SMALL AIRCRAFT CONCEPT FOR REGIONAL ON-DEMAND AIR MOBILITY

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Abstract

At the RWTH Aachen University in cooperation with the University of Applied Sciences Aachen the "Silent Air Taxi", a small aircraft for on-demand air mobility (ODAM) service for 4 passengers plus pilot, is developed up to Technology Readiness Level (TRL) 9. Based on preliminary requirements analysis, design studies have been performed with the aircraft design code MICADO. Hybrid electric propulsion provides a viable option for an air taxi with 500 km range. At speeds ≤ 300 km/h distributed propulsion did not show benefits. Pilot onboard is initially foreseen, but automation level allowing zero onboard-pilot is required to close business case for operators.

1 Introduction

The third spatial dimension is rarely used for regional transport of passengers (PAX) and cargo for travel distances below 500 km. In most cases such ranges are covered with ground-based transportation modes. Construction and maintenance of related road and rail infrastructure is costly, furthermore, it requires large land resources. The extension of road and rail networks are dependent on the intended service quality. However, for Germany for example the service quality in terms of door-to-door travel speed is already rated "very good" for the vast majority of travel routes (corresponding categories: Road: >75 km/h$|_{200km}$, >91 km/h$|_{500km}$; Rail: >60,5 km/h$|_{200km}$, >86,5 km/h$|_{500km}$) [1] and thus, only local improvement is foreseen.

In Germany, current scheduled regional air transport in many cases does not deliver a time advantage over the ground-based competitors. Taking the visionary goal of 4 h door-to-door travel time for journeys all over Europe to be reached by 90% of all travelers as stated in the "Flightpath 2050" document [2] it becomes clear that there is a substantial transportation gap, as the goal of 4h travel time cannot be met even for many routes within the borders of Germany. A solution could be a service with small air vehicles either for thin haul traffic if demand is appropriate or for individual on-demand air mobility (ODAM).

1.1 ODAM Research

At least since the trilogy of papers by Moore [3, 4, 5] the concept of small air vehicles for personal and on-demand transport is back on the common research agenda. Catalyst for the renewed interest are developments in the field of:

- Automation: smart systems will increase safety and eventually contribute to close the business case for air taxi operators by omission of pilots on board (first in an intermediate step for relocation/ferry flights),
- Electric mobility: adoption of momentum from automobile industry and benefit from related technology streams are feasible,
- Aircraft certification policy: respective working groups are established to prepare recommendations for either creating a new class for ODAM vehicles taking into account smart system architectures or adopting possible Unmanned Aerial Systems approach (certification for specific missions based on specific operations risk assessment), thereby reducing market entrance barriers for new competitors while maintaining safety level,

- Air Traffic Management: implementation of NextGen & SESAR, encrypted navigation services (e.g. Galileo PRS) and weather nowcasting is ongoing, providing required high continuity, safety/security and capacity/scalability for future air transport system incorporating ODAM operation.

Comprehensive transportation concepts for regional [6] as well as urban [7] ODAM have been published. As propulsive efficiency of air vehicles will always be inferior to ground-based vehicles, this disadvantage has to be made up by direct routing and added value to the customer like increased travel speed, choice of travel time, convenience, etc. Following an analysis by Cohen [8] the pursuit of sustainable development is one of many contemporary political goals but the realization of ODAM services will be likewise triggered by rival societal aspirations, i.e. the afore mentioned added values such as increased travel speed and convenience. Forecasts of ODAM market demand usually assume the passenger to decide like a homo economicus, which leads to conservative estimates since decisions concerning mobility often are not based on pure ratio (cf. individual, privately owned cars). Consumer preferences for ODAM service have been investigated in detail, e.g. by Lewe et al. [9] and Kreimeier et al. [10]. For application of ODAM service to Germany Kreimeier [11] investigated current technology options, proved concept viability and derived a comprehensive set of related Top Level Aircraft Requirements (TLARs).
Within a wide range electric motors can be scaled maintaining constant efficiency level. This fact, together with the goal of simple high lift devices for GA aircraft led to the development of dedicated distributed electric propulsion (DEP) concepts. DEP here serves as active high-lift system (therefore often called high-lift propeller) leading to achievable lift coefficients c_L beyond 5. This allows to reduce wing area and with it aerodynamic performance as well as ride quality can be improved. NASA is following this pathway with the X-57 Maxwell technology demonstrator [12].

1.2 ODAM Development Projects

A multitude of current projects deal with short-range air transport below 100 km, mainly for urban air mobility. Review articles summarizing the current status have been written by Liu et al. [13] and Shamiyeh et al. [14]. However, focus of this paper is regional air transport, thus, ranges between 100 km < R < 1000 km.
Most prominent current project for regional transport is the Lilium five-seater concept [15] aiming for an all-electric regional transport up to 300 km range at a cruise speed of 300 km/h in combination with vertical take-off and landing (VTOL) capability. VTOL will be realized with rotatable small electric fans distributed along the trailing edge of the main wing and rotatable fans at the canard (status: May 2018). VTOL capability requires a thrust-to-weight ratio beyond 1.2. Compared to thrust-to-weight ratios of below 0.4 of classical fixed wing aircraft (without VTOL) this shows that VTOL necessitates installation of extremely large engines and power supply systems, hence, it causes a weight penalty. Due to the complex transition from hover to forward flight and vice versa, Lilium will equip the vehicle with a substantial degree of automation. However, a pilot onboard is foreseen for the time being. While the very small diameter of the installed ducted fans is detrimental with regards to efficiency, the corresponding high rpm-level together with a large blade count might produce noise at high frequencies that dissipate rapidly in the atmosphere and that are close to the susceptibility limits of the human ear.
Eviation is developing an all-electric air taxi with a cruise speed of above 440 km/h [16]. The chosen configuration is unconventional, i.e. a propeller in pusher configuration is mounted at each wing tip counteracting the wing tip vortices and thereby reducing induced drag, whereas a third propeller is mounted on the rear end of the fuselage for propulsion and at the same time filling the wake of the fuselage. In case of outer engine failure, both outer engines are shut-down and the central engine provides minimal climb ratio. Pusher propellers in general have issues with high noise levels. The fuselage is designed to produce extra lift. With two pilots and nine

PAX onboard, classical batteries to power the electric motors and a design range above 1000 km, the battery weight alone will be around 3.5 tons. Any all-electric concept, either based on batteries or fuel cells, has to cope with substantial extra weight. Following an investigation of Roland Berger [17] an entry level of battery capacity required for turning batteries into a viable option for (small vehicle) air transport is 500 Wh/kg. Batteries have to be safe, technical workarounds to cope e.g. with thermal runaway as done in Boeing 787 are not acceptable for (hybrid-)electric ODAM.

Zunum Aero works on a more classical business jet type configuration with series hybrid electric propulsion for on-demand charter operation for up to 12 PAX [18]. With rear mounted ducted fans the vehicle reaches a cruise speed of 540 km/h and a range of around 1300 km. Noteworthy is the announced target of $250 hourly operating cost including fuel, electricity, and batteries. This would be equivalent to 8 cents per available seat mile (ASM). This is an exceptional low value as existing ODAM services, usually operating GA aircraft like e.g. Diamond DA42, rather run with operating cost of $1 per ASM or higher.

At RWTH Aachen University in cooperation with the University of Applied Sciences Aachen a regional air taxi is developed, cruising at 250-300 km/h [19]. The concept is planned to be brought to TRL 9, envisioned entry into service of the “Silent Air Taxi” is 2024. With 4 PAX a range of 500 km can be reached in hybrid-electric mode, with 2 PAX onboard the range increases to 1200 km. Due to current regulations the vehicle is designed to initially carry a pilot. However, it is equipped with a high level of automation, such that in the medium term safety pilots on the ground will take over control of the fleet of Silent Air Taxis if needed. The Silent Air Taxi has a short take-off and landing capability. Aiming for regional transport ranges, the capability for vertical take-off and landing is omitted due to efficiency considerations. Beyond 2030, in order to substantially decrease the door-to-door travel time, the Silent Air Taxi will be qualified for take-off and landing on ground based support systems, e.g. as developed in the GABRIEL project or GroLaS [20, 21]. This enables the Silent Air Taxi to operate from rooftops of large buildings with a minimum length of 150 m, such as train stations or malls. The Silent Air Taxi configuration will maintain a landing gear in order to allow for operation both from standard airfields and ground based support systems. A spacious cabin in combination with a lifting body concept satisfies expectations from business travelers and senior PAX alike. The ducted fans together with an optimized sound quality will enable 24/7 operation. Ticket prices will be similar to a 1st class train ride.

This paper deals with preliminary design work for the Silent Air Taxi. In Chapter 2 the requirements analysis done for the Silent Air Taxi will be described, Chapter 3 highlights specific aspects of the preliminary design and Chapter 4 discusses factors affecting the concept of operation.

2 Top Level Aircraft Requirements Analysis

Before 2030 the Silent Air Taxi is planned to operate from airfields. Thus, the proximity of airfields is crucial for the customer. A survey of suitable airfields in Europe (small and medium airfields only) revealed that 1774 (equal to 83.9 %) ICAO-code airfields have a runway length of 600 m or more, see Figure 1. The average distance from city center to the airfield for Europe (16937 cities in database) is 37.8 km. Doing the analysis for Central Europe only (6312 cities) shows an average distance of 19.2 km.

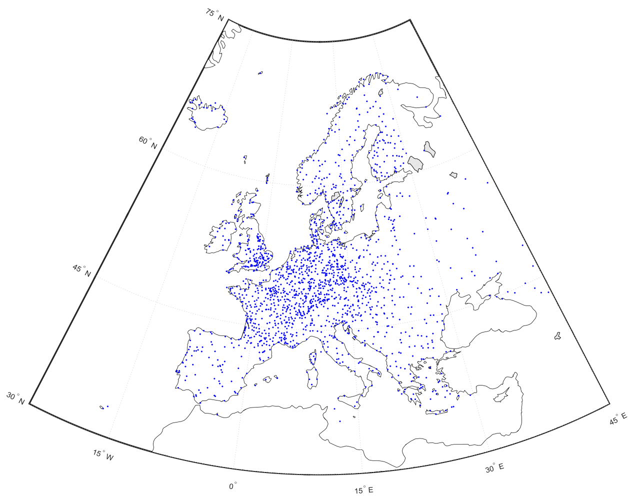

Figure 1: European ICAO-code airfields with runway length ≥ 600m

Counting the airfields with runway lengths ≥ 1000 m leads to 1042 (equal to 49.3 %), see Figure 2. The average distance from city center to airfield increases to 45.6 km for whole Europe and amounts to 29.9 km if accounting for Central Europe only.

As runway length is influencing to a large degree the aircraft design with respect to installed thrust and high-lift devices, it is important to analyze to which degree the parameter “distance to the airfield” is a good proxy for travel convenience and overall travel time. Thus, additional research has been performed for investigating passenger preference, solely based on travel time (without consideration of capacity constraints) [22].

It turns out that the success of an ODAM transportation option is highly dependent on individual airfield access and transport choice. Instead of the Silent Air Taxi, passengers residing in London or Paris will more likely use train connections, whereas more than 75 % of passengers from e.g. Birmingham, Lisbon, Bucharest or Katowice would opt for the air taxi when considering journeys with distances of 100-500 km due to poor public transport and road connections.

Surprisingly, despite other good transport choices, for the German cities Berlin, Frankfurt, Hamburg and Stuttgart the air taxi would still gain a transport share of ca. 50 % on average on distances of 100-500 km, if travel time is exclusive criterion. For details see [22].

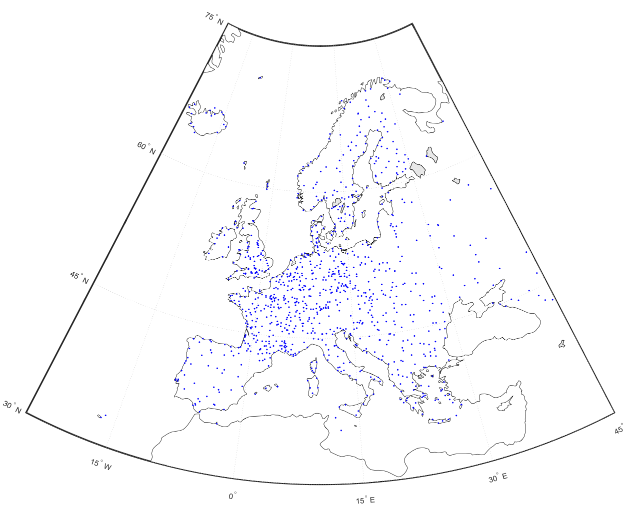

Figure 2: European ICAO-code airfields with runway length ≥ 1000 m

The cited investigations show for Germany [11] and Europe [22] that the travel option “Air Taxi” is scarcely chosen for distances beyond 500 km.

For Germany a respective little sensitivity with regard to travel speed is identified within the given range feasible for ODAM, see Figure 3.

Analyzing the sensitivity with respect to service provision costs it is, as expected, found to be far more pronounced. Assumed reference costs for cars are 0.3 €/km. Results for four different ODAM service costs ranging from 0.2-0.5 €/km (per traveler) are compared in Figure 4. Increasing the costs by 25 % from 0.4 €/km to 0.5 €/km lowers the ODAM market share from 19 % to 2 %. This low number of 2 % is still equivalent to 23 million trips per year and a detailed analysis of the distribution reveals that this means that there are 1,600 connections in Germany with more than five passengers per day.

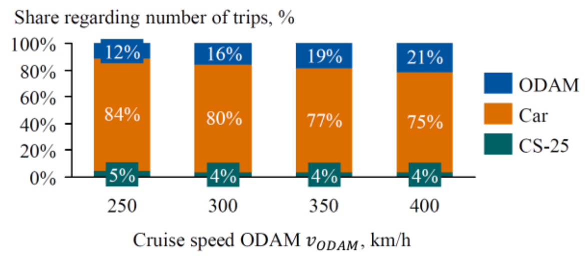

Figure 3: Market shares regarding number of trips for different ODAM aircraft cruise speeds [10]

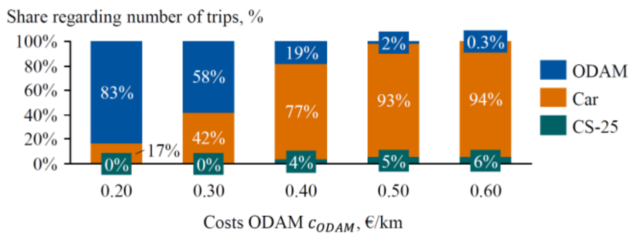

Figure 4: Market shares regarding number of trips for different ODAM costs [10]

In conclusion, the Silent Air Taxi concept should provide a range of 500 km @ maximum take-off mass. In the ramp up phase, a payload capacity of 4 PAX per vehicle seems sufficient. In terms of operating costs ODAM service should be less than 0.2 €/km above those for using an automobile. Following the economy of scale, later decreasing ODAM costs might render larger payload capacities reasonable. Design cruise speed should best be chosen around 300 km/h. However, even though the drop in market share from $16\,\%|_{300km/h}$ to $12\,\%|_{250km/h}$ is substantial, cruise speed should be traded against installed thrust and operating costs as lowering cruise speed might overly increase profitability of the concept. Similar, no required take-off length should be explicitly fixed beforehand but traded during optimization: the analysis shows a substantial drop of available coverage of airfields from $83\,\%|_{600m\ rwy\ length}$ to $68\,\%|_{800m\ rwy\ length}$ and down to $49\,\%|_{1000m\ rwy\ length}$. However, these average numbers oversimplify the situation as they assume constant travel speed from city center to airfield. Furthermore, the individual travel choices by far dominate passenger preference in the end and thus, within the design process sensitivity with regards to runway length may turn out to be of lower importance if compared with potential efficiency gains due to less installed thrust or less sophisticated high lift devices.

3 Vehicle Concept

The aircraft design code MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimization) [23] has been developed at the Institute of Aerospace Systems (ILR) of RWTH Aachen University. On behalf of Airbus it has been used to set up the Central Reference Aircraft Database (CeRAS, http://ceras.ilr.rwth-aachen.de/) [24] providing a verified and consistent open source documentation of a conceptual design of a short-range aircraft similar to an Airbus A320. The general flowchart of MICADO is shown in Figure 5.
Recently MICADO has be extended for design of CS-23 configurations by Kreimeier, see [11] for details. The CS-23 design logic and several underlying formulae are taken from the textbook by Gudmundsson [25]. In addition, Kreimeier implemented modules for all-electric and hybrid electric propulsion systems as well as for

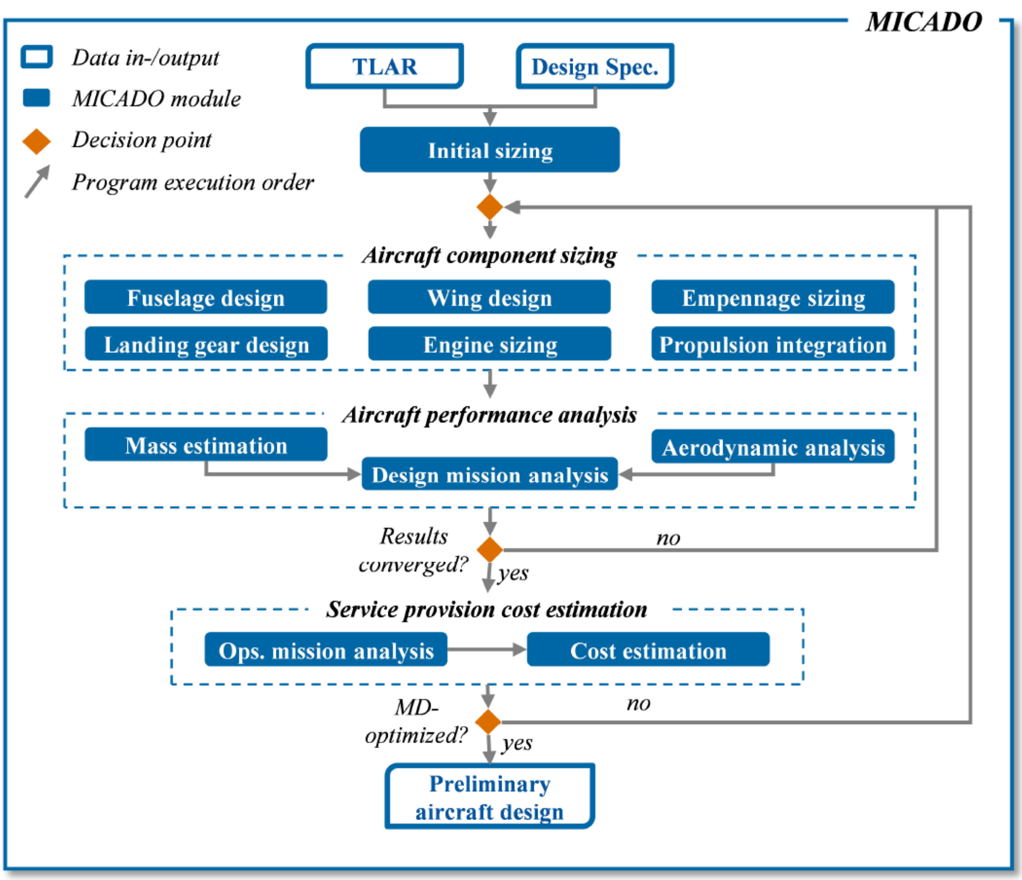

Figure 5: MICADO Flowchart [11]

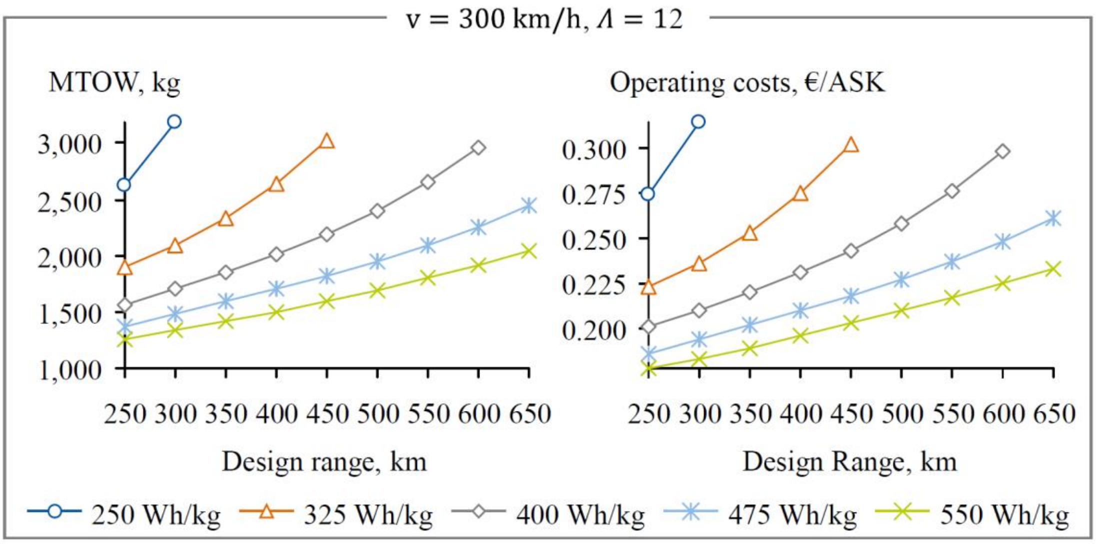

Figure 6: Sensitivity study with respect to Battery Gravimetric Energy Density [11]

assessing distributed electric propulsion concepts, resp. distributed high-lift propellers (HLP).

3.1 All-electric Design Studies

Advantage of electric propulsion in aviation is, in addition to emission-free operation, higher overall efficiency level and higher meantime between overhaul for the propulsion system, a potentially lower noise level. The electric motor in any case emits less noise than a conventional internal combustion engine, however, dependent on installed thrust level (potentially chosen at lower end in order to reduce battery weight) the climb ratio might be low. This can, despite electric propulsion, result in increased noise immission on the ground, e.g. see [26]. Furthermore, the propeller needs to be specifically designed.

Incorporation of electric power as "plug-in" without capitalizing on design options provided by electric systems leads to increased primary energy consumption (sum of electric energy from batteries and chemical energy of fuel for range extender) compared to classical architectures solely based on internal combustion engines. Battery technology at present is the limiting factor for application of electric mobility to aviation. Equipping a conventional GA-type aircraft, similar to a Cirrus SR-22 (cruise speed: 300 km/h, aspect ratio: 12), with all-electric propulsion (single front propeller) leads to a wide spread of achievable ranges and operating costs depending on assumed gravimetric energy density level, see Figure 6. Details are found in [11]. A technology level of 250 Wh/kg would result in a maximum range of 300 km and a take-off mass beyond 3,000 kg. Similar to the hypothesis of Roland Berger [17] a value of 400-500 Wh/kg represents a reasonable lower threshold for viable battery usage. The same can be seen when analyzing operating costs.

A sensitivity study with respect to cruise speed has been performed, assuming available battery technology with 400 Wh/kg and optimizing for lowest maximum take-off mass (which leads to different optimized wing aspect ratios). In Figure 7, the resulting maximum take-off masses and operating costs as function of design range are plotted. Cruise speeds beyond 300 km/h lead to significant weight gain and are therefore not reasonable as additional benefits due to shorter travel times do not overcompensate higher operating costs, as shown in [11]. Nonetheless, cruise speeds between 250-300 km/h would still deliver a substantial advantage over ground-based transportation modes (but original SR-22 cruise speed: 335 km/h @ 75% power).

Capitalizing on electric power would be enhanced if HLP are installed. HLP are high-lift propellers distributed along the wing leading edge that produce super circulation and reach a

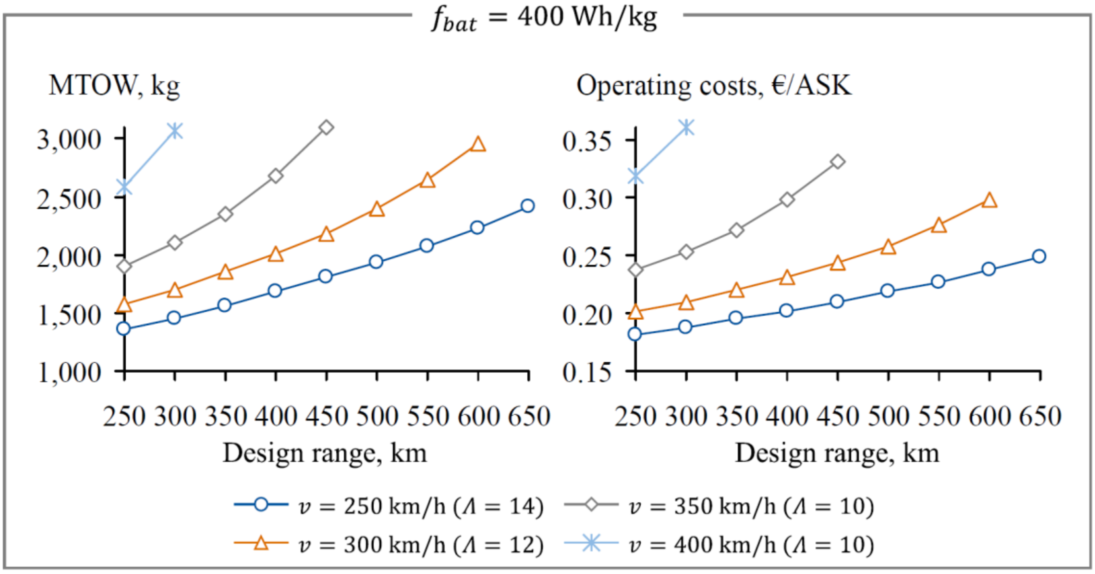

Figure 7: Sensitivity Study with respect to Design Speed [11]

$c_L \geq 5$ during take-off and landing if needed. This opens the door for better aerodynamic performance and ride quality by increased aspect ratio and wing loading. In cruise flight the HLP are folded back into the motor cowling producing a minimum (but non-zero) extra drag.

A sensitivity study has been done for a high wing airplane geometry similar to the NASA X-57, but scaled to match the TLARs of the electric GA-type aircraft used before. See [11] for details. The parameters "maximum lift coefficient" and "number of HLP motors" have been varied. The results are shown in Figure 8. Substantial advantages by incorporation of HLP can be obtained in high cruise speed regimes beyond 300 km/h. At 300 km/h and 250 km/h the benefit reached by HLP is negligible. This is true both in terms of maximum take-off mass of the vehicle and operating costs. It has to be noted that the calculation even represents an optimistic result as it did not incorporate the extra drag stemming from generated vortices on both sides of the cowlings (vortex generation is a function of angle of attack and planform discontinuity).

3.2 Hybrid-electric Design Studies

With current battery technology no reasonable all-electric regional (ranges up to 500 km) ODAM service can be achieved. A classical internal combustion engine has to be installed as range extender until either fuel cells provide an option to replace the combustion engine or battery technology has reached sufficient capability to switch to all-electric propulsion.

Even though offering weight benefits, in most cases a parallel hybrid architecture cannot be realized as electric motors usually are installed outside the fuselage and the combustion engine is placed inside the fuselage. Such set-up calls for a series hybrid architecture.

The hybridization degree states the amount of used energy for flight originating from batteries. In order to analyze the effect of hybridization degree a sensitivity study has been done for the low-wing GA configuration used before with a series hybrid electric propulsion architecture (Concept SH-A). Assuming a cruise speed of 250 km/h and wing aspect ratio of 14 the hybridization degree is varied from 20 % battery contribution at controller input to 50 %.

Low hybridization degrees in combination with small ranges lead to unreasonable high battery power discharge. Here, solutions with battery discharge above 3C are excluded. Figure 9 shows the results with regard to maximum take-off mass and operating costs as a function of design range. In general, to date best economics is achieved by opting for lowest hybridization degree possible. In this case, the battery essentially serves to buffer peak performance only.

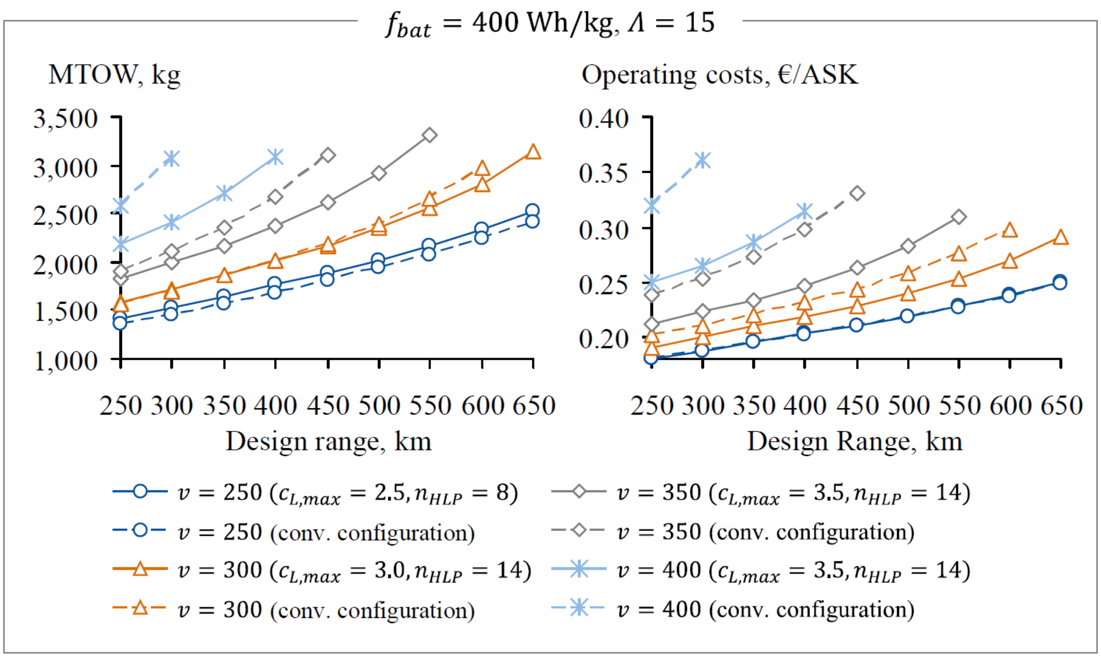

Figure 8: Sensitivity Study with respect to Design Speed & High Lift Propeller Layout [11]

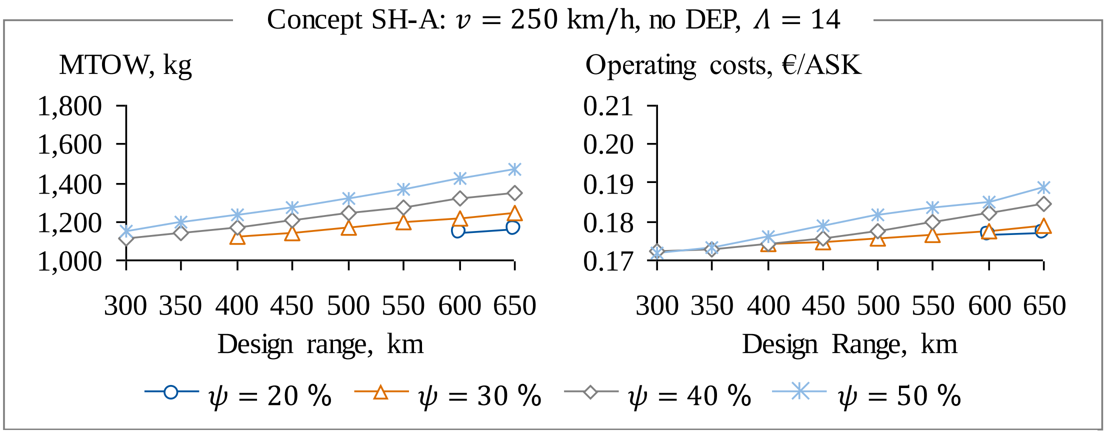

Figure 9: Sensitivity Study with respect to Hybridization Degree [11]

3.3 Lifting-Body Fuselage

Spacious cabins as planned for the Lilium Jet, Equator P2 or Silent Air Taxi require comparably large fuselage volumes. This gives the possibility to design the fuselage as lifting body and in return to reduce the wing area.

In the case of Lilium the initial design did not exhibit canard wings and thus, had to guarantee sufficient stability and control by shaping the fuselage geometry appropriately.

The lift carry-over effect furthermore helps improving lift distribution for reduced induced drag. However, a lifting body fuselage on a small aircraft configuration with standard wings usually increases the wetted surface area (in contrast to Blended Wing Body aircraft where a reduction of up to 1/3 of wetted surface area is achievable compared to a tube-and-wing configuration). Thus, the increased friction drag has to be overcompensated.

By applying an appropriate airfoil shape to the Silent Air Taxi fuselage and a rather rectangular planform a lift-to-drag ratio of 3.5 can be achieved with the fuselage only. However, fuselage drag is increased by 21 % compared to an axis symmetric fuselage shape (which in turn delivers a lift-to-drag ratio of around 1). Thus, decision for a lifting body concept is not straightforward but a result of overall optimization.

4 Concept of Operation

Once certification is settled, the huge potential market of ODAM services will drag non-aviation companies into the business (to date only Uber as prospective operator is promoting urban air transport [7]). However, in order to secure initial production rates the group of GA aircraft owners has to be acquired as early adopters. As well a Silent Air Taxi cargo version is envisioned.

For closing the air taxi service business case it is essential to eventually omit the pilot on board. For the time being such zero-onboard-pilot operation does not meet approval by the authorities and the public alike. During ramp up phase of operation this is not necessarily detrimental as pilots would take over the duty of assisting and instructing the passengers during boarding and deboarding until the volume of traffic reaches the required level to place dedicated personnel at the ground stations.

Since the Silent Air Taxi will not be equipped with a pressurized cabin cruising altitude will be limited to Flight Level 100. Weather nowcasting will enable the vehicle to circumvent weather phenomena compromising ride quality. Enabling enroute abort sequences for the case of zero-onboard-pilot operation is currently being investigated, be it caused by system degradation or triggered by any passenger on board.

When operating under IFR conditions and using piston engines, a twin-engine layout is required for certification for commercial passenger transport. In any case the hybrid architecture of the Silent Air Taxi guarantees a high level of redundancy. Dispatch reliability and availability of the Silent Air Taxi will not reach CS-25 standards, but must be substantially ahead of current GA operation in order to meet customer's expectations and render air taxi service into a viable transport choice.

Until the Silent Air Taxi is qualified for take-off and landing on ground-based support equipment in urban areas and such infrastructure is installed, the minimization of travel time with ground transportation to access the airfield and after touchdown to reach the final destination is crucial. Door-to-door travel speed ≥ 150 km/h for regional ODAM is seen as reasonable threshold in the case of Germany.

5 Conclusion

The following conclusions can be drawn from the investigations:

- A substantial transportation gap exists for travel distances from 100-500 km, justifying a regional ODAM travel option,
- Door-to-door travel speed and convenience are drivers for regional ODAM service,
- Vertical take-off and landing capability compromises vehicle performance and is given low priority for regional ODAM,
- Initial regional ODAM cruise speed should be above 250 km/h and payload capacity around 4 PAX without baggage (potential baggage/cargo would substitute PAX),
- Travel should be less than 0.2 €/km per traveler more expensive than the alternative travel option by car,
- Incorporation of electric power as "plug-in" without capitalizing on design options provided by electric systems leads to increased primary energy consumption,
- To date all-electric ODAM does not provide a viable option for regional transport,
- High-lift propellers provide substantial weight and cost benefits only at cruise speeds ≥ 350 km/h,
- Hybrid electric configurations (battery power plus internal combustion engine) provide viable option for regional ODAM,
- Low hybridization degree that only serves to buffer peak performance is preferential,
- Multi criteria decision making in preliminary aircraft design for regional ODAM should incorporate noise and comfort evaluation and maintenance and operation concepts,
- Lifting-body fuselage is not self-evident,
- Omission of pilot on board is necessary to eventually close the business case for air taxi operators,
- Progress in automation level, airspace integration and secure navigation/nowcasting provision are prerequisite for ODAM service,
- Decisions concerning certification requirements for ODAM vehicles and ODAM operation need to be taken in order to accordingly optimize ODAM configurations and to trigger ramp up of ODAM service.

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