Economically driven requirements for a hybrid-electric 19-passenger commuter aircraft

G Schuh¹, M Spangenberg² and Q Zhang³

¹ Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, 52074, Germany
² Air s.Pace GmbH, Wuersele, 52146, Germany
³ Rolls-Royce Deutschland Ltd. & Co. KG, Munich, Germany

Abstract. The appeal of reduced travel and transport times and electrification of aircraft drive the development of new aircraft for short distances. The goal of the CleanSky2 project ELICA (ELectric Innovative Commuter Aircraft) is to provide a preliminary design of a hybrid-electric 19-passenger commuter aircraft, whereby the passenger limit is defined by certification. This paper describes the initial set of Top Level Aircraft Requirements (TLARs) based on both a benchmark with existing 19-passenger commuter aircraft and the analysis of requirements derived from potential future markets Regional Air Mobility (RAM) and thin-haul air cargo services. Both of these are introduced briefly. A literature-based framework for TLARs and an analysis of existing airfield infrastructure in Europe and the US together with population data in the direct surroundings of such airfields are investigated. Additionally, insights on cabin design are discussed and important features such as noise emissions and operational cost of such aircraft are highlighted.

1. Introduction and objectives
The aviation industry is changing with rapid pace. Due to continuous globalisation and a growing wealth and world population that lives more connected than ever, air traffic is projected to double in the next 20 years – not considering the effects of the Covid19-pandemic [1]. However, CO₂-emissions need to be reduced significantly to achieve at least carbon-neutral growth of emissions created by aviation [2]. One solution could be the introduction of electric propulsion technology into commercial aviation. Due to the constraints of current energy storage technology, the market penetration of electric airplanes will likely start by the sub-regional class of aircraft. Only a successful market entry of such new regional aircraft can demonstrate the emission reduction, drive the technology maturation, and show the up-scaling potential of the technology into the larger scale commercial aviation, as recently supported by Airbus [3]. Due to this reason, beside the ecological advantages, the new aircraft must be economically competitive with existing aircraft. This challenge is analysed in this paper and translated to an initial set of technical requirements within this paper.

First, new future markets RAM and thin-haul air cargo services are described briefly. Second, a framework for TLARs is suggested and completed by conducting a technical benchmark in section 4 and an analysis of relevant market features in section 5. Results and a conclusion are given in the end.

2. New market opportunities
According to GRIMME et al. [4] who provide data for the global civil 19-passenger aircraft fleet derived from Cirium Fleets Analyzer [5], the market penetration reached its maximum in the early 1990s with
more than 3,200 aircraft operational servicing thin-haul routes for passengers or freight and military applications. Since then, a strong decline set in, diminishing slightly from 2010 onwards and leading to a current fleet size of about 2,300 aircraft and a CAGR of -1.4 %. The authors explain this decline with the rise of low-cost carriers and high-speed rail connections that offer faster and less expensive travel services. About two thirds of the (civil) missions performed by 19-passerenger commuter aircraft are dedicated to passenger transport and only 14 % to air cargo. Other important application fields are parachuting services, business aviation or air taxi.

Besides the established application areas for 19-passerenger commuter aircraft, at least two new business segments can be identified which shall be presented in the following: Regional air mobility (RAM) and thin-haul air cargo services.

2.1. Regional air mobility
According to the goals of ‘Flightpath 2050’, formulated by the European Commission [6], ‘90 % of travellers within Europe are able to complete their journey, door-to-door within 4 hours’. HOFMANN et al. [7] derive from this goal a growing demand for commuter aircraft to serve regional airports. This assumption is underlined by further scholars, such as SUN et al. [8], who analyse the market for more individual air transport within Europe. They estimate the door-to-door travel time for 100 large European cities to the rest of Europe, by comparing travel times of car, train, CS-25 (long distance) aircraft and air taxi services. The latter is defined as the transport of small groups of people using aircraft and airfields or regional airports and is therefore (partly) in line with the goals of ELICA. Their main result is that the car dominates short distances (< 100 km) and CS-25 aircraft long distances (> 500 km). The attractiveness of train connections of course heavily depends on the existing infrastructure. Air taxi services or RAM is the preferred mode of transport for distances averaging between 100 and 420 km. KREIMEIER [9] analysed RAM or On-Demand Air Mobility (ODAM) for Germany and derived a demand of more than 40,000 air taxis. Most trips shall have a length between 100 to 400 km. It has to be highlighted that Kreimeier has analysed the German market for a four-passerenger aircraft and also found out that the demand itself is quite cost sensitive. ELICA will have a larger passenger capacity and will therefore focus on more frequented routes than the air taxi services introduced by Sun and Kreimeier. Therefore, the market for ELICA can be understood as part of the air taxi markets introduced before.

Besides academia, also private companies are investing in the RAM-market. For example, e.SAT GmbH [10] from Aachen, Germany, that is currently developing the Silent Air Taxi (SAT), a small, piloted four-passenger aircraft with a high level of flight comfort and a hybrid-electric powertrain. SAT is focussing on business travellers and aims for a ticket price comparable to a first-class train ticket in Germany. Moreover, it assumes that silence is a key-enabler for that market, explaining why a huge technical effort is made to bring down noise emissions of the aircraft. Another example is Dufour Aerospace [11] developing the piloted aEro VTOL in Switzerland and also addressing the RAM-market. These examples indicate a demand for thin-haul air services in more rural parts of Europe that are not well enough connected to the main transport modes such as train, car or CS-25 aircraft. Important aircraft features are comfort for business travellers that have an assumable higher willingness to pay, the accessibility of small airfields and, therefore, reduced noise emissions to not disturb residents.

2.2. Thin-haul air cargo
Air cargo volume has grown significantly in the last years and is expected to grow even stronger within the next two decades – not considering the effects of the Covid19-pandemic. In the baseline scenario calculated by Boeing [12], a CAGR of 4.2 % is expected within the next 20 years. Strongest markets in terms of growth rates are forecasted to be domestic China (6.3 %), Intra-East Asia (5.8 %) and East Asia to both North America and Europe (both 4.7 %). Besides growing cargo volumes due to prospering world economics, which is favouring air transport, e-commerce is a strong driver for growth. Most important markets are the US and China. Especially Amazon is setting new standards in terms of customer expectations regarding delivery time and product diversity. To realise this, rising volumes of e-commerce goods are at least partly transported via air [13].
A strong argument for the cause is the newly developed Cessna SkyCourier by Textron Aviation, a 19-passenger commuter aircraft developed for both passenger and cargo transport. FedEx is an anchor customer that has ordered already fifty aircraft and indicated to purchase fifty more. The SkyCourier will replace the Cessna Caravan aircraft fleet operated by FedEx in the US for thin-haul air cargo services and is designed to carry three LD3 air cargo container [14]. Moreover, DHL has committed to reduce its CO₂-emissions to zero by 2050. A hybrid or fully electric cargo aircraft would help to reach this goal, as DHL is one of the big five air cargo operators worldwide [15].

In summary, air cargo is expected to grow strongly, especially to handle e-commerce and express freight. To further reduce delivery times, smaller aircraft are used to enable air cargo on thin-haul routes. Moreover, first operators have announced to reduce their CO₂-emissions and, therefore, will increase the demand for environmentally friendly air freighters of a smaller scale.

3. Framework for Top Level Aircraft Requirements

As literature is often unclear when it comes to specific TLARs (Top Level Aircraft Requirement), an analysis is carried out to identify major TLAR categories commonly used for aircraft design. To do so, twelve different papers focusing on aircraft design are analysed to derive a sound set of TLARs [16-27]. Results are shown in table 1 and form a framework for the economically recommended TLARs for ELICA. Almost all papers referred implicitly to a specific configuration, defined a certain cruise speed, payload, runway length and design range. About half of the analysed papers provided specific values for the certification basis, Maximum Take-Off Mass (MTOM), operational cost given as required revenue per passenger kilometre (RPK), CO₂-emissions and distinguishing features to outperform competitors. Such features include acceptable flight conditions, reduced noise levels, a modular flexibility of the cabin layout or further aspects.

Furthermore, for the purpose of this paper, basic requirement types are defined according to MATTMANN [28], as fixed requirements (a fixed value to be reached), range requirements (allowable interval or minimum or maximum value for the requirement), and optimum requirements (optimal value to be reached). About two thirds of the parameter can be derived from a benchmark with existing 19-passenger commuter aircraft, which is presented in the following section. Remaining criteria can be derived from an analysis of the dedicated new markets as described above and detailed out in section 5.

| TLAR                        | Rate of occurrence | Detailed parameter               | Source                      |
|-----------------------------|--------------------|----------------------------------|-----------------------------|
| Implicit configuration      | 12                 | Configuration                     | Benchmark                   |
| Cruise speed                | 12                 | Long range                       | Benchmark                   |
| Payload                     | 11                 | High speed                       | Benchmark                   |
| Required runway length      | 10                 | Payload                           | Benchmark                   |
| Required runway length      | 10                 | Take-off distance total           | Benchmark, analysis         |
| Required runway length      | 10                 | Take-off field length             | Benchmark, analysis         |
| Ranges                      | 10                 | Design range                      | Analysis                    |
| Certification basis         | 5                  | Maximum range                     | Benchmark                   |
| Mass budget                 | 5                  | Certification basis              | Benchmark                   |
| Economic parameters         | 5                  | Maximum MTOM                      | Derived from certification basis |
| Emissions                   | 5                  | revenue/RPK                       | Analysis                    |
| Distinguishing features     | 5                  | Hybrid powertrain                 | Derived from project goals  |
|                            |                    | Flight conditions                 | Benchark                    |
|                            |                    | Noise emissions                   | Benchmark, analysis         |
|                            |                    | Cabin layout                      | Analysis                    |

4. Benchmark of existing 19-passenger commuter aircraft

From the 1960s to the 1980s eleven 19-passenger commuter aircraft variants or comparable aircraft such as the PZL M28 Skytruck (18 seats) or the Harbin Y-12 (17 seats) were introduced to the market. In total about 5,500 aircraft were sold up to today. The most successful aircraft in terms of aircraft sold is
the Czech LET410 with 1,166 aircraft delivered, representing about 21% of the entire fleet. About 53% of all aircraft sold were manufactured by North American or British companies. As of today, only three separate aircraft are still in production (DHC-6-400 Twin Otter, PZL M28 Skytruck and Do 228 in India and Do 228NG in Germany). [4]

The two least sold aircraft (Short Skyvan and IAI Araya) are not examined due to lack of market success. In total, nine aircraft will be presented and discussed in the following. Most performance details of such aircraft are only known to the manufacturer or the aircraft operators. This benchmark is therefore based on several different types of official sources and some secondary data sources. The official data sources are composed of type certification data sheets (TCDS), Aircraft Flight Manuals (AFM) or Pilot Operating Handbook (POH) and official statements by manufacturers. The TCDSs are available for almost all the aircraft from the Federal Aviation Administration (FAA) and for most modern aircraft from the European Aviation Safety Agency (EASA). Those TCDSs contain basic information about the technical layout and safety relevant data. Detailed information is available in the AFMs and POHs. Those documents contain all relevant information for a pilot to operate the aircraft. Table 2 displays the results of the benchmark for 19-passenger commuter aircraft for the above indicated criteria. Minimum and maximum values are given, as well as average values and the relative standard deviation. Additional remarks precise the external conditions the indicated values are given for. Results will be discussed in section 6.

### Table 2. Benchmark data for 19-passenger commuter aircraft and selected parameter

| Parameter                  | Unit | Min   | Max   | Average | Rel. std. dev. | Remark                                      |
|----------------------------|------|-------|-------|---------|----------------|----------------------------------------------|
| Configuration              |      |       |       |         |                | Dragon configuration                         |
| Long range cruise speed     | km   | 244   | 456   | 376.2   | 80.9           |                                              |
| High speed cruise          | km/h | 300   | 518   | 428     | 71.5           |                                              |
| Payload                    | kg   | 1,400 | 2,268 | 1,950   | 252            |                                              |
| Take-off distance total     | m    | 454   | 1,066 | 719     | 172.8          | Sea level, MTOM, ISA, Flaps 50%              |
| Take-off field length       | m    | 675   | 1,440 | 1,111   | 276.5          | Sea level, MTOM, ISA, Flaps 50%              |
| Maximum range              | km   | 980   | 2,408 | 1,398   | 426.2          | Fast cruise, 1,500 kg payload, 100 NM alternate, 45 min reserve |
| Certification basis        |      |       |       |         |                | CS-23                                        |
| Maximum MTOM               | kg   | -     | 8,618 | -       | -              | Derived from certification basis             |
| Flight conditions          |      |       |       |         |                | VFR, IFR day and night, FIKI                |
| Noise emissions            | dB(A)| 76.5  | 83.5  | 80.5    | 2.4            | Take-off                                    |

### 5. Analysis of further design aspects

In the following section, take-off field length will be discussed with regards to the population in reach of the addressable airfields for both Europe and the US to allow for an initial market sizing. Moreover, relevance of low noise emissions will be highlighted due to the increased exposure at local airfields when RAM and thin-haul air cargo services will roll out. Additionally, recommendable design ranges are derived from literature and economic parameters are provided to allow for a competitive market offer. Finally, relevant features of the cabin layout recommendable for ELICA are presented.

#### 5.1. Take-off field length

To provide a sound decision base for take-off field length, existing airport infrastructure is analysed in the form of runway lengths and how much people live in a set radius around the airfields. For that grid population data from the 2011 EU census and statistical data for the US is used and extrapolated to the total population in 2020. To assure comparability and consistency for all countries, data from the website ourairports.com was selected to arrive at a more realistic picture of existing airfield infrastructure. This data can be considered consistent which is supported by the fact that the United Nations Office for the
Cooperation of Humanitarian Affairs (OCHA) also provides it to Non-Governmental Organisations (NGOs) around the world to organise their efforts. Results are depicted in figure 1.

Figure 1. Number of airfields / runway length (left); Pop. share / airfield distance & runway (30 km).

It is evident that the USA shows a denser network of airfields compared to Europe. Europe has a lot fewer airports with short runways below 1,000 m. This can be attributed to a much more active General Aviation community in the USA. Above 2,000 m of runway length this disparity does not exist anymore and there are about the same number of airfields in each region.

Next it is evaluated which share of the population lives within a radius \( r \) of 30 km away from airfields. Experience from earlier projects show that 30 km is a distance which can easily be driven by car. Results show that almost the entire population of the USA (99.76 %) lives within 30 km radius of an airfield with a minimum runway length of 500 m. In Europe, 81.48 % of the population lives within 30 km radius of an airfield with a minimum runway length of 500 m.

Findings indicate that an accessible runway length for ELICA of 1,000 m should be sufficient to penetrate both the US and the European market.

5.2. Noise emissions

Aside from typical emissions such as CO\(_2\) or NO\(_x\), there are other types of emissions with a significant share in the ecological footprint of aviation. One of these is noise pollution, which is often overlooked for effects on a global scale but very important for residents close to airports of all sizes. Noise pollution has a direct impact on risks for airport operators, regarding limitation on hours of operations etc. and on the cost structure of the airport. Those increased cost, for example to shield residents from certain noise levels are passed on to aircraft operators. To reflect the different impacts of different aircraft types, those fees are based on certified noise levels. Hence, there is a direct incentive to reduce noise pollution.

Noise originates from small differing levels of air pressure, which are transmitted as waves through the air. Scientific literature provides a proof, that it is not a question of whether noise has a health impact, but how big this impact is. World Health Organization (WHO) lists main health impacts of noise pollution, such as cardiovascular diseases, feelings of displeasure, restlessness and annoyance, insomnia, or cognitive impairment [29]. To build a basis for mitigating noise most countries detailed plans on how to and where noise levels must be monitored. To reduce the impact of aviation noise pollution Germany has defined requirements to monitor the levels and worked out detailed plans how the impact can be reduced. How extensively this work must be carried out depends on the airport category, derived from the annual number of commercial take-offs and landings. [30]

As there is a forecasted growth in air traffic, more airports will have to take stricter measures to prevent a growing number of citizens affected by aircraft noise. Therefore, those aircraft must produce less noise than current designs, otherwise operation will not be possible. In summary, the ELICA aircraft design process should consider noise emissions to develop and build a fully environmentally friendly aircraft.
5.3. Design range and economic parameters
For the purpose of this paper, the design range of the aircraft, in other words the typical mission distances, is chosen to be 420 km, derived from design range indications from GRIMMANN et al. [4], HOFMANN et al. [7], and SUN et al. [8] reflecting both classic and RAM-distances. Kreimeier et al. indicate furthermore the RPK as a relevant indicator for both operational cost comparison of different aircraft types and price indications for customers. In line with e.SAT and Dufour Aerospace (compare section 2.1), a price level of a first-class train ticket is envisioned. Desk research for the Deutsche Bahn train operator in Germany indicates a price range in between 0.5 to 0.7 €/km.

5.4. Cabin design
For the general public the aircraft is mainly visible through the interior. It is what defines the experience for them and for most of them the main thing that they will take away. Historically speaking a 19-passenger aircraft also carries cargo, patients in medical emergencies or military operators. This means that several different use cases are possible and the interior needs to be henceforth adapted. The more flexible a possible 19-passenger aircraft is the better what is defined by the aircraft’s cabin. Current 19-passenger aircraft already offer great degrees of flexibility. However, their cabins have been designed with either passenger or cargo transport as their primary objective. This means that flexibility is always limited and leaning to one side or the other. In order to achieve maximum flexibility an approach that could equally cater passenger and cargo transport should be pursued.

Adding to the obvious scenarios of passenger or cargo transport or the combination of both at the same time, medical evacuation (MEDEVAC) or surveillance operations of any kind are two other scenarios that aircraft in the 19-passenger segment are frequently used for. A modular cabin that can be changed within little time would increase versatility for the operator while in service.

The aircraft cross-section has a large influence on the passenger comfort. The most obvious example is the Beechcraft 1900D as the main feature of this derivative of the base B1900 model was the enlarged cross-section in order for passengers to be able to stand up straight. Another deciding factor would be whether or not to store air cargo industry standard LD3 containers. Utilising widely used containers increases efficiency for prospective customers as the turnaround time of the aircraft can be strongly decreased. If pressurisation is needed to fly faster at higher altitudes, then their accommodation would increase the size of the cross-section as a cylindrical cross-section is required leading in turn to higher drag or higher fuel burn. For a commercial passenger operation, the obvious choice would be to have a pressurised cabin, however a non-pressurised cabin could be of use in military environments. Since surveillance missions by 19-passenger aircraft usually take place below 3,000 m and as externally mounted sensors are constantly evolving their integration is eased by a big effort in a non-pressurised cabin. Moreover, having a non-pressurised cabin reduces complexity and frees up weight for other systems such as externally mounted sensors. As the market for thin-haul air cargo services should also be addressed by ELICA, it is recommended to focus on a non-pressurised cabin.

6. Results
Finally, specific TLARs for ELICA should be provided within this section. Table 3 provides an overview of suggested TLARs. This set of requirements has to be regarded as an initial design approach that forms a starting point and needs to be challenged, shaped, and detailed during the course of design. As MTOM is for now hard to assess due to not further specified hybridisation, maximum MTOM is reported according to the CS-23 certification regime. The payload is set to 2,000 kg and can be regarded as an optimum requirement type with limits in between 1,800 kg (minimum PAX mass) and 2,300 kg (top of the benchmark) – if an interval is preferred. Take-off field length can be used to assess the addressable airfields. According to the benchmark this value was set to maximum 1,000 m. In average situations, less runway is required for take-off – 700 m. Long range – in other words efficient – cruise speed should not fall below 375 km/h. High speed cruise can be set to 430 km/h according to the benchmark. As outlined above, a low noise level of ELICA will ease the increased utilisation of airfields and be moreover a unique selling point. Hence, it is suggested that ELICA should be at least quieter
than the quietest aircraft (BAe Jetstream 32 with 76.5 dB(A)). Design range was already discussed above. Maximum range with 1,500 kg payload is derived to be 1,400 km. As all aircraft have a dragon configuration, this configuration is also recommended for ELICA. However, a lot of variants are imaginable, e.g. high or low wings and different tail configurations that need to be analysed and decided by engineering. A revenue per RPK in between 0.5 to 0.7 € should be sufficient to cover all expenditures and provide a margin of more than ten percent for the operator. All other economic values (e.g. ELICA net price, energy consumption, maintenance efforts, etc.) can be derived from this figure. For this reason, no net price is recommended for ELICA.

| Table 3. Initial set of ELICA TLARs |
|-------------------------------------|
| Parameter                          | Value       | Remark                  | Req. type |
| Max. MTOM                          | 8,618 kg    | Certification limit     | Maximum   |
| Payload                            | 2,000 kg    | -                       | Optimun   |
| Take-off distance total            | 700 m       | Sea level, MTOM, ISA,   | Maximum   |
| Take-off field length              | 1,000 m     | Flaps 50%               | Maximum   |
| Long range cruise speed            | 375 km/h    | -                       | Minimum   |
| High speed cruise                  | 430 km/h    | -                       | Minimum   |
| Noise                              | 75 dB(A)    | ICAO Annex 16 Volume I  | Maximum   |
| Design range                       | 435 km      | 1,500 kg payload        | Optimun   |
| Maximum range                      | 1,400 km    | -                       | Minimum   |
| Configuration                      | Dragon      | -                       | Optimun   |
| Revenue/RPK                        | 0.5-0.7 €/RPK | First class train ticket | Range     |
| Certification basis                | CS-23       | -                       | Fix       |
| Flight conditions                  | VFR, IFR, FIKI | Required for weather independent operations | Fix 
| Powertrain                         | Hybrid      | -                       | Fix       |
| Cabin layout                       | Modular approach for PAX & Cargo transport or special missions, high passenger comfort | Fix |

To allow full operation during night-time or harsh weather conditions as well, ELICA should be designed for Visual Flight Rules (VFR), Instrumental Flight Rules (IFR), and Flight-into-know-Icing conditions (FIKI). Of course, a hybrid-electric powertrain is envisioned.

Finally, the cabin layout should be prepared for a modular approach to allow passenger, cargo and special mission operations. To achieve a high level of passenger comfort, an upright walk should be enabled by cabin height. Right now, an unpressurised cabin is recommended for ELICA. However, future performance calculations need to show whether potential energy savings due to higher flight levels might compensate for higher structural mass of a pressurised cabin.

7. Conclusion and outlook
In conclusion, a broad study on technical benchmark and analyses of future market features for 19-passenger commuter aircraft was executed. Derived figures were used for TLAR definition and can moreover be provided for aircraft design to challenge current engineering findings with industry standards. It has to be highlighted again that those figures should be seen as an initial approach for the first design calculations for ELICA and need to be challenged and adjusted to the specific technical solutions derived from the further technological development. The next step in the project is both the design of the hybrid-electric powertrain and the overall aircraft design. In accordance with that TLARs will be challenged and potentially adapted.

8. References
[1] IATA 2018 20 Year Passenger Forecast
[2] ICAO Secretariat 2019 Environmental Report Aviation and Environment chapter 4 pp 111-5
The presented studies have been partly financed by the project ELICA (ELectrive Innovative Commuter Aircraft), funded by the European Commission within the research program Clean Sky 2 (CS2 GA No. 864551).

Acknowledgments
The presented studies have been partly financed by the project ELICA (ELectrive Innovative Commuter Aircraft), funded by the European Commission within the research program Clean Sky 2 (CS2 GA No. 864551).