

AETHER

Executive Summary



**Vertical Flight Society
39th Annual Student Design Competition**



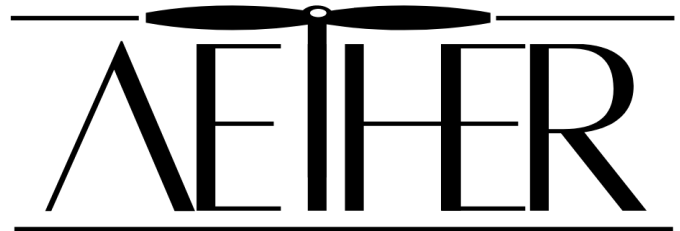
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Executive Summary

by

Antonio E. García Bulder Laura Domenech Garrido
Jonathan Tegischer Nanami Hashimoto
Keiya Iwamida Yaren Curgul

for the Vertical Flight Society's 39th Annual Student Design Competition



Tutor: Dr. Marilena D. Pavel
Coaches: Ir. Nils Barfknecht and Johan Leijtens
Institution: Delft University of Technology
Place: Faculty of Aerospace Engineering, Delft
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Signature Page



Antonio E. García Bulder
BSc Aerospace Engineering student
Delft University of Technology
A.E.GarciaBulder@student.tudelft.nl



Laura Domenech Garrido
BSc Aerospace Engineering student
Delft University of Technology
L.DomenechGarrido@student.tudelft.nl



Jonathan Tegischer
BSc Aerospace Engineering student
Delft University of Technology
J.Tegischer@student.tudelft.nl

Nanami Hashimoto

Nanami Hashimoto
BSc Aerospace Engineering student
Delft University of Technology
N.Hashimoto@student.tudelft.nl



Keiya Iwamida
BSc Aerospace Engineering student
Delft University of Technology
K.Iwamida@student.tudelft.nl



Yaren Curgul
MSc Aerospace Engineering student
Delft University of Technology
Y.Curgul@student.tudelft.nl

Under the guidance of



Dr. Marilena D. Pavel
Associate Professor
Delft University of Technology



Ir. Nils Barfknecht
PhD Aerospace Engineering Student
Delft University of Technology



Johan Leijtens
Systems Engineer at LENS Research and Development
Delft University of Technology

Permission for Posting

To the Vertical Flight Society,

The members of TU Delft's undergraduate team Aether, hereby grant the Vertical Flight Society permission to publish the present work as part of their 39th Annual Student Design Competition.

Yours sincerely,

Team Aether

Executive Summary

Project Overview

The beginning of the 21st century is undoubtedly a time when conventional aircraft design is challenged and revolutionized by the need of innovative, yet cost-effective aircraft with low-carbon footprint and by the emergence of Advanced Air Mobility (AAM). AAM is a new concept of air transportation using electric Vertical Takeoff and Landing (eVTOL) aircraft, integrating new, transformational designs and flight technologies into existing and modified airspace operations. In this context, Aether design is living up to this vision presenting a full eVTOL concept aircraft adapted to the requirements of a unique spectrum of travelers, i.e. Passengers with Reduced Mobility (PRM). PRM are people who have transport difficulties but might not regard themselves as being disabled. PRM include disabled people as a primary focus but may also include for example older people who are frail, pregnant women, parents with small children, passengers with luggage, visitors or tourists and people with temporary impairments such as a broken leg. Note therefore that Aether design also encompasses this broader range of users with mobility constraints and needs seen as “hidden disabilities”. Aether is an aircraft blend between fixed-wing aircraft and rotorcraft, being an optimized solution for urban, suburban and rural travel. It transports passengers between hubs and airports, called vertiports, separated by 100 miles in just under an hour. It is a human piloted hybrid aircraft - a helicopter during take-off, climb and descent and an airplane during cruise, which can transport 2 PRMs, including one helper, or 4 passengers with full mobility. Figure 1 shows the basic requirements that constitute the concept of the proposed aircraft. Aether is the Delft University of Technology's student team project answering to the 39th Vertical Flight Society (VFS) Annual Student Design Competition request for proposal of year 2021-2022 sponsored by Bell Helicopters.

Requirements

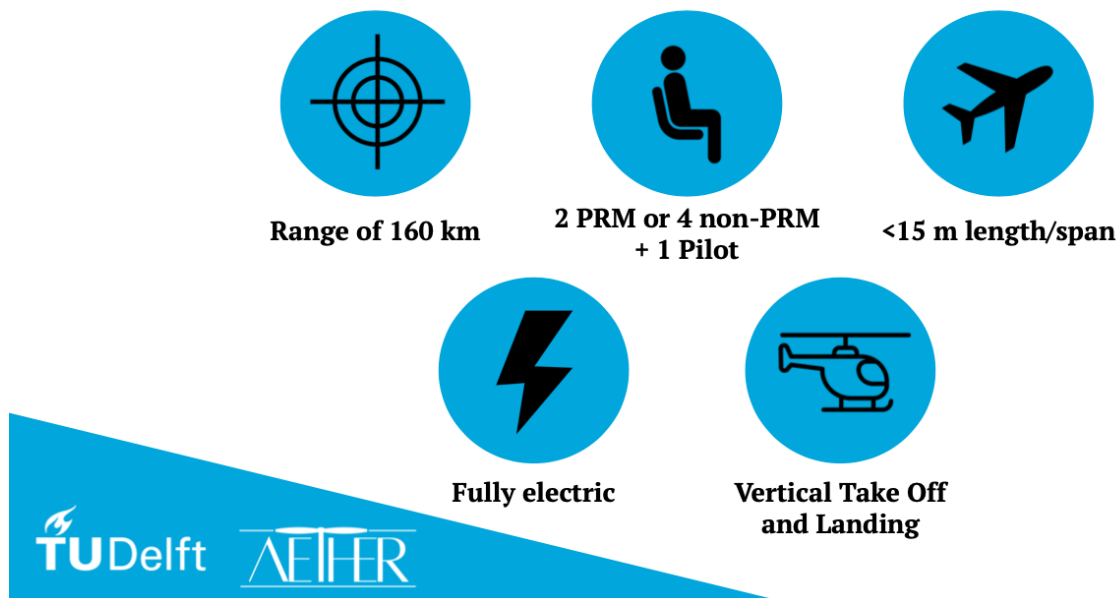


Figure 1: Mission requirements for the VFS Student Design Competition 2022.

Market Analysis

The services provided by Aether at early business stages aim to target a wide range of customers. Therefore, the initial target case of the business is the transportation of passengers between two cities or two major transportation hubs. The target customers include business persons who seeks for a transportation mode reducing travelling time as compared to classic modes of transportation, and travelers that prefers to avoid other modes of transportation due to physical/psychological reasons or complicated local traffic. The market needs considered by Aether are as follows: while most eVTOLs recognize the needs of a safe and comfortable transport service with an affordable price, the need to accommodate passengers with reduced mobility is often overlooked. The United Nations (UN) estimates that between 6 to 10 percent of people in developing countries experience a disability – equivalent to some 400 million people world-

wide (UN, 2011). A comparison of several currently developed eVTOLs such as Lilium, Joby, Aurora, Airbus A3, Volocity, etc. that may potentially be competitors of Aether show the inability to accommodate passengers with reduced mobility that require a wheelchair or a stretcher.

Conceptual Trade-off

Three aircraft concepts were generated for the above-given requirements: blended wing body concept, tiltrotor aircraft concept, and multirotor concept. The first concept, sketched in Figure 2, portrays a blended wing body aircraft with tilt rotors on the front and back of the fuselage. Figure 3 shows a design with tilt rotors and a fuselage of similar shape as a light jet. Finally, Figure 4 depicts a multirotor design with coaxial rotors connected by a central fuselage section.

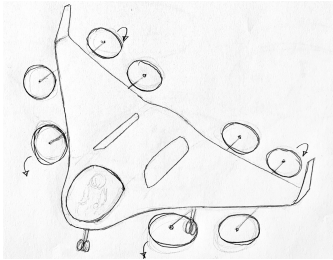


Figure 2: Flying Wing sketch

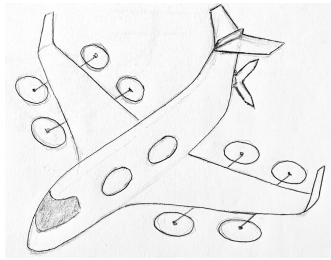


Figure 3: Tiltrotor Aircraft sketch

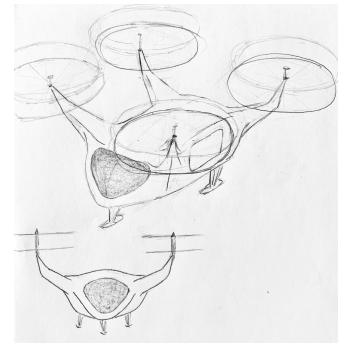


Figure 4: Multirotor sketch

The trade-off methodology started by selecting the appropriate criteria for the purpose. The criteria considered were passenger comfort, sustainability, cost, technology readiness level and safety. The definitions for the 5-level rating were also defined. Finally, the weighting of the criteria was chosen by calculating the average weighting based on each team member's perspective, and critically examining the result. Table 1 shows a comparison of the key specifications for the aircraft concepts.

Table 1: Specification sheet of preliminary concepts of three designs.

Specification	Flying Wing	Tiltrotor	Multicopter
Gross weight (kg [lbs])	2296 [5062]	2471 [5448]	2471 [5448]
Cruising speed (m/s [ft/s])	53 [174]	50 [164]	34 [112]
Time to complete mission (min)	55	56	60
Max power required (kW [hp])	738 [990]	790 [1059]	633 [849]
Total energy consumed (kWh)	179	224	368
Battery weight (kg [lbs])	447.5 [987]	560 [1235]	920 [2028]

As a result of the trade off, the tiltrotor concept was selected as the final concept, as it scored the highest out of the three concepts. The Blended Wing Body concept had the second highest score and the multirotor concept scored the lowest among the three. Moreover, as a result of the sensitivity analysis, this concept remains as the best concept when the result was examined by removing each trade off criteria from the trade-off. The breakdown of the trade-off scores are shown in Table 2.

Table 2: Final trade off summary. Higher scores represent a better result.

Top level criteria	Weight	Sub criteria	Weight	Multirotor	Tiltrotor	Blended wing body
Sustainability	16	Noise	9.4	3	2	2
		Energy consumption	6.6	2	4	4
Cost	20	Production cost	13.2	4	4	3
		Operational cost	6.8	3	4	5
Passenger comfort	27	Cabin comfort	12.7	4	3	4
		Trip time	14.3	3	4	4
Technology readiness level	13	Fuselage	4.7	4	5	3
		Propulsion	3.4	5	4	3
		VTOL configuration	5.1	5	3	2
Safety	24	Risk	N/A	3	4	4

Total	341.6	368.9	357.3
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Final design

A final design of Aether in its hover and cruise configurations are shown in Figure 5 and Figure 6, respectively. It is a tiltrotor aircraft equipped with 6 rotors: 4 rotors on the front wing and 2 rotors on the tail. The aircraft has a high-wing configuration for minimum clearance between the fuselage and the ground to allow easier boarding of passengers. The vertical tail has a T-tail configuration for clearance of the rear rotors. Table 3 gives a summary of all the technical specifications of the aircraft.

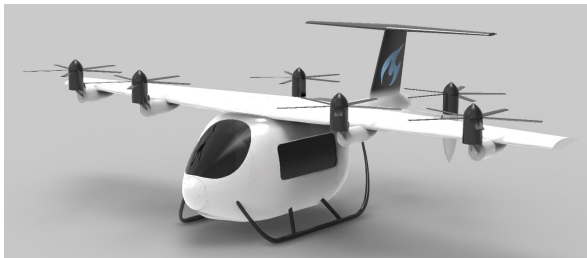


Figure 5: Render of the Aether aircraft in its hover configuration.

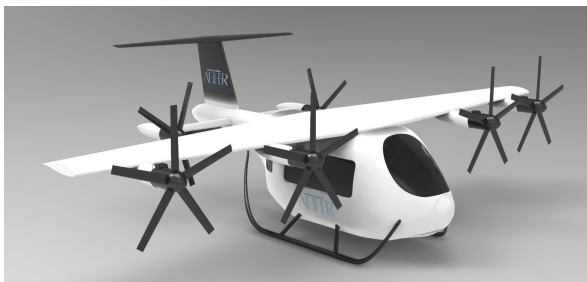


Figure 6: Render of the Aether aircraft in its cruise configuration.

Table 3: Specifications of the Aether aircraft

MTOW	2667 [kg] (5880 [lb])
Passengers + Pilot	5 passengers
Passenger mass	100 [kg] (220 [lb])
Range	161 [km] (100 [mi])
Flight Time	56 [min]
Operating Altitude	1219 [m] (4000 [ft])
Cruise Speed	49 [m/s] (161 [ft/s])
Vertical Climb Speed	0.813 [m/s] (2.667 [ft/s])
Vertical Descent Speed	0.813 [m/s] (2.667 [ft/s])
Wing Span	15 [m] (49 [ft])
Rotor Radius	1.4 [m] (4.6 [ft])
Disk Loading	73 [kg/m ²] (15 [lb/ft])
Noise	86 [dBA]
Maximum Tip Speed	182 [m/s] (597 [ft/s])
Hover Power Required	580 [kW]
Maximum Power Required	588 [kW]
Battery Mass	520 [kg] (1146 [lb])
Battery Energy Density	400 [Wh/kg] (181 [Wh/lb])
Battery Cell Type	Li-ion
Materials of Structure	CFRTP/Al-Li 2198

Passenger Experience

For the design of the Aether's cabin, safety and comfort were the key considerations. By considering the passenger needs based on all types of disabilities and the specific request for proposal (RFP), the preliminary sizing of the cabin was performed. Eight groups of people with similar needs were identified, and are listed as follows:

- Wheelchair or stretcher user
- Passenger requiring full-time assistance
- Portable oxygen concentrator user
- Limited strength passenger
- Visually impaired passenger
- Hearing impaired passenger
- Passenger with intellectual and/or hidden disabilities
- Passenger requiring a service animal

The most restrictive passenger types for the cabin sizing and design corresponded to passengers traveling in a wheelchair (since it was crucial for these passengers may have the choice of staying on their own wheelchairs throughout the whole flight experience and be as independent as possible). In this way, most of the Aether cabin parameters were based on wheelchair certifications, such as aisle width, door width and seat width and length, providing total passenger security during flight. A chair was then designed that was able to accommodate passengers without a wheelchair and passengers with a wheelchair together with the medical equipment they might carry. Several visual representations for this chair are shown in Figure 7, Figure 8 and Figure 9.



Figure 7: PRM seat extended for use of a passenger without a wheelchair.



Figure 8: PRM seat folded for use of a passenger with a wheelchair.

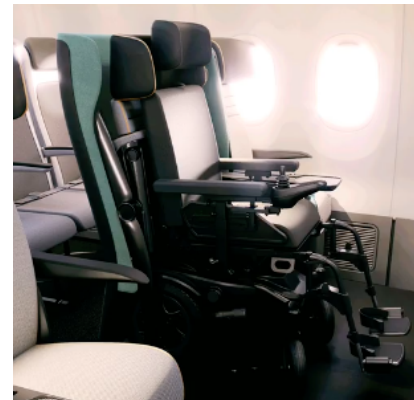


Figure 9: PRM seat folded with a wheelchair allocated.

The cabin was also designed for the passengers travelling on stretchers are for the entrance and exit of the cabin, Aether is equipped with a ramp as well as tactile paving. The height of the cabin was also designed to allow for vertical standing in all points necessary. Additionally, different luggage compartments were designed to place checked luggage as well as carry-on luggage. Figure 10 shows the top view and the front view of the cabin, and Figure 11 shows an artistic impression of the cabin interior.

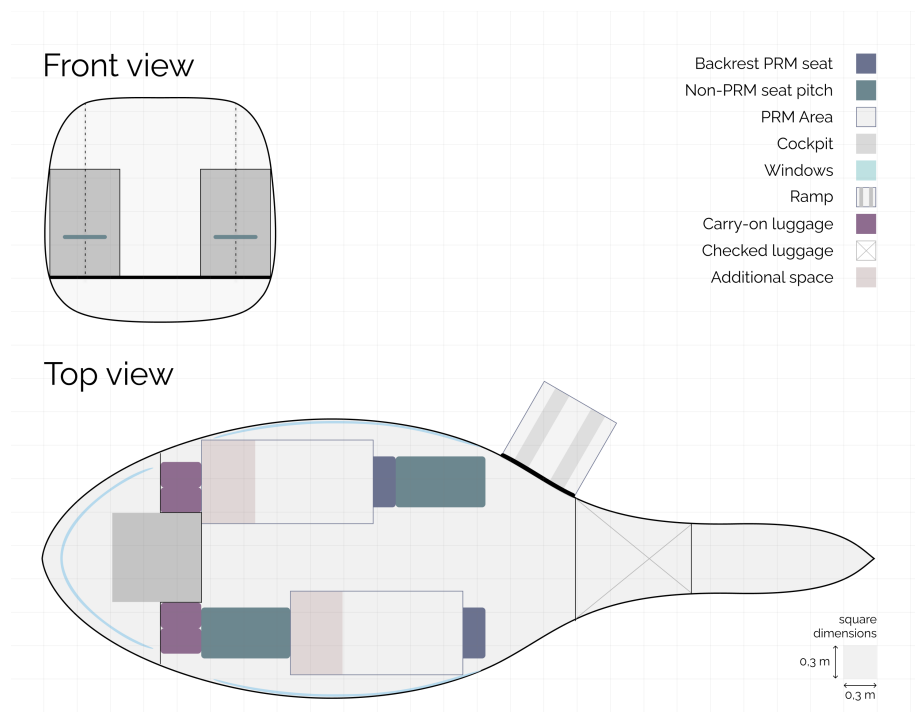


Figure 10: Scaled sketch of the front and top view of the cabin. Square dimension 0.3 x 0.3 [m] (0.98 x 0.98 [ft])

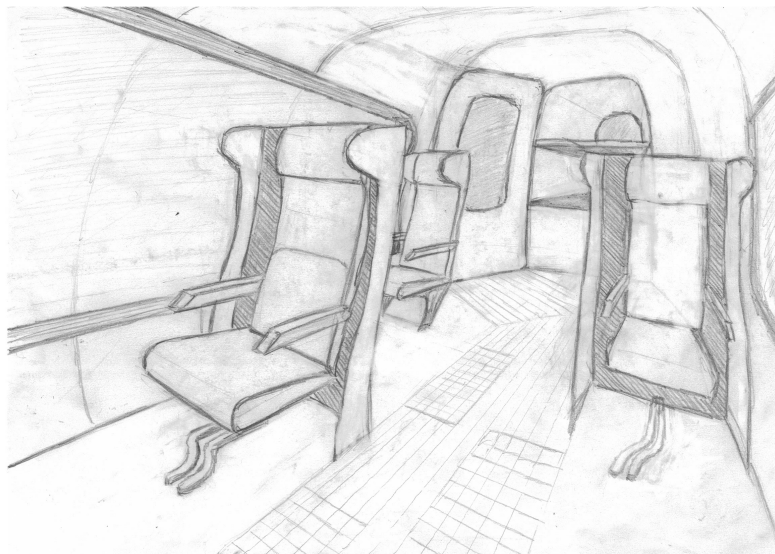


Figure 11: Artistic impression of cabin interior

Propulsion and Power

The sizing for the propulsion system and the general performance was based on the power requirements for each flight phase, i.e. vertical take-off, climb, cruise, descent, land. The wing sizing was performed for every design iteration using the optimized estimation of the MTOW (maximum takeoff weight). The sizing of the propeller was determined based on geometrical factors, namely requirement on maximum allowable design width, fuselage width and clearance between propellers and the fuselage. It was determined that the radius of the propeller is 1.384 [m]. As a result of the power required estimation, the transition phase from OGE (out-of-ground effect) hover to climb proved to be the largest power requirement. The class I and class II mass estimation, determined as a result of the propulsion system sizing, yielded a maximum takeoff weight value of 2230 [kg] and 2799 [kg], respectively. Finally, for the sizing of the propeller blades, the Clark Y airfoil was selected with a twist of -51.4 [deg], a solidity of 0.18, and 5 blades per propeller. As for the material of

the blade, the Toray BT250E-6 cure epoxy prepreg was chosen. The final analysis has shown that the propulsion system will be able to perform its prescribed mission, with the provision that the battery meets the power density requirements.

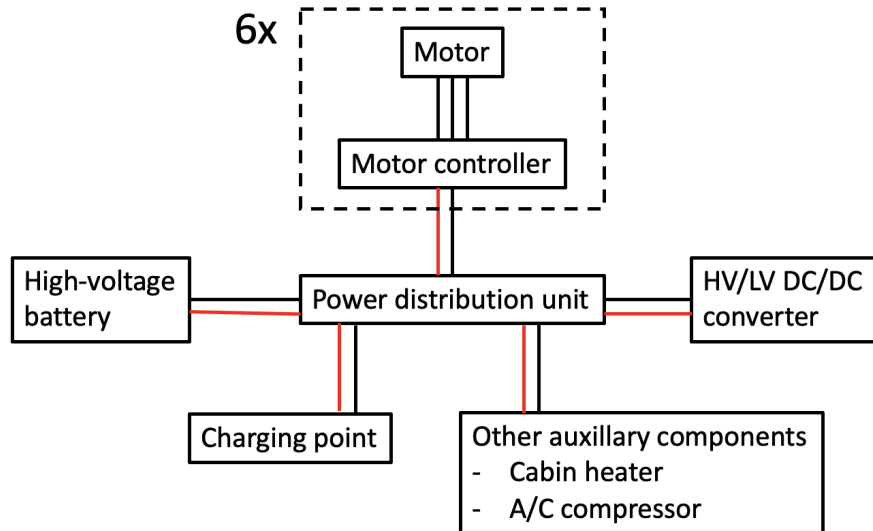


Figure 12: High-voltage bus architecture

The Aether aircraft features two different busses: a low-voltage bus at 28[VDC] and a high-voltage bus at 800[VDC]. Low power requirement components such as lights, electric control units or small actuators are connected to the low-voltage bus, and the main drive systems are connected to the high voltage bus. The high-voltage bus is shown in Figure 12. The sizing of the motor is based on the highest power required per rotor, which was calculated to be 174.43[kW]. To meet this requirement, the front motor was sized to be 104.6[mm](4.12[in] in length and 348[mm](13.7[in] in diameter, and this provides a nominal torque of 1281.23[Nm] with a maximum RPM of 1300. The rear rotors were sized to be 506.59[mm](19.94[in] in length with the same diameter as front rotors, providing a nominal torque of 1850.76[Nm] with a maximum RPM of 900. The high-voltage battery was designed based on the power requirements during the mission and the current drawn with the voltage chosen for the high-voltage bus. The battery mass is estimated to be 389[kg](858[lbs]), with a volume of 4.19[m³](148[ft³]).

Aerodynamics

A lift and drag tool based on Lifting line theory and Vortex Ring method was realized for the determination of the forces on the wing and optimization of the basic geometric features. Using inputs from Propulsion, a wing planform of 27.5 [m²] with a span of 15 [m] was determined and the NACA 63(2)-615 airfoil was selected based on maximum lift and lift-to-drag ratio at low angles of attack. Figure 13 shows an image of the wing design. The tail sizing methodology followed is similar to the one used in wing design and was later optimized for minimized span of both the horizontal and vertical tail. A T-tail configuration was chosen for accommodating further clearance between the horizontal tail and the rear rotors. The fuselage drag was analyzed to be further used by the Stability group and was found to be approximately 4 [kN]. Noise calculations were performed for the rotorcraft phases of the flight. It was determined that maximum sound pressure level (SPL) occurs during vertical climb and is 86[dBA]. The peak frequency emitted by the aircraft is 4 · 10³[Hz].

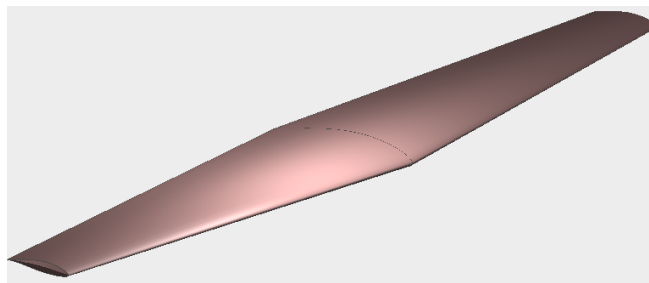


Figure 13: Wing design

Structures & Materials

The material selection of the structures as well as the sizing for the main structure of Aether was performed. These being the wing box and the structure for the support of the proprotors. The wing box is the structure in charge of carrying the loads acting in the wing during all flight phases. It is compound of two spars located in 0.2 and 0.7 of the chord connected by the skin of the wing. An analysis of the internal loads acting in this structure during cruise and hover was performed for a later detailed wing box design and sizing. For the structure supporting the proprotors, two different structures were designed. For the rear rotors, a hollow shaft was designed. Analysing the structure in bending during hover, it was found that the minimum thickness needed is of 3.2 [mm]. For the wing mounted rotors, a shaft structure which serves as rotating axis for the tilt-rotors was analysed in a three-point bending situation during hover. It was found that a minimum diameter of 3 [cm] is needed.

Stability and Control

The design for stability and control consisted of four main parts: Center of Gravity range, static stability, dynamics stability, and controller design. In the beginning of this analysis, the CG range was calculated by using the class II weight estimation method and loading calculation of payload. The results showed that the CG range was between 0.23 to 0.34 of the mean aerodynamics chord, and it is also presented as a so-called potato diagram. Then, the longitudinal static stability analysis was calculated, and the minimum required horizontal tail area was concluded to be as 19% of the main wing. Vertical tail size was decided based on empirical data, which resulted in 4.43 [m²]. Following the static stability, the dynamics stability analysis in longitudinal direction was performed. A state space model was created for a 3-degree of freedom longitudinal model with quasi-dynamic inflow model. Two flight modes were found, both low damped oscillatory modes, corresponding to phugoid and short period modes. The eigenvalues of these modes in cruise are $-0.0432 \pm 1.5327 i$ and $-0.0049 \pm 0.0119 i$ respectively. This concludes that both modes of motion are barely stable. Furthermore, a controller architecture for hovering condition was developed.

Cost

The life cycle cost of Aether has been broken down into four main phases: Research and development, production, operation, and disposal. For each phase the associated costs have been calculated. For the research and development costs, the testing phase amounts to the highest single cost and investment for the whole project due to the high certification costs. It was found that operating in the USA is desirable due to the lower direct energy costs as compared to Europe, and thus the cost analysis is made with the assumption of being located in the USA. For the production costs, a calculation of the 1st and 100th unit produced is done that incorporates the learning curve, and the disposal cost analysis found that recycling carbon fiber is responsible for the majority of the disposal cost. Table 4 summarises the total costs of each life cycle cost phase, considering that operation is located in the USA, and Figure 14 shows the breakdown of the life cycle cost for one Aether aircraft.

Table 4: Breakdown of Aether costs, which assumes operation in the USA.

Life cycle cost phase	Total cost (USD)
Research and development	51,867,062
Operation (1 year)	561,374
Production (1st unit)	4,360,827
Production (100th unit)	990,176
Disposal	5,533

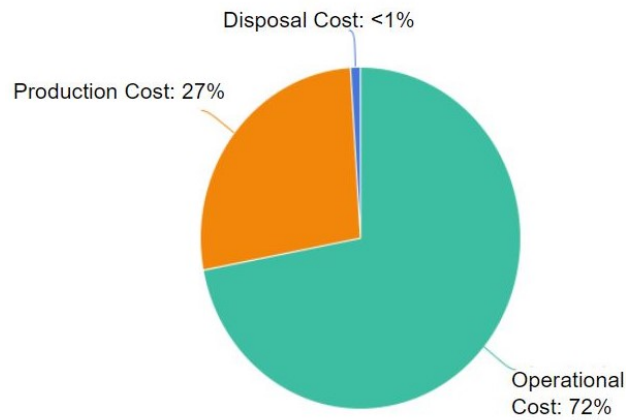


Figure 14: Life cycle cost breakdown of one Aether aircraft.

Once all the costs were calculated, the ticket prices could be computed. Including the reduction of production cost due to the learning curve, the maximum ticket price for a break even point of 10 years totaled 146 \$ for the 1st unit and 115 \$ for the 100th unit. This translates to a cost per mile of 1.46 \$ and 1.15 \$ for the 1st and 100th unit, respectively.

Operations and Logistics

An outline of the operations and logistics are presented to show how the aircraft will be used and interacts with the passengers in real-life application. An insight into the use case shows that sizing the scale of operations within a service area requires an assessment into multiple aspects such as the number and location of vertiports, the possible range of service according to possible risks of operation over certain locations, and expected number of service according to needs and acceptance of the public on novel vehicles. Figure 15 shows the range of possible flights for operation based in Amsterdam Schiphol Airport.



Figure 15: Mission range mapped for operations in the Netherlands

An outline of the necessary infrastructure is also presented, and this evaluates the necessary functions of every vertiport as well as the central vertiport of a service area. Figure 16 shows an artist impression of the boarding process at a vertiport. Maintenance and air traffic management are also necessary infrastructures for the operation and the basic operation of these facilities are also elaborated. An evaluation of the operation procedures show the basic flow of service for the passengers, and it outlines the customer interface, the pre-flight operations, the in-flight operations, the post-

flight operations and the emergency procedures. Finally, the battery recharging system and the vehicle maintenance is briefly described to conclude this chapter.



Figure 16: Design render of the boarding process at a vertiport.

Sustainable Development Strategy

A major objective of Aether is to be competitive in the eVTOL market while simultaneously staying sustainable to the environment and community. In terms of the environmental sustainability, the noise levels are acceptable for use in the city and in vicinity of animals, and the disposal of the aircraft will be carried in the most sustainable way possible by reusing or recycling as much of the aircraft as possible. For the economic advancements in the community, Aether will provide numerous jobs at the headquarters and at vertiports, and will allow people to improve by providing jobs in the tertiary sector. Furthermore the reduction of road traffic will significantly reduce costs for the road traffic management, while also reducing emissions from the decrease use of automotive vehicles. Finally, Aether will increase the accessibility and ease of access of social activities and work opportunities for many people, and consequently increase the happiness index of the community. Reduction in traffic will also reduce anxiety and stress level which will also create a happier and safer community.

Final Remarks

The Aether aircraft is designed to serve the mission need statement to "Sustainably and securely transport passengers with reduced mobility from point A to point B through air." According to the research conclusions of this report, an aircraft similar in the design of this report would only be feasible with batteries of energy density of 400 [Wh/kg]. In terms of cabin design, considering all passenger needs found from the market analysis, a comforting and accessible cabin has been designed for, so that people with disabilities of all types are able to use the aircraft safely. Control and stability issues have been addressed, as Aether has been designed so that any single failure of the motors or electrical system would have minimal consequences on the mission. Also, analyses show that the aircraft is stable when on ground and in flight, with a controller architecture ensuring easy control of the aircraft for pilot. Finally, affordability wise, the Aether aircraft has been found to be most affordable and convenient when used for intracity rather than intercity travel, providing a faster and cheaper travel when compared to current transportation means. Choosing the right location of operations of maximum demand, (such as inter-island travel, for example) is crucial for the design to succeed and profits to be maximised by filling the market gap, while at the same time providing high class air travel quality to the under served disabled passengers around the globe.



Figure 17: *Design render of the Aether aircraft flying over Rotterdam city.*

Limitations and Recommendations

Finally, going into preliminary and detailed design phases would require significantly more detailed analysis of all the subsystems and their integration with each other. It is expected that with the use of advanced softwares and analysis tools, that the design would become more refined and part of the subsystems would change. Mockups of the cabin would be highly beneficial to find out how the passenger experience could be further improved such that as many people with reduced mobility would have the ability to fly comfortably with the aircraft. Furthermore, a more detailed analysis of the cost will be necessary, as the preliminary methods used related to old aircraft data regressions.

A large section of the requirements from the FAA which was not analysed in the report relates to ditching and emergency procedures of the aircraft. In the initial conceptual design brainstorm, an inflatable raft attached in the inside of the undercarriage was proposed to be incorporated into the design. However, due to the limited time frame of this project, this design option was not analysed and sized for, and thus it is recommended that an appropriate raft is chosen and that enough space is made in the undercarriage to accommodate the raft. For emergency landings, an extensive analysis would have to be made on the landing stability of the aircraft in the event that the aircraft must land on rocky or uneven terrain. Furthermore, a lot of smaller FAA regulations were not considered due to the conceptual nature of the design. It is recommended that if the design were to continue to the preliminary and detailed design phase, a revision of the requirements would have to be made such that all regulations from the FAA are adhered to.