Deutscher Luft- und Raumfahrtkongress 2021
DocumentID: 550081

REQUIREMENTS AND CHALLENGES FOR THE NEXT GENERATION OF LIGHT FIXED-WING AIRCRAFT PROPULSION SYSTEMS

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Abstract

Unlike commercial airliners, which are almost exclusively powered by turbofan engines, light fixed-wing aircraft apply a variety of different propulsion systems. This market segment has long been dominated by General Aviation for individual usage and sports, for which operational efficiency is a subordinated requirement. As upcoming novel approaches on air commuting services and personal air vehicles arose, also the interest in efficient propulsion systems for engines below the regional prop segment increases.

The choice of a specific propulsion system is a major design decision as it predetermines fundamental performance characteristics and thereby the application capabilities of an aircraft concept. This contribution does not point on simply replacing conventional propulsion systems, but to use novel technology's characteristics in the most useful and practical way. Therefore, identifying and describing the rationales of current aircraft designs can facilitate the development and evaluation of novel propulsion systems.

This article developed a systematic approach on propulsion system requirements to describe limitations on current technology engines, but also to identify potentials of upcoming propulsor systems powering light fixed-wing aircraft. In a first step, requirements on light aircraft's powerplant and propulsion system were reviewed and identified based on parameters of early aircraft design studies in the General Aviation segment. In a second step, this contribution applies these requirements and analyzes specification data of common light fixed-wing aircraft and their powerplants statistically. The established database consisted (primary) of General Aviation aircraft and their corresponding engines. The large majority is powered by piston, turboprop or turbofan engines. The results showed that the predominant propulsion and powerplant systems do not only differ in their limitations to the mission envelops or the specific fuel burn, but that a variety of requirements such as the powerplant's frontal area, as well as maintenance cost and intervals influence the engine choice.

Keywords

General Aviation, Requirements on Propulsion, New Propulsion Systems

1. INTRODUCTION

Light aircraft are usually summarized as General Aviation (GA) and represent a wide range of applications, which are mainly characterized by private individuals (or at least non-aviation corporates) owning and operating aircraft. Their applications differ largely, whereas aircraft for sports, individual and non-scheduled corporate flights, instruction training, as well as air taxis dominate this segment [1]. Although GA accounts for 90 % of the aircraft registered in the USA, their importance for global traffic must be seen as marginal [2]. Although their share of the registered fleet is high, their manufacturers face low annual production volumes. TABLE 1 shows the distribution of aircraft by propulsion system for the US in 2017 [1]. With 65.9 % of the active GA fleet being older than the average life span of a commercial airliner, light aircraft significantly longer service lifes [1].

Light aircraft's propulsion systems have long been a field of limited public interest, but as major global policy makers agreed to obligatorily curb greenhouse gas emissions, the necessity to initiate effective steps towards an emission reduction in aviation increases [3]. Foreseeable novel propulsion technologies such as battery- or hybrid-electric systems, are not applicable for large-scale commercial airliners yet, although they would likely allow a significant reduction in greenhouse gas emissions [4]. Therefore, several light aircraft demonstrators were developed in the course of the last years as prototypes for electric propulsion and battery systems (see Rolls-Royce ACCEL, Airbus' E-Fan). Nonetheless, these aircraft concepts are not designed to be brought to the market, so that the question arises which characteristics novel propulsion systems for light aircraft are required to have in order to be a useful and practical alternative in GA propulsion.

Therefore, this contribution aims to derive and describe characteristics affecting the propulsion system's design, based on current aircraft designs. To do so, it follows a two-stepped agenda: Firstly, it focusses on reviewing the early design parameters of light aircraft's powerplant. It analyses aircraft design studies in order to identify and organize requirements which have a potential impact on the powerplant design. Secondly, it aims to describe these requirements in the context of current aircraft types to understand how each propulsion system is applied to make use of its individual characteristics. Therefore, a database of aircraft and powerplants specifications has been established and statistically analyzed depending on their applied powerplant systems.

For this examination the relevant scope was defined as light fixed-wing aircraft, which belong to the GA segment. These are aircraft, which are primarily used for sports, training, non-scheduled travel, as well as commuter aircraft. Ultralight aircraft are the non-included bottom boundary, as are regional aircraft and business jets for long-haul operations the non-included upper boundary. Partly, military applications such as (jet) trainer and medium altitude long endurance drones (MALE) were considered. To allow a sufficient comparability between aircraft types, only fixed-wing aircraft are considered, neglecting any helicopter or rotorcraft.

Unlike commercial airliners, which are almost exclusively powered by turbofan engines, light aircraft show a variety of applied powerplant systems. In the examined segment, aircraft are equipped with piston, turboprop (TP) and turbofan (TF) engines. These technologies allow a classification in accordance with their main properties. Firstly, they differ in their thermodynamic cycles, whereas the piston engines follow the cyclical Otto process (some exceptions Diesel process), TP and TF follow the continuous Joule-Braydon cycle. The second major difference is the propulsion unit: piston and TP engines are designed to convert a large part of the power to drive a shaft which is mechanically linked to a (freestream) propeller. In contrary, TF engines create thrust as the core engine drives a (geared) ducted fan, but retains a considerable part of the thermodynamic energy in the exhaust gas. These general differences in energy conversion and propulsion result in different operational characteristics in the course of a flight.

Historically, piston engines were predominant in all segments of motorized aviation. Aircraft piston engines were manufactured especially for aviation applications in a broad power range. In the course of the 1930-1940s, the development made major improvements, so that the thermodynamic and mechanical limitations of this technologies were foreseeably reached [5]. Piston engines of up to 3,500 kW shaft power can be seen as the peak of piston engine development. Nonetheless, their maximum flight altitude is limited, which requires the usage of turbochargers and gearboxes for higher altitudes. The use of turbochargers extends the aircraft's and engine's mission ability; however, the technical complexity increases as well. Thereby, negative effects on powerplant's weight, failure rate and thermodynamic efficiency are probable [6]. The cooling of the cylinder heads and valves, as well as the engine's frontal area has long been seen as problematic for high-performance engines [7].

With the emergence of turbo engines, piston engines were displaced for several applications: starting with fighter aircraft, their compact, high-power V engines for high airspeeds were replaced by turbojets in the 1940s. However, transporters and passenger aircraft were equipped with high-power radial engines until the 1950s when TP, and later TF, arose [6]. Only flat and compact opposed piston engines, kept their relevance for GA applications, where they were further developed for their specific areas of applications with lower power requirements. Although gas turbine thermodynamic efficiency is inferior, transformation to turbo engines extended the mission envelop and allowed a higher airspeed and flight altitude [6].

TP and TF apply similar engine core technologies; however, TF are optimized for high altitudes and high Mach numbers. Large TP and TF engines doubtlessly became the dominant propulsion technology for airliners, nonetheless small turbo engines for light aircraft show significantly divergent technical and economic trade-offs than large engine systems. Therefore, small turbo engines cannot just be perceived as down-sized derivates of large turbo engines. Major challenges which have a negative influence on a simple down-sizing are blade clearances and losses, constant friction coefficients of surfaces, as well as turbine cooling and thermal stresses of materials [8, p. 18ff].

From an economic perspective, the cost structure and the absolute cost levels differ largely between propulsion systems as can be seen in FIGURE 1. A major difference exists in the average utilization (measured in annual flight hours). As utilization is low, the share of fuel and crew costs decreases. However, the direct operating costs (DOC) are increasingly depending on insurance payments, amortisations and maintenance. It should be noted, that this cost comparison in FIGURE 1 is based on flight hours. Therefore, aircraft with higher cruise speeds cover longer distances at higher fuel consumption per time unit.

TABLE 1. Fleet and Utilization of US GA

	Piston	TP	TF, TJ
Active Aircraft (USA 2016) [9]	142,638	9,889	13,751
Annual Utilization [1]	102.1 FH/a	255.7 FH/a	264.7 FH/a

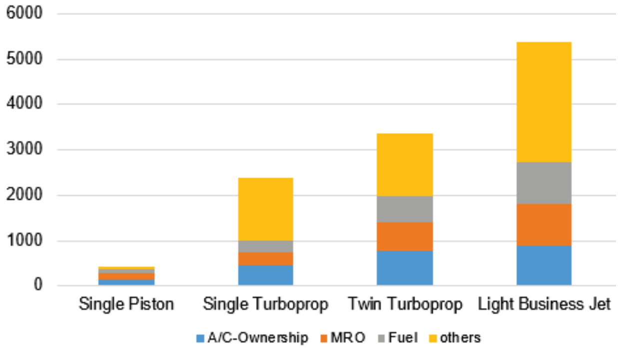

FIGURE 1. Aircraft Cost [USD/FLH] by propulsion system [10,11,12]

As the examined conventional powerplant technologies show major technical and operational limitations and disadvantages, the following section will derive requirements and their importance for light aircraft propulsion and characterize these requirements for the current applications.

2. REQUIREMENTS OF GENERAL AVIATION PROPULSION

In a first step, this work addresses the requirements, which influence the powerplant's choice, as well as the aircraft and engine interaction. To derive and identify requirements on the propulsion systems a systematic review of design studies was conducted. It stipulates a qualitative analysis of existing design studies in the field of GA aircraft.

2.1 Method

Design studies with conventional, as well as battery- and hybrid-electric propulsion systems were selected to identify their explicitly stated general design parameters. Underlying parameters, which were not stated, were disregarded for this consideration. By consulting additional sources of secondary literature related to powerplant systems (such as Meinig 2003a, Meinig 2003b, Leyes & Fleming 1999) and collating it to the design studies, it was possible to identify parameters with a major impact on the powerplant system. They were classified and weighted for further processing. In a last step, these requirements were evaluated according to their comparability between aircraft and propulsion systems, as well as data availability.

2.2 Database

A set of ten design studies, all published between 2012 and 2020, was chosen to represent a broad set of mainly conventional – but also novel – powerplant systems. They all belong to the class of GA aircraft and can be found in the list of references [13-24].

2.3 Results

The examined design studies show parameters related to powerplant systems which suggested a classification into three major categories. The resulting requirements are presented by category. For the given data of this study, a choice had to be made. Therefore, the requirements analysed in section 3 were chosen to represent a broad field of characteristic. They are explained in the following section. An extensive overview can be found in APPENDIX A.

2.3.1 Aircraft Design

Classical requirements on an aircraft design depend significantly on the choice of a properly dimensioned powerplant. These requirements are the aircraft's range, flight altitude and maximum speed, as well as length of runway. Both, the maximum airspeed and the required take-off runway length depend largely on the engine's excess power – however, the requirements in both mentioned operating points differ significantly. Furthermore, the engine's frontal area was identified as it affects the aerodynamic drag and thereby the maximum speed notably. Large frontal areas limit the pilot's visual field, as well as the potential engine installation and integration.

2.3.2 Powerplant

In the early design stage, the powerplant is mainly defined by a specific power requirement, which results in the later engine sizing. Further requirements are the complexity of the powerplant, which strongly effects operational cost mainly through specific fuel consumption and maintenance effort. For further noise and propulsor efficiency considerations, the core engine's and power shaft rotational speed is an important parameter.

2.3.3 Operations

Operational factors focus on the technical operations and economic factors of GA aircraft. Operations are dominated by the initial costs for the powerplant and its direct operating costs. As aircraft utilization in GA are low (see TABLE 1, FIGURE 1), the initial costs can only be distributed on a lower base of flight hours, which increases the ownership costs per hour significantly. Two major factors of the direct operating costs are the total mission fuel costs, as well as maintenance costs. Further requirements relate to the conditions and availability of suitable fuels and the noise level at take-off conditions.

3. CHARACTERIZATION OF POWERPLANTS

On the base of the established specification database, several descriptive statistical analyses were conducted.

3.1 Method

To describe the identified requirements for the set of considered aircraft, the following characteristics were analysed:

To illustrate the major mission limitations the Mach number in cruise flight over the flight altitude are shown for every aircraft of the database. The Mach number was derived based on the calibrated maximum airspeed in cruise as stated by the manufacturer's datasheets and related to the speed of sound at standard conditions at flight altitude. If cruise flight data were not available, the max. operational airspeed (as stated in the type certification) were applied. Flight altitude data were stated in the type certifications.

The mass specific power of the powerplant was calculated as the maximum continuous shaft power in relation to the powerplant's dry weight. Both parameters are stated in the type certification. For the relevant power ranges, a linear regression for piston and TP engines was conducted.

The frontal areas of the powerplants were determined depending on the powerplant's design. The majority of studied piston engine are designed as boxer engines, so that the frontal area (*FA*) could be calculated based on the powerplant's height (*H*), width (*W*) and the relation between *H* in the center and height at the outer edges (*a*). This relation *a* was derived based on graphical approximation of common engine types.

$$FA = W * H - 0.5 * W * H * (1 - a) \tag{1}$$

The frontal area of radial piston engines, TP and TF was simply described by the circular area corresponding with the largest diameter of the engine. For the relevant power ranges, a linear regression was conducted for the powerplant systems of piston (with and without turbocharger), as well as TP.

In a last step the SFC at sea level take-off conditions (stated in manufacturer's datasheet) and engine maintenance intervals (stated in type certificates) were compared. For piston and TP engines, the brake specific fuel consumption (BSFC) is related to the engine's shaft power. For TF engines, the thrust specific fuel consumption (TSFC) is related to the engines maximum continuous thrust.

3.2 Database

Based on the applied definition of light fixed-wing aircraft, a set of 97 aircraft types and subtypes was identified. For these aircraft types, the EASA and / or FAA type certification documents, as well as OEM specification data sheets were assessed.

These aircraft types were assigned to 88 different powerplant types and subtypes, whereas 34 were piston, 34 TP and 29 TF / turbojet engines. Their specifications were derived based on EASA and / or FAA type certification documents, OEM specification data sheets and further comparing technical literature. A more detailed description of the underlying aircraft and engines is provided in APPENDIX B.

3.3 Results

To characterize the applications of the powerplant systems, the first analysis focused on the interaction between aircraft design and the applied powerplant system, therefore it illustrates the general mission limitations in FIGURE 2. As a general mission limitation, the Mach number in cruise flight and the flight altitude were identified. The analysis showed a clear three-parted division of data: piston engines are concentrated on a flight altitude range of 4,000 - 5,500 m with a group of outliers at 8,000 m. The maximum Mach number in cruise flight does not exceed Ma 0.4. TP-powered aircraft focus around 8,000 - 9,000 m with outliers at 12,000 m. Due to the higher flight altitudes, Mach numbers of up to Ma 0.6 are possible. TF allow significantly higher flight altitudes of up to 16,000 m and high subsonic Mach numbers.

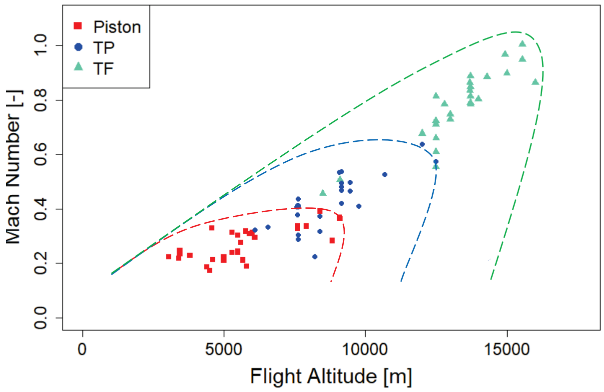

FIGURE 2. Mach number and Flight altitude

In a next step, the mass specific power of the shaft power engines was compared, as can be seen in FIGURE 3: piston engines showed specific shaft power of circa 1 $\frac{kW}{kg}$, whereas the trend had a moderate increase in the relevant range. TPs show a specific shaft power of circa 2.8 - 4.5 $\frac{kW}{kg}$, whereas the trend is increasing with a 1.5 times higher slope.

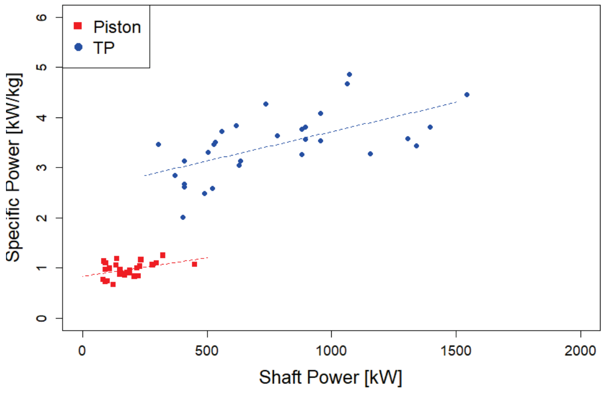

FIGURE 3. Specific power depending on shaft power

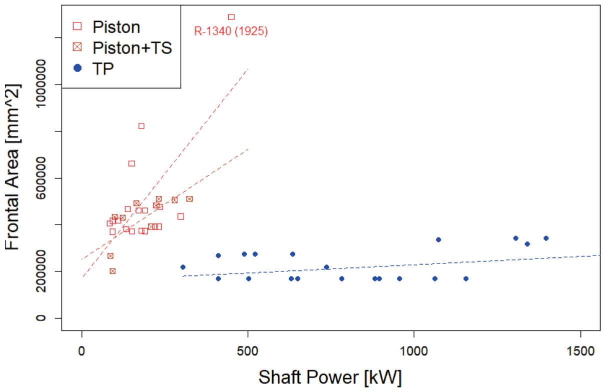

FIGURE 4. Frontal area depending on shaft power

As mentioned in the section 2, the powerplant's frontal area has a strong effect on the aerodynamic drag of the engine's nacelle and therefore the aircraft's aerodynamic drag in cruise flight. This effect increases at high velocities. Considering the lower shaft power of piston engines, their specific frontal area is notably larger and increases with greater slope. Compared to the moderate increase for TP engines of about 71 mm²/kW, the slope for piston engine with turbochargers of 946 mm²/kW and piston engine without turbochargers of 1,796 mm²/kW are significantly greater.

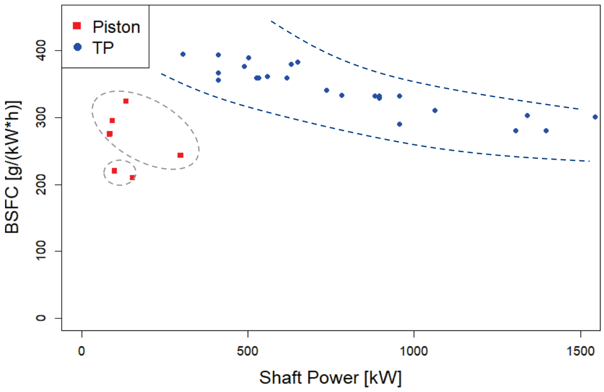

FIGURE 5. BSFC depending on shaft power

As a major requirement with an impact on the aircraft's operating costs, FIGURE 5 shows the specific fuel consumption for shaft power engines and TF engines depending on their shaft power and thrust. Piston engines show a BSFC of 200 - 300 $\frac{g}{kW*h}$, whereas Otto piston engines are on the upper limit and Diesel piston on the bottom limit of this range. TP's BSFC ranges from 320 - 400 $\frac{g}{kW*h}$, whereas a clear tendency is visible with larger TPs having a lower specific consumption. A similar observation can be identified for TF engines in FIGURE 6.

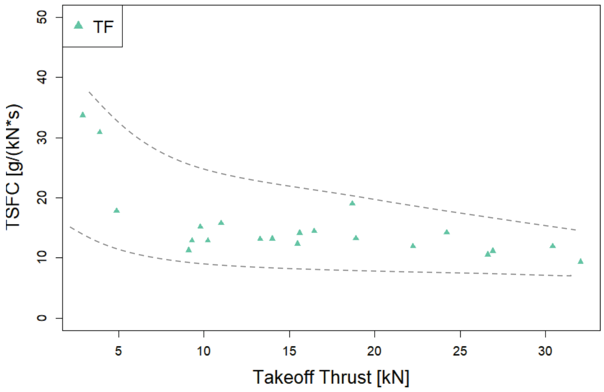

FIGURE 6. TSFC depending on shaft power

The second major impact factor on general aviation's DOC are the maintenance costs. These heavily depend on the overall intervals (TBO, time between overhaul) and the costs per overhaul. TBO-data are defined for certification, whereas the cost per event are barely comparable. Therefore, the costs per maintenance event are not analysed statistically, but a cost range per maintenance event can be seen as reference in TABLE 2.

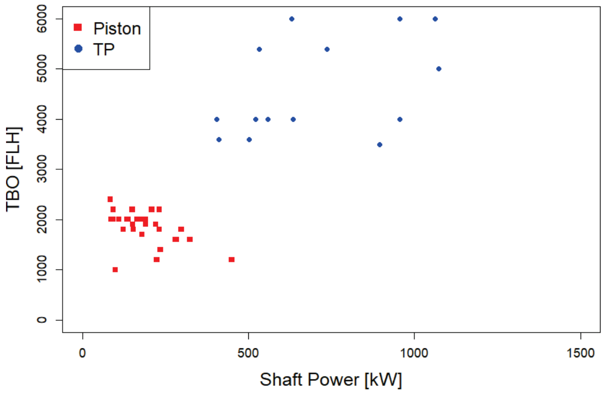

FIGURE 7. TBO depending on shaft power

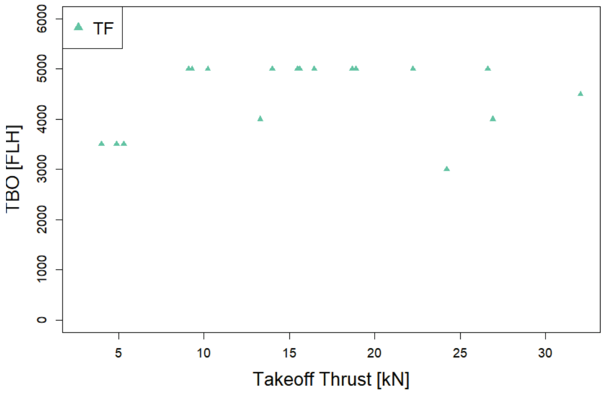

FIGURE 8. TBO depending on thrust

TABLE 2. Maintenance Costs per Engine [25,26,27]

	Piston	TP	TF, TJ
Cost Range per Overhaul [USD]	25-60.000	230-333.000	650-950.000

An overview on the derived characteristics can be found in APPENDIX C.

4. DISCUSSION

To evaluate the applicability of novel powerplant systems, it is necessary to consider aircraft propulsion in the context of the requirements of their expected missions. Therefore, design studies of future GA aircraft were examined. It was found that requirements on the powerplant system of GA differ compared to requirements on commercial aviation in their prioritization and weighting [28,29]. The identified requirements showed and explained a subdivision of the examined GA aircraft segment.

The derived requirements of the powerplant address three major categories, whereas the first group of parameters described general characteristics of the aircraft design itself, such as range, air speed and altitude, but also the aerodynamic drag related to the powerplants. A second group of requirements concentrated on the powerplant system itself, where the mass specific shaft power and the general engine complexity are of major importance. Furthermore, engine cooling and the powerplant's shaft rotational speed are critical for powerplants. Operational considerations aggregated all these parameters, which influence the practical operability of the aircraft and its powerplant. These consists of the initial costs, (mission) fuel consumption costs and maintenance costs. Further parameters address the general cost and availability of fuels, as well as the noise level of the overall propulsion system. In this context, a further economic influence factor is that GA aircraft are characterized by low utilizations (annual flight hours), which shifts the distribution of DOC: at low utilizations fuel and crew costs have a less dominant impact on DOC, compared to an increasing share of amortisation and maintenance costs.

Current aircraft types and engines were examined considering these derived requirements. They characterised the applications for the three powerplant technologies as follows: Piston engines are predominant in the bottom segment of GA in a shaft power range of up to 300 kW. Their SFC is comparably low, while their initial and maintenance costs are significantly lower compared to turbo engines. Most piston engines are limited in their flight altitude to about 6,000 m, and therefore in their maximum Mach number of < 0.45. Furthermore, the piston engine's vibration level requires shorter maintenance cycles on the engine and airframe [7]. To cope with low production volumes in the GA segment, manufacturers produce their established Otto piston engine designs as long as possible, which can be seen as current Otto piston engines for aviation applications date back to the 1950s and 1960s. Current development and engine programs concentrate on the adaption of automotive diesel engines for GA applications. These offer higher power outputs at high altitudes, but have an inferior specific shaft power and problematic vibration characteristics [30]. To mitigate this problem, current research programs aim to develop less vibration-sensitive propeller for diesel piston engine applications [31].

TP and TF engines are characterized by a high power to weight ratio (or specific thrust for TF), therefore they allow medium- to high-power applications at significantly lower engine weights as this would be possible for piston engines. Their SFC tends to be higher compared to piston engines. However, TP and TF engines show strong scale effects, so that their SFC improves with increasing power (or thrust). Their mission envelop allows high flight altitude, whereas TP's airspeed is limited by the propeller. TFs are optimized for high flight altitudes at high Ma number (Ma < 1). As the production volumes are even lower, manufacturers aggregate production volumes by offering an engine portfolio, which is based on derivates of engines first designed in the 1960s and 1970s with a high share of common parts. TP's and TF's initial costs are a multiple of comparable piston engine's costs.

Current development programs focus to adopt large TF's core engine technology into the context of TP and small TF engines. Technologies, such as high-pressure turbine film cooling [32] are likely to increase the powerplant's complexity and manufacturing costs by far, and thereby increase the initial and maintenance costs. Thus, new development programs show an upward shift of their power range.

Application and mission specific characteristics and their prioritization are of superordinate importance for the evaluation of suitable powerplant systems. Current powerplant requirements justify a variety of powerplant systems for GA aircraft in parallel. Each of the conventional powerplant systems found their justification and specific roles for which they constitute suitable characteristics.

From the manufacturer's perspective, this division in three conventional powerplants intensifies the problem of high development and certification costs at even lower production volumes with low utilizations in their service life. Under the current circumstances, this limits the initial costs and therefore the applicable technological level significantly. However, it can be expected that new applications, such as urban air mobility or MALE, will impact mission profiles, so that utilization pattern change significantly, which would impact the powerplant development parameters.

Thus, it is all the more important that the current state of technology in powerplant technology is constantly evaluated in the context of current and upcoming requirements to optimize the coordination of aircraft and powerplants with all their characteristics and potentials.

As this work aims to give a general overview on current powerplants for GA applications and their requirements, it makes some underlying assumptions. These assumptions and limitations are explained in this concluding section. First of all, the analysis only considered those requirements and parameters, which were stated explicitly. Often these parameters already consider implicit assumptions on the aircraft's design and number of engines. However, these factors were neglected, as they would limit comparability. Furthermore, the analysis assumes that requirements on future propulsion systems can be derived from current technology aircraft. This assumption is based on the observation, that GA aircraft designs follow a rather conservative approach with minor changes over the last decades. Analyzed aircraft and powerplant data were based on type certification and manufacturer's documents, therefore these data were simplified considered as static. For an extensive comparison of specific powerplant systems, it would be recommended to integrate a dynamic mission calculation, which takes account of different thrust requirements depending on the aircraft's and engine's weight on specific missions. Especially, regarding battery-electric propulsion it is recommended to consider the weight of the powerplant including its energy source.

5. CONCLUSION

This present work examined essential requirements on light fixed-wing aircraft. Several demonstrators of battery- and hybrid-electric propulsion already exist; however, they are not supposed to be publicly available for purchase, but shall facilitate experiences in the field of novel propulsion systems. Therefore, the question arose which specific requirements GA aircraft have in regard to their powerplant and propulsor.

This contribution studied requirements and design parameter of aircraft design studies and found that the cost structure and operational considerations had a strong impact. Low annual utilizations cause that fuel consumption costs have only a minor share in the DOC to operate a GA aircraft.

The derived requirements were studied in the context of today's light aircraft and powerplants specifications. The characteristics of the currently applied conventional powerplants were identified and characterized.

To establish novel propulsion systems, which not only replace existing propulsions, these characteristics can be seen as a guideline to address specific problems or short comings of conventional systems, so that novel powerplant and propulsion systems are applied in the most useful technical and operational environment.

6. REFERENCES

[1] United States Bureau of Transportation Statistics, "General Aviation and Air Taxi Activity Survey Chapter 2", 2019

[2] AOPA, "State of General Aviation", 2019

[3] EU Commission, "Revision of the EU Emission Trading System Directive 2003/87/EC concerning aviation", 03 Jul 2020, https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12494-EU-Emissionshandelssystem-aktualisierte-Vorschriften-fur-den-Luftverkehr_de, last accessed 18 Aug 2021

[4] IATA, "Aircraft Technology Roadmap to 2050" Report, Geneva, 2019

[5] Meinig, U., „Hundert Jahre Kolbenflugmotor – Teil 2:

Die Zeit zwischen 1919 und den 1950er-Jahren“, MTZ 11/2003 Jahrgang 64

[6] Lorenz H., „Von der Aufspaltung in leichte und schwere Propellerturbinen“, Das Turbinenflugzeug „Dresden-153A von 1959“, Druck- und Verlagsgesellschaft Marienberg, 2015

[7] Meinig, U., „Hundert Jahre Kolbenflugmotor – Teil 3: Aktuelle Konzepte“, MTZ 12/2003

[8] Leyes R.A. and Fleming W. A., „The History of North American Small Gas Turbine Aircraft Engines“, American Institute of Aeronauticals And Astronautics, Inc, Reston, Virginia. 1999

[9] FAA, “General Aviation and Air Taxi Activities – Survey”, 2016

[10] Wyndham D., „What Does it Cost to Operate a Turboprop?“, avbuyer.com, https://www.avbuyer.com/articles/operating-costs/what-does-it-cost-to-operate-a-turboprop-112769, last accessed: 28 Jul 2021

[11] Wyndham D., „What Does it Cost to Operate a Light Jet?“,avbuyer.com,https://www.avbuyer.com/articles/operating-costs/what-does-it-cost-to-operate-a-light-jet-112746 , last accessed: 28 Jul 2021

[12] Wyndham D., “What Does it Cost to Operate a Medium Jet?“, avbuyer.com, https://www.avbuyer.com/articles/operating-costs/what-does-it-cost-to-operate-a-medium-jet-112719, last accessed: 28 Jul 2021

[13] Cinar G., Cai Y., Chakraborty I. and Mavris D. N., „Sizing and Optimization of Novel Generel Aviation Vehicles and Propulsion System Architectures“, AIAA Aviation Technology, Integration and Operations Conference, Atlanta / Georgia, 25-29 Jun 2018

[14] Finger F. and Bil C., „Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft“, Journal of Aircraft, Vol 57. No.2., March-April 2020

[15] Finger F., Braun C., and Bil C., „Case Studies in Initial Sizing for Hybrid-Electric General Aviation Aircraft“, AIAA Propulsion and Energy Forum, 9-11 Jul 2018, Cincinatti / Ohio

[16] Finger F., Götten F., Braun C., and Bil C. „Mass, primary energy, and cost: the impact of optimization objectives on the initial sizing of hybrid-electric general aviation aircraft“, CEAS Aeronautical Journal (2020)

[17] Hospodar P., Klesa J. and Zizkovsky N., „Design of distributed propulsion system for general aviation airplane“, MATEC Web of Conferences 304, 2019

[18] Ludowcy, J., Rings R., Finger D.F., Braun C. and Bil C., „Impact of Propulsion Technology Levels on the Sizing and Energy Consumption for Serial Hybrid-Electric General Aviation Aircraft“, Asia Pacific International Symposium on Aerospace Technology. Gold Coast, 4-6 Dec 2019

[19] Moxter T., Enders W., Kelm., Scholjegerdes M., Koch C., Garbade M. and Dahmann P. „Investigation of alternative Propulsion concepts for small aircraft with the hybrid electric motor glider FVA 30, Deutscher Luft- und Raumfahrtkongress 2020

[20] Rings R., Ludowicy J., Finger D.F., Braun C., and Bil Cees, „Sensitivity Analysis of General Aviation Aircraft with Parallel Hybrid-Electric Propulsion Systems“, Asia Pacific International Symposium on Aerospace Technology. Gold Coast, 4-6 Dec 2019

[21] Seeckt K. and Scholz D., „Jet versus Prop, Hydrogen versus Kerosene for a Regional Freighter Aircraft“, Deutscher Luft- und Raumfahrtkongress 2009

[22] Seitz, A., Schmitz O., Isikveren A.T., and Hornung M., „Electrically Powered Propulsion: Comparison and Contrast to Gas Turbines, Deutscher Luft- und Raumfahrtkongress 2012

[23] Shamiyeh M., Rothfeld R. and Hornung M., „A Performance Benchmark of Recent Personal Air Vehicle Concepts for Urban Air Mobility“, 31st Congress of the International Council of the Aeronautical Sciences, Belo Horizonte, Brazil, September 2018

[24] Yoon J., Nguyen N., Choi S., Lee., Kim S. and Byun Y., „Multidisciplinary General Aviation Aircraft Design Optimization Incorporating Airworthiness Constrains“, 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 13-15 Sep 2010, Fort Worth / Texas

[25] Continental Overhaul Cost, Manufacturer’s online price list, http://blog.overhaulbids.com/continental-overhaul-cost/, last accessed: 10 Aug 2021

[26] Pratt & Whitney Canada, Flat Rate Overhaul Program, Manufacturer’s online price list,, https://www.pwc.ca/en/products-and-services/services/maintenance-programs-and-solutions/pwcsmart-maintenance-solutions/pwcsmart-pt6a/flat-rate-overhaul-program, last accessed: 10 Aug 2021

[27] Pratt & Whitney Canada, Manufacturer’s online price list, http://blog.overhaulbids.com/pratt-whitney-jt15d-overhaul-cost/, last accessed: 10 Aug 2021

[28] Schmitt, D. and Gollnick, V.,” Air Transport System”, p. 107ff, Springer-Verlag Wien, 2016

[29] Conrady, R., Fichert, F. and Sterzenbach R., „Luftverkehr“, p. 128-131, 6th Edition, DE GRUYTER Olderbourg, Berlin / Bosten, 2019

[30] Centurion, “Developent of the CENTURION Jet Fuel Aircraft Engines at TAE”, 25 Apr 2003, DGLR Friedrichshafen

[31] Argos, “Clean Sky 2: ARGOS – Experience & Synergy”, Clean Sky 2 Conference, 15 Feb 2017

[32] GE Aviation, “The Biggest Win: New Engine Set to Lift GE’s Turboprop Business to New Heights”, GE Company Report, November 16, 2015, https://www.ge.com/news/reports/the-biggest-win-new-engine-set-to-lift-ges-turboprop-business-to-new-heights, last accessed: 28 Jul 2021

APPENDIX A

CATEGORY	IDENTIFIED PARAMETER	PART OF ANALYSIS
Aircraft Design	Range	
	Flight altitude	Flight altitude
	Cruise Speed	Cruise Speed or Max. Opt. Speed
	Aerodynamic Drag of Powerplant	Frontal Area
	Length of Runway	
Powerplant	Excess Power	
	Spec. Power	Spec. Power
	Powerplant Complexity	
	Powerplant Cooling	
	Rotational Speed (N1)	
Operations	Direct Opt. Costs	
	Mission Fuel Costs	BSFC or TSFC
	Maintenance Effort	TBO
	Initial Costs	Costs per Overhaul
	Fuel Availability & Costs	
	Noise	

APPENDIX B

	MIN	**AVERAGE**	**MAX**
AIRCRAFT (n=97)			
TOW [kg]	599	5,424	21,910
Entry into Service	1947	1986	2020

POWERPLANTS (n=88, P: 34, TP: 34, TF:29)			
Zertification	1939	1985	2020
Piston: Shaft Power [kW]	84	179	450
TP [kW]	305	760	1,544
TF [kN]	3.1	14	32

APPENDIX C

	Piston	**Turboprop**	**Turbofan**
Power Range	< 300 kW	> 350 kW, Focus 600-900 kW	
Specific Power	c. 1 kW/kg (independent from power)	c. 3.5-4.5 kW/kg (increasing in power)	
Utilization [1]	102 FLH/a	255 FLH/a	263 FLH/a
Cruise	V_{cruise} limited by Prop, Ceiling up to 6,000 m	V_{cruise} limited by Prop, Ceiling up to 12,000 m	Fan for high Ma (<1), Ceiling 10-12,000 m
Front Area	Large (w/ Turbocharger: 946 $\frac{mm^2}{kW}$, w/o Turbocharger 1,796 $\frac{mm^2}{kW}$)	Small (increases by 71 $\frac{mm^2}{kW}$)	Small
SFC	220-300 $\frac{g}{kW*h}$	300-400 $\frac{g}{kW*h}$ (decreases in power)	10-20 $\frac{g}{kN*s}$ (decreases in thrust)
Maintenance [26] [27] [28]	TBO: 1,000-2,200 h, @ c. 25-60,000 US$	TBO: 3,800-4,000 h, @ c. 230-330,000 US$	TBO: 3,500-5,000 h, @ c. 650-900,000 US$
Others	Vibration, Fuel Availability		Takeoff-Performance problematic