engineering proceedings

MDPI

Proceeding Paper

Simulation-Based Assessment of the Control of a Hybrid ECS Including a Vapor Cycle System †

Arnav Pathak and Victor Norrefeldt *

Fraunhofer Institute for Building Physics IBP, Fraunhoferstr. 10, 83626 Valley, Germany; arnav.pathak@ibp.fraunhofer.de

* Correspondence: victor.norrefeldt@ibp.fraunhofer.de

† Presented at the 14th EASN International Conference on "Innovation in Aviation & Space towards sustainability today & tomorrow", Thessaloniki, Greece, 8–11 October 2024.

Abstract: Within the Clean Sky 2 regional project, a hybrid environmental control system has been conceived that combines the classical bleed air approach with a vapor cycle cooling in the recirculation air. To protect partners' IP, a functional mock-up (FMU) model of the hybrid ECS was provided describing the system behavior. This model was interfaced with a zonal model of a 100-passenger regional aircraft cabin to investigate comfort and air quality conditions within the cabin. The interfacing reveals that some optimization of the control algorithm is possible for the hybrid ECS, while some operational points already perform as intended. Hence, the coupled simulation approach, at an early design stage, already shows the strengths and weaknesses of the system conception. Recommendations from the simulation study can subsequently be incorporated into the design before a physical demonstrator is produced.

Keywords: virtual demonstration; hybrid ECS; digital twin; zonal modelling; Clean Sky 2

1. Introduction

Cabin ventilation is one of the major non-thrust power consumers on board an aircraft. The provision of bleed air is especially energetically expensive, as compressed air from the engine is removed. Furthermore, this air requires extensive conditioning to lower its supply air temperature from >200 °C to a typical cabin supply air level of around 15 °C. Hence, the reduction of bleed air may be one measure by which to further reduce the energy consumption of aircraft systems. However, this may lead to the requirement to cool recirculation air to meet the cabin thermal balance. In the automotive sector, air cooling is achieved by using a vapor cycle system; however, in the aerospace sector this system has not yet been deployed. The introduction of novel systems and system designs is a costly task in the aerospace industry. Such modifications must mature along all required TRL levels prior to industrializing them onboard the aircraft. With the ongoing digitalization of industrial processes, the virtual demonstration becomes ever more interesting. In this approach, the systems behavior is represented by physical modelling and component interactions can be investigated and optimized. Such an approach allows detecting strengths and weaknesses of a system design prior to investing in testing effort.

In the frame of the Clean Sky 2 regional project, a virtual demonstration of a hybrid environmental control system (H-ECS) has been performed. Hybrid refers to an aircraft ECS system that mainly uses the conventional bleed air system, but boosts its cooling capacity by using a vapor cycle system (VCS) in the recirculation air path. Load peaks or

check for updates

Academic Editors: Spiros Pantelakis, Andreas Strohmayer and Nikolaos Michailidis

Published: 27 March 2025

Citation: Pathak, A.; Norrefeldt, V. Simulation-Based Assessment of the Control of a Hybrid ECS Including a Vapor Cycle System. *Eng. Proc.* **2025**, *90*, 80. https://doi.org/10.3390/engproc2025090080

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

failure cases, that are typically the drivers for system sizing, are buffered by the additional cooling capacity provided by the VCS.

A conventional aircraft uses bleed air. This air is compressed in the engine and extracted before it enters the combustion chamber. Due to the compression, its temperature can exceed >200 °C and thus a primary heat exchanger is used to cool this air. Additional cooling of bleed air is achieved by an air cycle machine, where air is compressed, cooled by a ram air heat exchanger, and expanded before being provided to the mixing chamber [1]. In the mixing chamber, this fresh air is mixed with recirculated, HEPA-filtered cabin air. This mixture is supplied to the cabin air outlets to ventilate the cabin. Excess air is ejected overboard through the overflow valve, which at the same time regulates the cabin pressurization [2]. The minimum fresh airflow rate is 0.55 lb/min per passenger and total flow rate, being a mixture of fresh and recirc air, must at least be 1.12 lb/min; however, 1.49 lb/min is recommended [3]. As the bleed air extraction reduces the amount of power available in the engine, bleedless architectures are currently researched. However, the reduction of the bleed air intake also reduces the amount of conditioned air available on board the aircraft and thus ultimately the cooling capacity. In a subject study on increasing the recirculation airflow rate, it was concluded that this can lead to the requirement to additionally cool the recirculation air [4]. The introduction of a VCS onboard the aircraft is a potential technical solution to achieve this cooling.

This paper presents a virtual demonstration of the cabin conditions using an H-ECS with a VCS in the recirculation line. The reference aircraft for this demonstration is the novel regional aircraft cabin developed by the project partner Leonardo within the Clean Sky 2 regional project. This cabin has a 3–2 abreast seat arrangement and accommodates 100 passengers.

2. Simulation Method and Evaluation

The cabin is modelled using the velocity propagating zonal model (VEPZO), developed at Fraunhofer [5]. Based on the interior geometry, the model is automatically generated [6] by dividing the interior space into 3D zones exchanging air. Through this approach, the impact of the location and intensity of sinks and sources, like airflow openings, heat loads, moisture and contaminants, on the indoor environment can be considered. The model is coupled to enclosure thermal models in order to simulate the heat flow through walls. The zonal model predicts the local distribution of temperatures, humidities and CO_2 concentrations in the cabin. The zonal modelling approach has been validated in former work for a business jet aircraft cabin and for a train carriage [7,8].

The cabin model consists of 112 zones (Figure 1) and has an internal load of 100 passengers and 3 crew members, each assumed to emit 75 W of dry heat, 71.6 g/h of moisture [9] and 21 l/h of CO_2 [10]. The underfloor zone consists of a single-zone volume, and it is assumed that 3.5 kW of heat from systems is emitted there. Air is supplied through ceiling and lateral air outlets along the length of the cabin (blue arrows). Air is extracted below the dado panels close to the floor and directed to a one-node underfloor node. Here, air is split to exhaust air that is extracted overboard and recirculation air that is treated by the vapor cycle system. The fresh air, either supplied from engine bleed or the APU is conditioned in the packs. Fresh and recirculation air are mixed and supplied into the cabin.

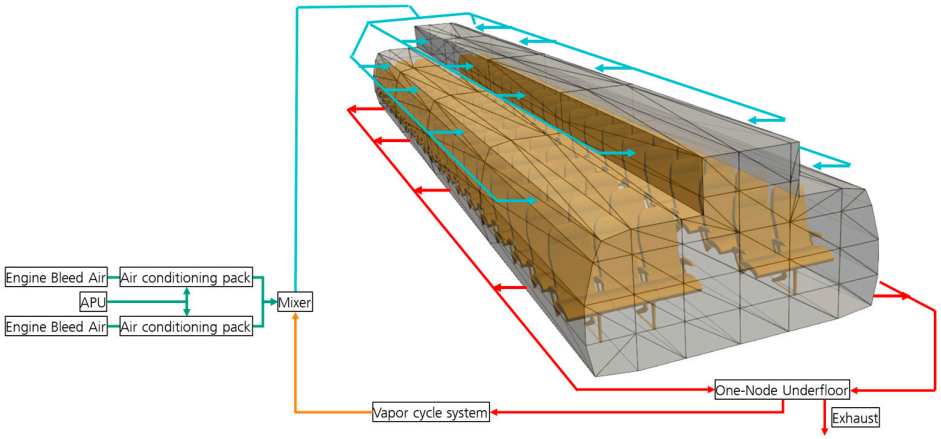


Figure 1. Cabin zonal model and ventilation pattern. Green arrows: conditioned outside air, orange arrows: conditioned recirculation air, blue arrows: cabin supply air, red arrows: cabin exhaust air.

Within Clean Sky 2, the model was extensively validated on a Fraunhofer thermal test bench [11]. Recent applications of the zonal modelling focused on the spread of tracer gases and contaminants in the indoor environment [12,13].

The H-ECS model and its controls was supplied by the project partner Liebherr Aerospace Toulouse SAS in the form of an FMU. It includes the bleed air and conditioning part together with the recirculation air path with the vapor cycle system. The FMU format allows the exchange of models between different entities to simulate cyber–physical systems [14]. One disadvantage of the FMU is that it can lead to a slower model convergence compared with a plain readable model connection. As this issue was encountered when coupling the H-ECS FMU with the zonal aircraft cabin model, a two-step approach was selected. In a first stage, the H-ECS FMU is connected to a single-node cabin model considering only temperature and humidity of the air. This node exchanges heat through cabin walls and all passenger and system heat and moisture outputs are added to this model by summing them. This simulation is performed for specific static points and mission profiles. In the second step, the predicted temporal profile of the H-ECS FMU (airflow rates, temperature, relative humidity) were applied to the zonal cabin model. CO_2, as a marker of air quality, was added in this simulation as a tracer gas travelling with the air.

The comfort evaluation is performed by comparing simulations results to relevant norms and publications. The thermal conditions are compared with limits set out in ASHRAE 161 [3] specifying 18.6 to 26.7 °C as a cabin temperature range and that stratification should not exceed 4.4 K. The per passenger fresh airflow rate should be at least 3.5 L/s, the total airflow rate at least 7.1 L/s (corresponding to 0.55 lb/min and 1.12 lb/min). The recommended total flow amounts to 9.4 L/s (1.49 lb/min). There are no prescribed ranges for cabin humidity and CO_2 concentration. In a literature review [15], 16 ± 5% RH and 1315 ± 232 ppm CO_2 concentration were found as typical ranges. In a subject study, ref. [4] found only a 2% decrease of passengers' rated air quality acceptability in a fully occupied cabin when increasing the CO_2 concentration to approx. 2200 ppm.

3. Virtual Demonstration Results

The virtual demonstration focused on normal and failure operation cases on the ground and while airborne.

3.1. Normal Operation Cases

3.1.1. Boundary Conditions

The investigated normal operation cases focus on an exterior temperature of 25 °C with two operating packs and the VCS system activated in the recirculation line. An immobile ground case using bleed air from the APU and a cruise case extracting engine bleed at 25.000 ft and 0.53 mach are considered. The boundary conditions are summarized in Table 1.

Table 1. Boundary conditions for normal operation cases.

	Ground	Cruise
Bleed air source	APU 2 air conditioning packs VCS activated	Engine 2 air conditioning packs VCS activated
Outside temperature	25 °C	25 °C
Cruise	0 ft 0 mach	25.000 ft 0.53 mach

3.1.2. One-Node Model Coupling Results

Table 2 shows the simulation results for the H-ECS output conditions during operation. The recirculation fraction is 33% on ground and 25% in cruise.

Table 2. Results of H-ECS output in normal operation cases.

		Ground	Cruise
Mass flow rates	ECS packs outlet VCS outlet	98 lb/min. 48 lb/min.	112 lb/min. 37 lb/min.
Airflow temperatures	ECS packs outlet VCS outlet	6.5 °C 0.5 °C	16.6 °C 0.9 °C

3.1.3. Zonal Cabin Model Results

The one-node H-ECS model air output conditions were applied as boundary conditions of the zonally refined cabin model. Predicted mean cabin temperature, stratification, relative humidity, and CO_2 concentrations are summarized in Table 3. In the ground case, it became obvious that the H-ECS model provided oversaturated air, resulting in unrealistically high cabin relative humidity. Hence the inclusion of water condensation in the cooling process should be extended in the model. Table 4 shows the detailed distribution of average cabin temperature along the height and width of the cabin considering the occupied space of up to 1.3 m.

Table 3. Results of zonal model output in normal operation cases.

		Ground	Cruise
Cabin temperatures	Average Stratification (feet–head level)	14.3 °C 0.5 K	20.4 °C 0.5 K
Relative humidity	Average	100%	19.1%
CO_2 concentration	Average	1258 ppm	1183 ppm

Table 4. Detailed temperature distribution in °C for normal operation cases.

Temperature Distribution in °C	Height	Row E	Row D	Row C	Aisle	Row B	Row A
Ground conditions	1.3 m	12.1	15.5	15.3	14.1	14.6	11.7
	1.1 m	13.1	15.4	15.1	14.2	14.8	12.8
	0.6 m	13.7	15.4	15.3	14.2	15.0	13.3
	0.1 m	14.6	15.5	15.1	14.5	14.8	13.9
Cruise conditions	1.3 m	18.6	21.5	21.4	20.6	20.3	18.1
	1.1 m	19.2	21.5	21.4	20.6	20.3	18.7
	0.6 m	19.8	21.5	21.4	20.7	20.7	19.2
	0.1 m	20.8	21.7	21.2	20.6	20.7	19.8

Figure 2 shows the distributions of temperature, relative humidity and CO_2 concentration in the cabin. The cabin air inlet areas are visible through a locally lower air temperature, humidity, and CO_2 concentration.

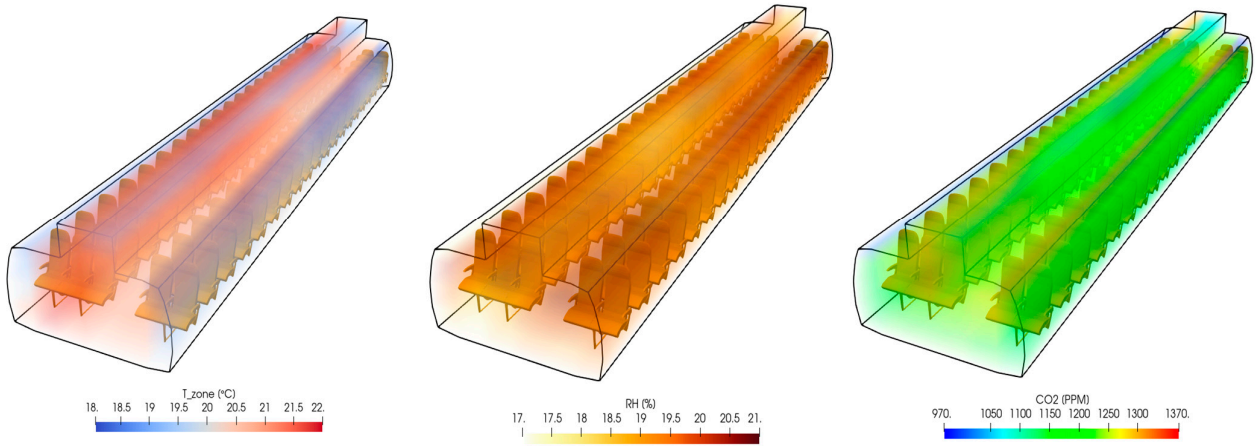


Figure 2. Temperature, relative humidity and CO_2 concentration distribution for the normal operation cruise case.

3.1.4. Comfort Evaluation

Table 5 summarizes the comfort criteria that can be evaluated based on the simulation data. Results prove the further potential for energy savings by supplying less cooling power in the ground case, as the cabin is cooled below ASHRAE 161 limits. Furthermore, the fresh airflow rate exceeds requirements and thus could be reduced to lower the bleed air offtake.

Table 5. Comfort assessment based on simulation results in normal operation case.

		Ground	Cruise
Cabin temperatures	Average	Too cold	Compliant to ASHRAE 161
	Stratification	Compliant to ASHRAE 161	Compliant to ASHRAE 161
Airflow rates	Fresh	Higher than required by ASHRAE 161	Higher than required by ASHRAE 161
	Total	Compliant to ASHRAE 161	Compliant to ASHRAE 161
Relative humidity	Average	Unrealistic simulation result	Higher than measured in service (more comfortable)
CO_2 concentration	Average	Lower than measured in service (better air quality)	Lower than measured in service (better air quality)

3.2. Failure Operation

3.2.1. Boundary Conditions

The investigated failure operation cases focus on an exterior temperature of 25 °C with only one operating pack and the VCS system activated in the recirculation line. An immobile ground case using bleed air from the APU and a cruise case extracting engine bleed at 15.000 ft and 0.43 mach were considered. The boundary conditions are summarized in Table 6.

Table 6. Boundary conditions for failure operation cases.

	Ground	Cruise
Bleed air source	APU 1 air conditioning pack VCS activated	Engine 1 air conditioning pack VCS activated
Outside condition	25 °C	25 °C
Cruise	0 ft 0 mach	15.000 ft 0.43 mach

3.2.2. One-Node Model Coupling Results

Table 7 shows the simulation results for the H-ECS output conditions during operation. The recirculation fraction is 48% on ground and 45% in cruise.

Table 7. Results of H-ECS output in failure operation cases.

		Ground	Cruise
Mass flow rates	ECS packs outlet VCS outlet	53 lb/min. 48 lb/min.	53 lb/min. 43 lb/min.
Airflow temperatures	ECS packs outlet VCS outlet	5.4 °C −1.2 °C	7.4 °C −0.1 °C

3.2.3. Zonal Cabin Model Results

The one-node H-ECS model air output conditions were applied as boundary conditions of the zonally refined cabin model. Predicted mean cabin temperature, stratification, relative humidity, and CO_2 concentrations are summarized in Table 8. In the ground case, it became obvious that the H-ECS model provided oversaturated air, resulting in unrealistically high cabin relative humidity. Hence the inclusion of water condensation in the cooling process should be extended in the model. Table 9 shows the detailed distribution of average cabin temperature along the height and width of the cabin considering the occupied space of up to 1.3 m.

Table 8. Results of zonal model output in failure operation cases.

		Ground	Cruise
Cabin temperatures	Average Stratification (feet–head level)	16.2 °C 0.6 K	18.0 °C 0.6 K
Relative humidity	Average	100%	100%
CO_2 concentration	Average	2100 ppm	2075 ppm

Table 9. Detailed temperature distribution in °C for failure operation cases.

Temperature Distribution in °C	Height	Row E	Row D	Row C	Aisle	Row B	Row A
Ground conditions	1.3 m	13.3	17.4	17.2	16.0	16.2	13.1
	1.1 m	15.0	17.3	17.1	16.3	16.3	14.4
	0.6 m	16.0	17.6	17.2	16.5	16.6	15.0
	0.1 m	16.8	17.7	17.1	16.5	16.4	15.6
Cruise conditions	1.3 m	18.6	15.1	19.2	19.1	17.9	18.0
	1.1 m	19.2	16.9	19.1	18.9	18.2	18.1
	0.6 m	19.8	17.8	19.4	19.1	18.3	18.4
	0.1 m	20.8	18.7	19.5	18.9	18.3	18.3

3.2.4. Comfort Evaluation

Table 10 summarizes the comfort criteria that can be evaluated based on the simulation data. The cabin is overcooled and stabilizes below the lower limit of 18.3 °C (ASHRAE 161). This proves the further potential for energy savings by supplying less cooling power in the ground case. It should be noted that ASHRAE 161 requirements for the airflow rate apply to normal operation conditions, whereas here failure conditions are considered.

Table 10. Comfort assessment based on simulation results in failure operation case.

		Ground	Cruise
Cabin temperatures	Average Stratification	Too cold Compliant to ASHRAE 161	Too cold Compliant to ASHRAE 161
Airflow rates	Fresh	Very close to requirement by ASHRAE 161 (total of 2 lb/min missing)	Very close to requirement by ASHRAE 161
	Total	Close to requirement by ASHRAE 161 (total of 11 lb/min missing)	Close to requirement by ASHRAE 161 (total of 16 lb/min missing)
Relative humidity	Average	Unrealistic simulation result	Unrealistic simulation result
CO_2 concentration	Average	Within range not leading to complaints in subject study [4]	Within range not leading to complaints in subject study [4]

4. Conclusions and Discussion

The work presented a coupled simulation of the indoor cabin environment and a hybrid ECS system consisting of the normal bleed air system and an additional vapor cycle system to condition the recirculation air.

The simulation study shows some optimization potential on the H-ECS system, as follows:

- Improved temperature control to avoid cabin overcooling.
- A clear margin for further bleed air reduction under normal operation.

The simulation-based approach proved an effective means to obtain early insight into the orchestration of the systems and the optimizations that should be performed prior to a potential physical test. With this, the selected model-based approach proved its usefulness in helping reduce cost and labor time. In an industrial design process, these findings would, as a first step, lead to a deeper analysis of conditions in which the cabin control deviated from expected behavior—i.e., where the cabin became too cold or was overventilated. This analysis should cover the steps of reviewing the control logics and possible system sizing limitations, e.g., necessitating the ECS system to not operate below a certain threshold. Hence, an oversizing of the system could be detected and potentially lead to the redesign of a smaller system. In terms of decision making, the current implementation would not yet be considered ready to fly until the model predicts satisfactory thermal and sufficient, but not overventilated, airflow in all considered design points.

Despite the advantage of the FMU providing IP protection, it also generates some limitations. Where flaws become obvious in the integrated simulation, this can only be solved by sharing the simulation results with the FMU developer and after rework and reintegration of a new FMU. The simulation performance showed a noticeable decrease when coupling to the FMU compared with applying the boundary conditions predicted by the FMU as a direct input to the model.

The modelling is performed at an early stage—i.e., models validated on other platforms are adapted and expected to remain accurate. To overcome this, the approach to perform a parallel setup of the modelling and validation environment is considered the most reliable method. Nevertheless, the modelling can be used to detect early-stage problems and further improve the system once more mature validation data become available. Furthermore, the testing effort can be reduced by covering a larger number of conditions in modelling.

Author Contributions: Conceptualization, V.N.; methodology, V.N.; software, A.P.; validation, A.P.; formal analysis, A.P.; investigation, A.P.; resources, V.N.; data curation, A.P.; writing—original draft preparation, V.N.; writing—review and editing, A.P.; visualization, A.P.; supervision, V.N.; project administration, V.N. All authors have read and agreed to the published version of the manuscript.

Funding: The presented project has received funding from the Clean Sky 2 joint undertaking under grant agreement No 945583. The authors are responsible for the content of this publication.





Data Availability Statement: Data could be shared upon request as long as this does not involve partners' IP.

Acknowledgments: We wish to thank Leonardo Velivoli and Liebherr Aerospace Toulouse SAS for the cooperation in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. National Research Council. *The Airliner Cabin Environment: Air Quality and Safety*; The National Academies Press: Washington, DC, USA, 1986; p. 42. [CrossRef]
2. Oehler, B. Modeling and Simulation of Global Thermal and Fluid Effects in an Aircraft Fuselage. In Proceedings of the 4th International Modelica Conference, Hamburg, Germany, 7–8 March 2005.
3. *ASHRAE Standard 161*; ASHRAE 161: Air Quality Within Commercial Aircraft. ASHRAE: Atlanta, GA, USA, 2006.
4. Norrefeldt, V.; Mayer, F.; Herbig, B.; Ströhlein, R.; Wargocki, P.; Lei, F. Effect of In-creased Cabin Recirculation Airflow Fraction on Relative Humidity, CO_2 and TVOC. *Aerospace* **2021**, *8*, 15. [CrossRef]
5. Norrefeldt, V.; Grün, G.; Sedlbauer, K. Velocity propagating zonal model for the estimation of the airflow pattern and temperature distribution in a confined space. *Build. Environ.* **2012**, *48*, 183–194. [CrossRef]
6. Pathak, A.; Norrefeldt, V.; Lemouedda, A.; Grün, G. The Modelica Thermal Model Generation Tool for Automatted Creation of Coupled Airflow, Radiation Model and Wall Model in Modelica. In Proceedings of the 10th Modelica Conference, Lund, Sweden, 10–12 March 2014.
7. Norrefeldt, V.; Pathak, A.; Lemouedda, A.; Siede, M.; Grün, G. Validation of the zonal thermal model VEPZO/RADZO for cold outside conditions on a business jet mock-up. In Proceedings of the AST 2025 Conference, Hamburg, Germany, 24–25 February 2025.
8. Will, H.; Stratbücker, S.; Norrefeldt, V.; Reith, A.; Scherer, C. Risikoeinschätzung zur Ansteckungsgefahr mit COVID-19 im Schienenpersonen- Sowie im Straßenpersonennah- und -Fernverkehr; Forschungsbericht 12. Deutsches Zentrum für Schienenverkehrsforschung beim Eisenbahn-Bundesamt: Dresden, Germany, 2021. [CrossRef]
9. *VDI 2078*; Berechnung der thermischen Lasten und Raumtemperaturen (Auslegung Kühllast und Jahressimulation). VDI-Richtlinien: Düsseldorf, Germany, 2015.

10. *VDI 4300-7*; Messen von Innenraumluftverunreinigungen—Bestimmung der Luftwechselzahl in Innenräumen. VDI-Richtlinien: Düsseldorf, Germany, 2001.
11. Lindner, A.; Pschirer, M.; Norrefeldt, V. Model validation for a transient ECS failure case in a business jet mock-up. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1226*, 012110. [CrossRef]
12. Pathak, A.; Norrefeldt, V.; Pschirer, M. Validation of a Simulation Tool for an Environmentally Friendly Aircraft Cargo Fire Protection System. *Aerospace* **2021**, *8*, 35. [CrossRef]
13. Pathak, A.; Schneider, K.; Norrefeldt, V. Use of Modelica to predict risk of Covid-19 infection in indoor environments. In Proceedings of the 14th International Modelica Conference, Linköping, Sweden, 20–24 September 2021. [CrossRef]
14. Available online: https://fmi-standard.org/about/ (accessed on 16 July 2024).
15. Chen, R.; Fang, L.; Liu, J.; Herbig, B.; Norrefeldt, V.; Mayer, F.; Fox, R.; Wargocki, P. Cabin air quality on non-smoking commercial flights: A review of published data on airborne pollutants. *Indoor Air* **2021**, *31*, 926–957. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.