Organisation, Montreal, 2017.

[26] Zurich Airport: *De-Icing Wastewater*, Zurich Airport, Zurich, 2019, www.werbeschmiede.ch (flughafen-zuerich.ch) [Access 30.04.2023].

[27] Gesellschaft für Enteisen und Flugzeugschleppen am Flughafen München: *Enteisen - Wir machen Flugzeuge startklar*, Gesellschaft für Enteisen und Flugzeugschleppen am Flughafen München, München, 2023, EFM: Flugzeuge rangieren, enteisen und klimatisieren - Flughafen München (munich-airport.de) [Access 30.04.2023].

[28] E. Peltzer: *Sach- und umweltgerechter Einsatz von Schaummitteln*, Fachempfehlung Nr. DFV-FE-76-2022, Deutscher Feuerwehrverband, Berlin, 2023, Fachempfehlung Nr (feuerwehrverband.de) [Access 30.04.2023].

[29] European Chemicals Agency: *ECHA's committees: EU-wide PFAS ban in firefighting foams warranted*, European Chemicals Agency, Helsinki 2023. https://echa.europa.eu/-/echa-s-committees-eu-wide-pfas-ban-in-firefighting-foams-warranted [Access 26.06.2023].