DOI: 10.13009/EUCASS2023-908

EVALUATION OF HYBRID ELECTRIC POWERTRAIN TOPOLOGIES AND THEIR INTEGRATION IN FUTURE AIRCRAFT CONCEPTS FOR GENERAL AVIATION

Thorben Hammer†* *Stefanie de Graaf**
**German Aerospace Center (DLR)*
52074 Aachen, Germany; 03046 Cottbus, Germany
Thorben.Hammer@dlr.de – Stefanie.deGraaf@dlr.de
† Corresponding Author

Abstract
The presented paper introduces a methodology to evaluate novel powertrain topologies in early stages of the conceptual aircraft design. This methodology can be adapted to the requirements of an investigated aircraft concept. Specific criteria and weighting factors were derived from the requirements in preparation of the evaluation. The evaluation allows the identification of the most promising options for the powertrain topology. After the evaluation, a sensitivity study of the methodology was conducted, analysing the influence of the weighting factors on the final outcome. Furthermore, an integration concept of the selected powertrain topology for one aircraft concept is presented.

1. Introduction
The European Union has defined goals for the European aviation industry for the year 2050 in the `Flightpath 2050` document. At its core is the reduction of CO_2 emissions by 75 %, NO_X emissions by 90 % and noise emissions by 65 % compared to new aircraft technologies from the 2000 [1]. In the `Waypoints 2050´ document the `Air Transport Action Group´ (ATAG) presents different possible scenarios to achieve net-zero emissions by 2050 [2]. With the anticipated introduction of new propulsion system architectures and the associated alternative energy sources for power generation, considerable changes to the aircraft design are required. This, however, offers an opportunity for a wider design space and novel aircraft concepts. There are several different powertrain (PT) topologies being studied in the literature today. They range from `All electric´ and `Hybrid electric´ PT topologies all the way to `Turboelectric´ PT topologies. While the introduction of electric propulsion systems would lead to an elimination of CO_2 emissions, the specific power and specific energy of battery and hydrogen-based fuel cell systems are significantly lower than those of conventional aeronautical engines using kerosene [3]. Therefore, `All electric´ propulsion systems are currently only considered to be feasible for small aircraft and short distance missions based on the state-of-the-art technologies. A promising alternative to reduce in-flight emissions lies in the combination of different technologies, resulting in hybrid electric propulsion topologies. This could be, for example, fuel cells and batteries coupled with a gas turbine or the combination of an electric generator and an internal combustion engine (ICE). Consequently, these power and propulsion systems would allow for more degrees of freedom in the design space as well as in terms of operating strategies. Due to the increased complexity of these novel PT topologies and their impact on the aircraft design process, the decision for one specific topology is not trivial.

In the early stages of the conceptual design, the aircraft's outer shape as well as the number of engines and propulsors may not be fixed yet. Therefore, a numerical analysis including all possible aircraft and PT variations and combinations would lead to high computation cost and would take considerable amounts of time. Within the presented paper a different approach was used to evaluate the most promising options for the PT topologies regards the specific needs of the aircraft concepts. First the required criteria and discrete metrics to evaluate each PT topology were defined. As the importance of each criterion might vary with respect to the overall project target, a criteria weighting was conducted to adapt the evaluation based on the top-level aircraft requirements (TLAR) as well as operational and safety requirements. Based on the evaluation results the investigated PT topologies were ranked and the most suitable PT topology could be selected. During a sensitivity analysis the influence of variations in the criteria weighting on the overall result was investigated. In addition, the most promising options were checked against weak characteristics by performing a vulnerability analysis. This method has been used for technical decisions and is described by Feldhusen *et al.* [4], Lindemann *et al.* [5], Pahl *et al.* [6]. An application of the method in the field of variable pitot inlets is presented by Kazula [7].

Copyright © 2023 by Thorben Hammer. Posted online by the EUCASS association with permission.

DOI: 10.13009/EUCASS2023-908

The presented method was applied within the DLR internal project FGAA (Future General Aviation Aircraft). Within the project the main goal is to design a climate neutral general aviation aircraft for nine passengers. This target is to be reached in three phases. First, the most promising aircraft concept is to be identified as well as a suitable PT topology. Afterwards the design and optimization of the chosen PT topology has to be performed. In the end all the acquired results from the aircraft design are to be validated through scaled flight testing.
In the early stages of the project, the definition of the TLARs was conducted with the method described by Will *et al.* [8] and are presented by Will *et al.* [9]. A few overall requirements, directly influencing the evaluation of the PT topology are mentioned here. Within the project a distributed electric propulsion (DEP) should be possible with the PT topology. Furthermore, the overall requirement was defined to be as flexible as possible for new technologies within the PT. Updating the PT to an `All electric´ PT topology in future, when a suitable battery technology arises. In addition, the selected PT should consist of different operational modes in order to optimize the aircrafts performance for various missions. Of course, one important requirement is to reduce costs for development, production and also for operations. The general procedure elaborating the most promising combination of the aircraft concept and the PT topology within the project is depicted in Figure 1.

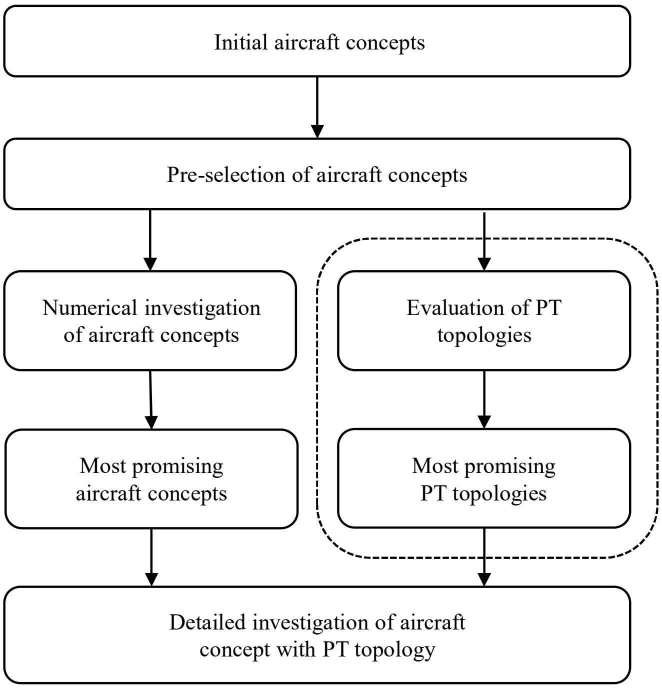


Figure 1: Procedure of investigating the aircraft concept and the PT topology

First, a selection of nearly 30 possible aircraft concepts were collected based on discussions with several aeronautical engineers related to the project. After a pre-selection of all possible aircraft configurations four seemed to be the promising options to achieve the required performances. These are displayed in Figure 2. The aircraft design team within the project investigated the aircraft concepts in further detail. In parallel, the presented method was used to evaluate all potential PT topologies and identify the most suitable one. After both evaluations, the results serve as inputs for a detailed investigation of the aircraft concepts with the implemented PT topology. This last step of the conceptual design could be an iterative process, investigating a few promising integration concepts.

Since the aircraft concept has an immense influence on the PT topology, a brief overview of the promising aircraft concepts is given here. Concept 1 is a twin boom empennage design combined with a high wing and DEP along the wing. Originating from the NASA/DLR design challenge from 2019 [10] aircraft concept 2 features the `HyBird´ design with electrical motors located at the tip of the wing and the V-Tail. Purpose of the wing tip and tail tip propulsors is to decrease the induced drag of an aircraft when acting as a counter vortex propulsor [11]. The aircraft concept 3 represents a business jet with a low wing design and two main propulsors in the rear of the fuselage. A conventional transport aircraft empennage in combination with a high wing design and DEP is represented with concept 4.
The number of propulsors for concepts with DEP has not been defined in that early stages of the conceptual design. This is an optimization problem which is influenced by all aviation disciplines and is therefore, be investigated at a later design stage.

DOI: 10.13009/EUCASS2023-908

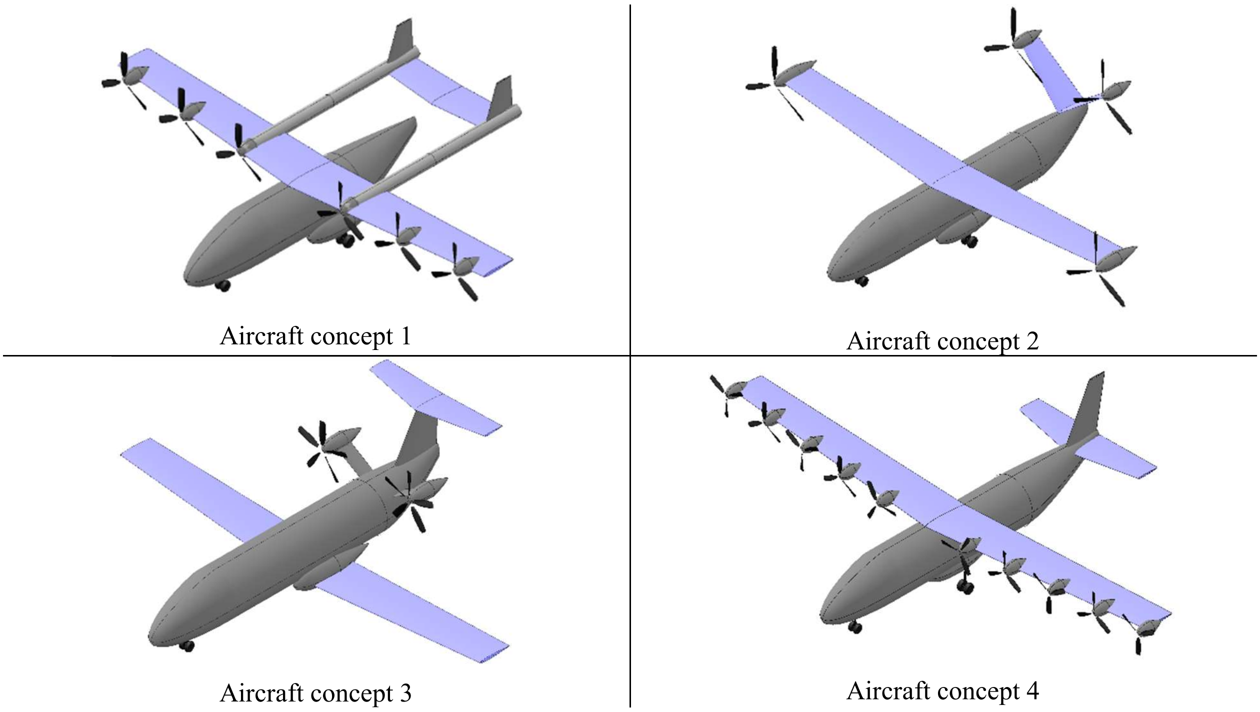


Figure 2: Promising options of aircraft concepts

Although the promising options of aircraft concepts were reduced to four promising concepts, the possible options for the PT topology and its integration are numerous. Performing numerical analysis for all aircraft concepts and all PT topologies would lead to an extensive computational effort and would be heavily time consuming. Within this paper a methodology was used to reduce the existing PT topologies to fewer options based on the aforementioned requirements and overall project goals.

2. Overview of novel aviation propulsion systems

Novel PT topologies have been presented in the literature in recent years. They can be divided into three different categories. First the `Turboelectric´ PT topologies where all propulsive energy is fuel based. In general, the ICE can be either a piston engine or a gas turbine. In contrast, an `All electric´ PT topology is based solely on electrical energy sources such as batteries or supercapacitors to feed the electric motor. In between these two categories hybrid electric PT topologies as a combination of the two aforementioned are to be found. These PT topologies can have different ratios between fuel-based energy and electrical energy and will be further defined using simplified representation of the necessary components, which will be defined in more detail at a later design stage. Hereafter the used propulsors within the PT topologies are depicted as propellers, because the defined propulsor type in the project is a propeller. However, a fan type propulsor would be feasible as well. A legend of all symbols used can be found in Figure 3.

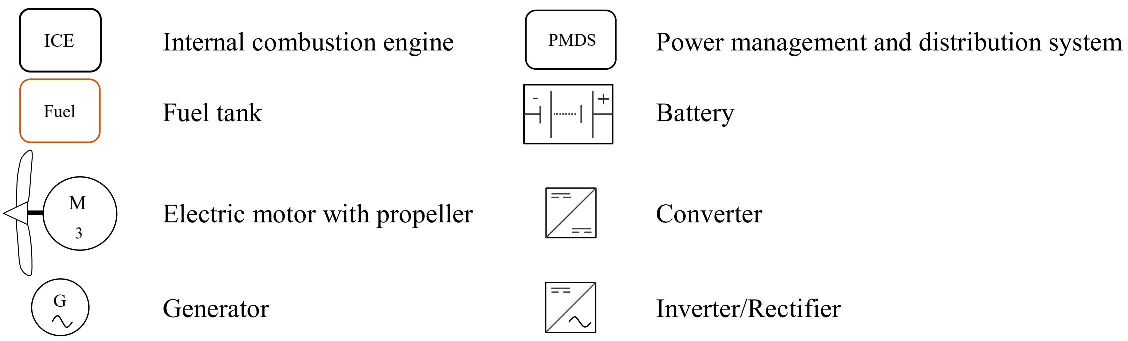
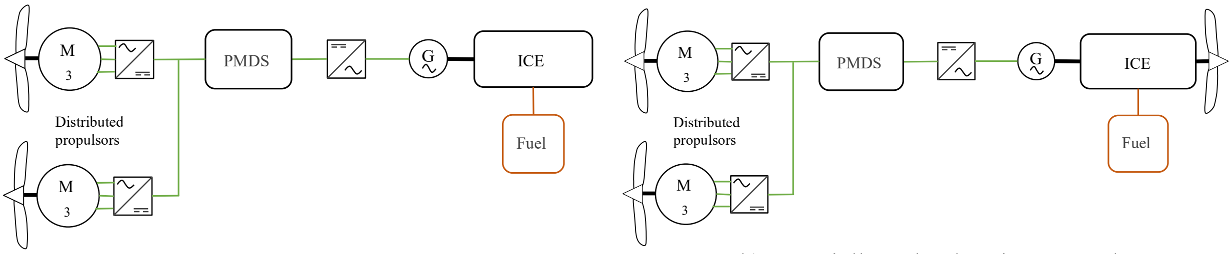


Figure 3: Overview of symbols for simplified PT topologies

Figure 4 a) shows a general overview of a `Turboelectric´ PT topology. The propulsors are driven by three phase electric motors which are connected to a power management and distribution system (PMDS) via an inverter. An ICE transforms the chemical energy stored in the fuel to mechanical, rotational energy. A generator is connected to the shaft of the ICE converting the mechanical energy to electrical energy. This electrical energy is than fed to the PMDS

DOI: 10.13009/EUCASS2023-908

via a rectifier. Since the number of electric motors can be adapted based on the aircraft concept, DEP is possible with this type of PT topology.
Compared to the `Turboelectric´ topology, the `Partially turboelectric´ PT topology consists of an ICE driving its own propulsor (Figure 4 b). With adapting the number of electric engines, it is possible to create a DEP concept with this PT topology as well. The ICE for both PT topologies needs to be controllable throughout the missions to deliver the correct power for all mission stages.



a) Turboelectric PT topology b) Partially turboelectric PT topology

Figure 4: Turboelectric and partially turboelectric PT topology

The only energy source of the `All electric´ PT topology in Figure 5 is a battery pack. Batteries are providing electrical energy to the PMDS, which is then transferred via inverters to the three-phase electrical motors. When adapting the number of electric motors, a DEP concept could be easily realised with this PT topology.

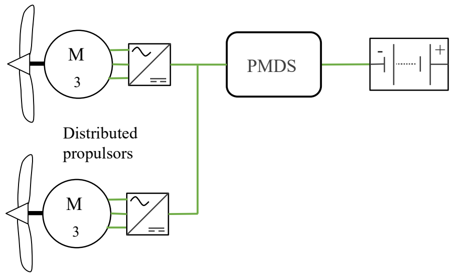
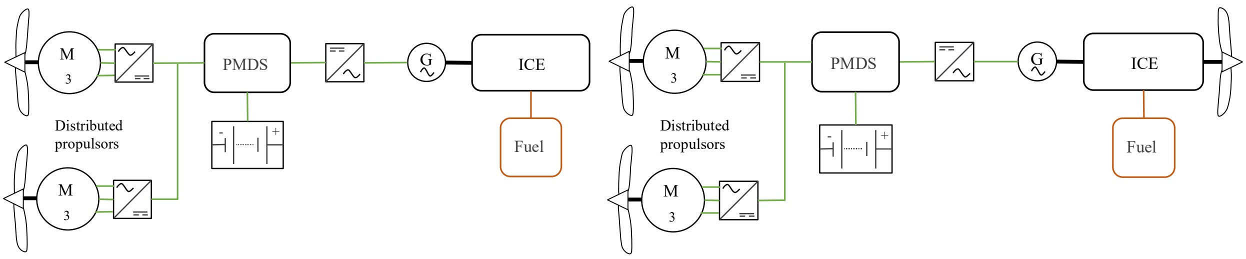


Figure 5: All electric PT topology

Figure 6 a) illustrates a `Serial hybrid electric´ PT topology. This PT topology is similar to the `Turboelectric´ PT topology, but contains an additional electrical energy source. With this acting as a redundant energy source the required electrical energy originates from fuel and batteries. Varying the number of electric motors, a DEP concept could be realised with this PT topology. It is possible to design the system such that the ICE is running in the most efficient design point throughout the entire mission.
Adding a battery system to the `Partially turboelectric´ PT topology results in `Serial/parallel partial hybrid electric´ PT topology, shown in Figure 6 b). The electric motors are feed with electric power by the ICE combined with a generator and by a battery system. The ICE itself also drives a separate propulsor producing thrust. Therefore, the ICE needs to run from idle to full thrust.



a) Serial hybrid electric PT topology b) Serial/parallel partial hybrid electric PT topology

Figure 6: Serial hybrid electric and serial/parallel partial hybrid electric PT topology

Generating the rotational power for the propulsors by a combination of electric motors and an ICE, is being referred to as `Parallel hybrid electric´ PT topology. Two potential options are shown in Figure 7 a) and Figure 7 b). The required energy is stored in fuel and batteries. In general, the rotational power for the propulsor is provided by the ICE and the electric motor. More specifically, Figure 7 a) shows the option where the electric motor and the ICE are connected to the same shaft propelling one common propulsor. This could be realized with a gearbox. Figure 7 b)

DOI: 10.13009/EUCASS2023-908

shows the option of each engine being connected to a separate propulsor. A DEP system is possible for both options. However, the second option is more suitable for DEP concept.

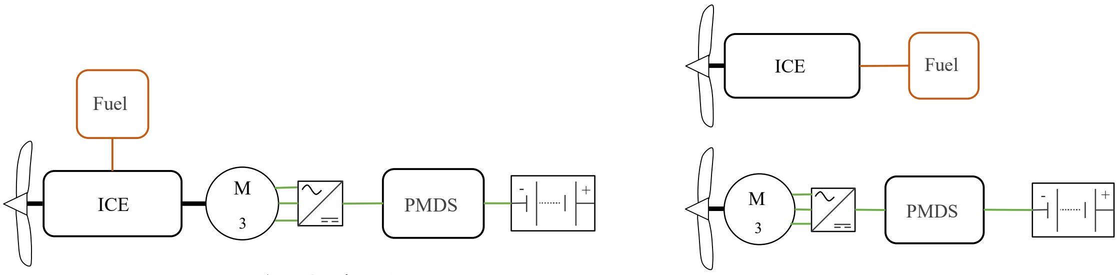


Figure 7: Parallel hybrid electric PT topologies, adapted from [12]

Analysing an in-house database, created within a literature review, including aircraft projects and concepts with various sizes using novel PT topologies hints the current dissemination of different types of PT topologies. The database includes 60 aircraft concepts within various design stages including demonstrators and a first aircraft in service for training purposes, the `Pipistrel Velis Electro´. Inputs for the database include examples from industry and academic research projects. Mainly, the aircraft maximum take-off mass (MTOM) ranges from about 400 kg to about 10 000 kg, representing general aviation and regional transport aircraft. In addition, there are 7 aircraft representing the transport aircraft sector with a maximum take-off mass of up to 200 000 kg. Figure 8 illustrates the percentage distribution of each PT topology within the database. The category `Hybrid electric´ includes `Serial hybrid electric´, `Parallel hybrid electric´ and `Serial/parallel partial hybrid electric´ PT topologies. `Turboelectric´ and `Partially turboelectric´ PT topologies are prescribed to the `Turboelectric´ category.

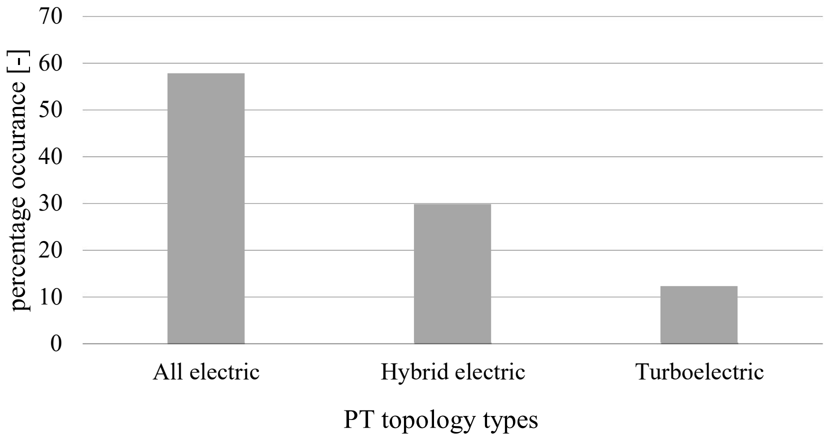


Figure 8: Percentage distribution between novel PT topologies in current aircraft projects

Of the aircraft concepts analysed, 58 % are based on an `All electric´ PT topology. These aircraft are either low range and low PAX or concepts with a low technology readiness level (TRL) and relatively late entry into service (EIS), relying on improvements in battery technologies. About 30 % of the PT topologies are `Hybrid electric´ PT topologies while 12 % belong to the `Turboelectric´ category.

For these novel PT topologies, the degree of energy hybridization and the degree of power hybridization can be identified for an aircraft PT topology. The degree of energy hybridization H_E is defined by the ratio of installed electrical energy E_{Elec} to the total installed energy through

$$H_E = \frac{E_{Elec}}{(E_{Elec} + E_{Fuel})}, \tag{1}$$

where E_{Fuel} is the amount of chemical energy stored in fuel. Installed electrical energy includes the energy stored in electrochemical cells, such as batteries or supercapacitors. The degree of power hybridization H_P is defined by the ratio between the electrical installed power and the total installed power through

DOI: 10.13009/EUCASS2023-908

$$H_P = \frac{P_{EM}}{(P_{EM} + P_{ICE})}. \quad (2)$$

For a `Parallel hybrid electric´ PT topology $P_{EM}$ is the power of the installed electric motors and $P_{ICE}$ the power of the ICE [13]. Since in a `Serial hybrid electric´ PT topology all propulsion comes from electric motors, the ICE driving a generator is not considered as installed combustion power.
Characterized with the hybridization degree with regards to power and energy, Figure 9 displays different aircraft concepts in terms of their degree of power hybridization (ordinate) and their degree of energy hybridization (abscissa). The diagram shows an excerpt of the analysed database with only displaying the aircrafts with known hybridization degrees. The hybridization degree was known for 44 aircrafts, with 33 `All electric´ aircraft and the remaining aircrafts displaying in the diagram below. For `All electric´ only an excerpt of available aircrafts is shown in the diagram.

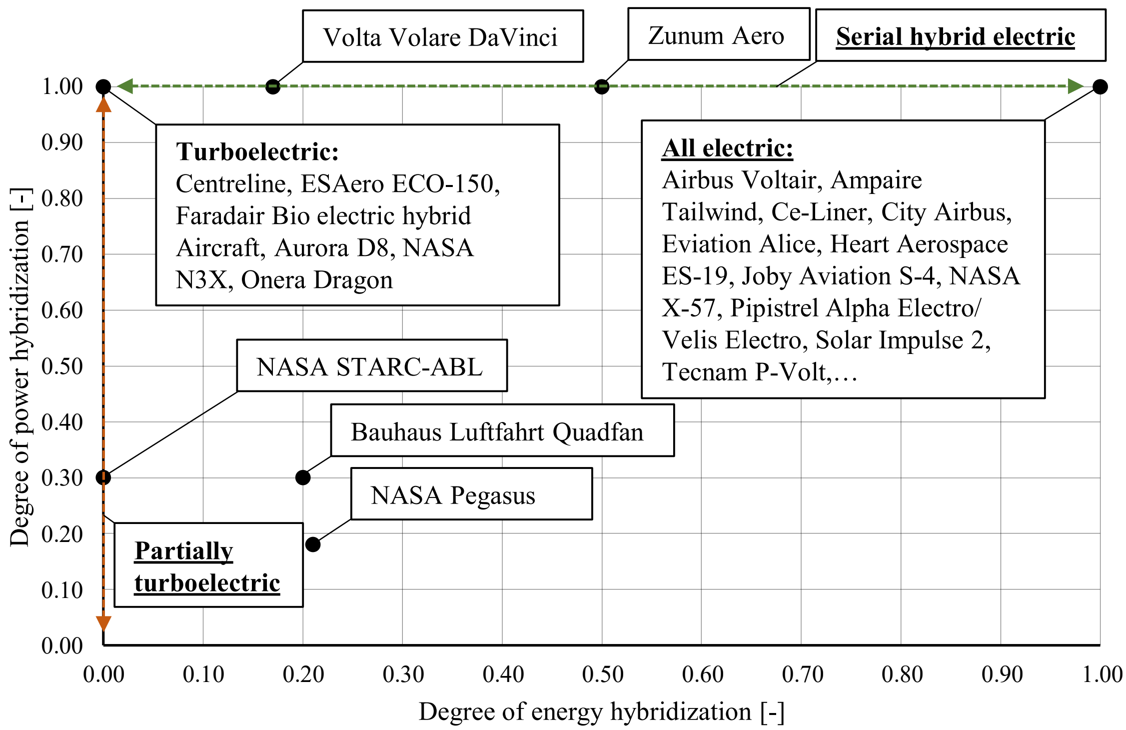


Figure 9: In-house database analysis of PT topologies from various projects and concepts

Aircrafts located on the ordinate in the diagram are equipped with `Partially turboelectric´ PT topologies with various power ratios between electric motors and ICEs. This line is displayed with the red dotted line. The only aircraft with a `Partially turboelectric´ topology, is the `NASA STARC-ABL´. It is described by Delbecq [14], Gray *et al.* [15], Kenway *et al.* [16] and Welstead *et al.* [17]. The specific point (0;1) with zero energy hybridization and only electric motors represents the `Turboelectric´ PT topology as for example the blended wing body design from NASA presented by Felder *et al.* [18]. At the horizontal line at a degree of power hybridization of one, aircrafts with `Serial hybrid electric´ PT topologies are located with different ratios between fuel energy and battery energy. Using only electric motors and 50 % of the energy derived from a turbogenrator, `Zunum Aero´ is one example for a `Serial hybrid electric´ concept [19]. At point (1;1) with only electric motors propelling the aircraft and all the required energy originating from batteries, the `All electric´ PT topology is located. Prominent example are the `Eviation Alice´ Eviation [20] or the `NASA X-57´ described by Borer *et al.* [21] and Hall *et al.* [22]. An aircraft with a `Parallel hybrid electric´ PT topology is located depending on the power hybridization and the energy hybridization within the diagram but not on the aforementioned specific lines or points. The `NASA Pegasus project´ dealt with a `Parallel hybrid electric´ PT topology, published by Antcliff *et al.* [23] and Francisco *et al.* [24].

3. Evaluation

In the early stages of the conceptual design of an aircraft the exact geometry of the aircraft has not been defined yet. Thereby, an accurate investigation with every PT topology for each aircraft concept would result in an extensive effort. In order to generate efficient results in the early stages, a qualitative approach was selected with the goal to get an indication about the most promising options for the PT topologies based on the project targets. In the field of

DOI: 10.13009/EUCASS2023-908

engineering, a qualitative evaluation can be conducted for a lot of different decisions. In the literature various qualitative approaches for technical applications are described in Feldhusen *et al.* [4] and Lindemann [5]. Such a qualitative assessment has been conducted by Kazula *et al.* [25] to identify the most suitable fuel cell types for aviation application.
In this work a point-based evaluation with weighted criteria was applied as it is most suitable for the early conceptual design phase in a project. It allows the evaluator to assign the appropriate importance to each criterion in order to reflect the project requirements and goals. All criteria were derived from the project requirements as well as requirements considering aviation standards of safety and reliability. Furthermore, the criteria are weighted based on the importance for the project via an interview with various project members. As an overall result the weighting factors and the point-based evaluation are summed up in the overall evaluation result.

3.1 Methodology

A detailed overview of the evaluation process is shown in the flow chart in Figure 10. First, the criteria were defined with respect to the overall project goals. In a second step, discrete metrics were formulated in order to rate all PT topologies with regards to each criterion. Than the defined criteria were weighted pairwise by various engineers related to the project and the average weighting was determined. After that, each PT topology was evaluated by a point-based system according to the fulfilment of each criterion. With the weighted criteria and the PT topology rating the overall score can be computed. In a last step the evaluation is analysed with regards to its sensitivity. By varying the weighting factors, the results can be analysed regarding uncertainties in the evaluation process.

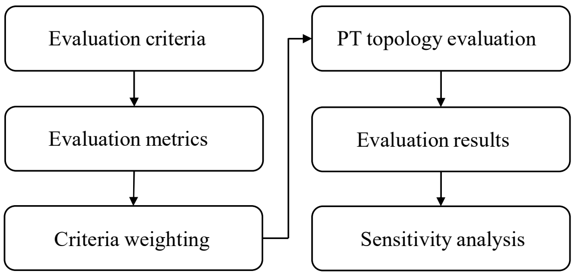


Figure 10: Flow chart for the weighted, point-based evaluation method; adapted from [4]

3.1.1 Evaluation criteria

First, the specific evaluation criteria were defined. These criteria were defined based on the overall aircraft requirements defined during the early project phases and important project goals such as, for instance, a high degree of flexibility with regards to future PT technologies. Eventually six evaluation criteria were chosen. In addition, metrics were defined to evaluate each PT topology for each criterion and are listed in Table 1.
The criterion `Performance and efficiency´ (P) is linked to the operating efficiency and overall potential performance of the PT topology. Furthermore, the operating points of a possibly ICE is considered as well. Dealing with the complexity of the PT topology and therefore, with the expected effort developing an integrational concept for the PT topology `Ease of integration´ (I) is the second defined criterion. Moreover, the defined requirement of having the option to realise a DEP concept is represented by this criterion as well. In the criterion `Weight´ (W), the evaluation metric consists of the expected power and energy density for each component, the sizing point of a possibly ICE and the requirement of additional batteries to handle a dynamic behaviour of the PT. The next criterion `Safety´ (S) is about the redundancy in energy sources and thrust generation for each PT topology. Since one key aspect is the assessment of the aircraft's development and operational costs, with the aim to reduce these costs, in order to develop and operate the aircraft in accost efficient way, the criterion `Development and operational costs´ (C) was defined. In particular, the criterion considers the necessity to develop complex and therefore, expensive components for the PT topology (e.g. propulsion control systems or mechanical couplings such as gearboxes). The last criterion `Flexibility´ (F) represents the requirement of a flexible PT topology. The goal is to design an aircraft with a PT topology which could be upgradeable in the future when new technologies for batteries arises. This criterion also represents the characteristics that the PT topology should have the capability to operate in different modes, so that the aircraft can be optimized for various flight missions.

DOI: 10.13009/EUCASS2023-908

Table 1: Discrete metrics for the evaluation of each criterion

Criteria	Evaluation metric
Performance and Efficiency (P)	-Operating efficiency and overall performance of the PT topology -Operating point of the ICE
Ease of Integration (I)	-Complexity of the PT topology and the required maintenance procedures -Suitability for DEP
Weight (W)	-Power and energy density of components used -Sizing point of the ICE -Necessity for buffer battery to achieve targeted dynamic behaviour
Safety (S)	-Redundancy in thrust generation -Redundancy in energy sources
Development and operational costs (C)	-Necessity for complex, expensive components during development (e.g. propulsion control system, gearboxes)
Flexibility (F)	-Flexibility regarding future technology improvements – allowing for replacement of components in the PT-Different operational modes are possible for different applications / missions

3.1.2 Criteria weighting

The criteria weighting was executed via a pairwise comparison between each criterion as described by Feldhusen *et al.* [4] and Lindemann [5]. All criteria are compared against each other in a matrix and the corresponding cell is filled with a specific value depending on which criterion is more important. If the criterion located in the row is more important than the criterion from the column, the value two is inserted in the cell. Whenever both criteria are equally important, a one has to be inserted. If the criterion in the row is less important than from the column, the cell is filled with a zero. After the matrix is filled all values in each row are summed up to s_j. This value is then divided by the overall sum of all matrix cells S, leading to the relative weighting factor for each criterion w_j. An example is shown in Table 2.

$$\mathrm{w_j} = \frac{s_j}{S} \tag{3}$$

Table 2: Example for a pairwise comparison to weight the evaluation criteria

Criteria	P	I	W	S	C	F	Sum of the rows	relative weighting factor
Performance and efficiency (P)	-	2	2	1	2	2	9	0.3000
Ease of integration (I)	0	-	0	0	1	1	2	0.0667
Weight (W)	0	2	-	0	2	1	5	0.1667
Safety (S)	1	2	2	-	2	2	9	0.3000
Development and operational costs (C)	0	1	0	0	-	1	2	0.0667
Flexibility (F)	0	1	1	0	1	-	3	0.1000
Sum							**30**	**1**

This procedure was performed by seven engineers from the aerospace sector independently and all are directly working on the project or closely linked to the project. The resulting weighting factors from all engineers were averaged and served as the weighting factors for the evaluation process. These averaged values are shown with the corresponding standard deviation in Figure 11. The most important criteria are \`Safety´ and \`Performance and efficiency´. This corresponds with the criteria weighting by Kazula *et al.* [25]. They compared their weighting results with aviation literature and reveals that \`Safety´ and \`Performance and efficiency´ are the most important parameters for fuel cell applications in aviation. The standard deviation for the criteria \`Safety´ and \`Development and operational costs´ is about 10 % and thus, nearly twice the amount of all other criteria. This indicates are relatively wide spread understanding of the importance of these two criteria amongst the engineers.

DOI: 10.13009/EUCASS2023-908

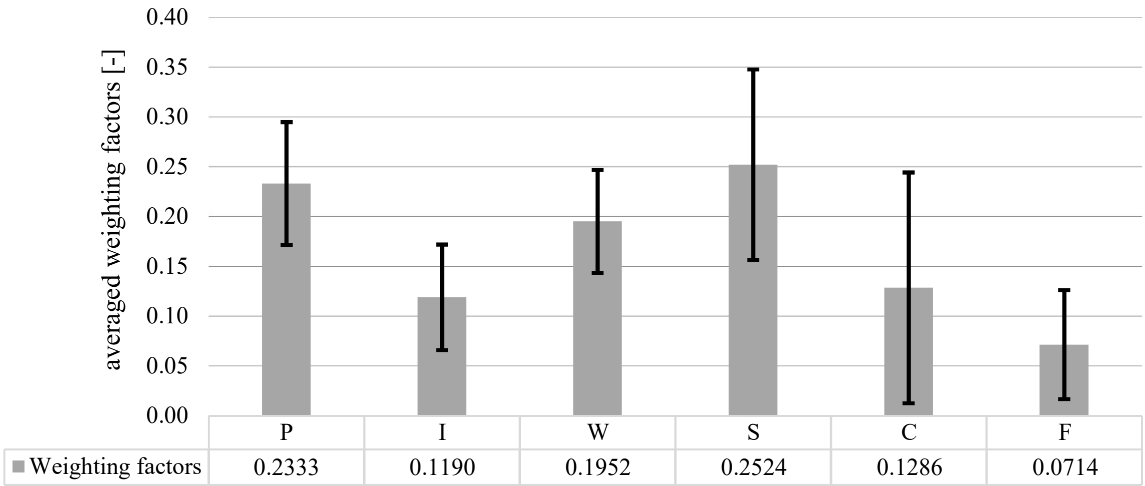


Figure 11: Averaged weighting factors and standard deviation

3.1.3 Powertrain topology rating

Next, the evaluation of each PT topology is performed by assigning a score to each option for each criterion. Thus, a numerical scale with a discrete dimension has to be defined and has to be used throughout the evaluation process [5]. With smaller scales, a misjudgement at one point has a higher influence on the overall result compared to a misjudgement on a larger scale. Therefore, smaller scales are more sensitive to misjudgements [25]. On the other hand, smaller scales are more suitable when a detailed understanding of the characteristics is not available in early conceptual design stages [6]. Wider scales offer the ability for a finer evaluation, but require a more detailed understanding of each PT topology. In Lindemann [5] and Pahl *et al.* [6] the scale varies between 0 to 4 and 0 to 10 depending on the level of detail known and required. Since the evaluation took place in the early conceptual design a scale with points from 0 to 4 was used in the presented evaluation.
The assignment of the points was performed with an extensive literature review, including basic literature and reports from aircraft projects in various development stages. First, the PT topologies with the worst and best characteristics for each criterion were rated. Afterwards, all PT topologies in between were fitted in the evaluation as described by Pahl *et al.* [6]. Similar to Kazula *et al.* [25], the points are assigned by mathematical operators with the following logic:

- very good fulfilment: 4 points = ++
- good fulfilment: 3 points = +
- average fulfilment: 2 points = 0
- bad fulfilment: 1 point = -
- very bad fulfilment: 0 points = --

The evaluation results are shown in Table 3.

Table 3: PT topology rating based on the defined metrics

	Serial hybrid electric	**Parallel hybrid electric**	**Serial/parallel partial hybrid electric**	**Turboelectric**	**Partially turboelectric**	**All electric**
Performance and efficiency (P)	-less efficient than parallel hybrid electric [26] -ICE can run in optimal design range [26]	-more efficient than serial hybrid electric [12] -ICE have to run in various operating points	-similar efficiency as serial hybrid electric [27] -ICE have to run in various operating points	-less efficient than parallel hybrid electric -ICE have to run in various operating points	-similar efficiency than serial hybrid electric -ICE have to run in various operating points	-most efficient PT topology; but poor overall performance with current technology
	+	++	0	0	0	+

DOI: 10.13009/EUCASS2023-908

Ease of integration (I)	-simple PT topology [26] -well suited for DEP [13]	-low complexity -not well suited for DEP	-high complexity -DEP is possible with limitations	-comparable to serial hybrid electric -well suited for DEP	-medium to high complexity -DEP is possible with limitations	-lowest complexity -well suited for DEP
	+	0	-	+	-	++
Weight (W)	-EM has to deliver full thrust; more weight [12, 26] -large battery mass is required [26]	-ICE and EM can be sized smaller compared to serial hybrid electric [12] -battery only for dynamic behaviour	-ICE and EM can be sized smaller compared to serial hybrid electric -large battery mass is required	-EM has to deliver full thrust; more weight -avoids battery weight penalty	-ICE and EM can be sized smaller compared to serial hybrid electric -battery only for dynamic behaviour	-only EM necessary -Specific energy and specific power of batteries are too low
	0	+	0	+	+	--
Safety (S)	-redundant energy sources [26] -no redundant propulsors (unless DEP)	-redundant energy sources -no redundant propulsors (unless DEP)	-redundant energy sources -redundant propulsors	-no redundant energy sources -no redundant propulsors (unless DEP)	-no redundant energy sources -redundant propulsors (unless DEP)	-no redundant energy sources -no redundant propulsors (unless DEP)
	+	+	++	-	0	-
Development and operational costs (C)	-ICE and EM are not mechanically coupled [28] -possibility to rely on existing technology for ICE	-coupling of EM and ICE necessary [26] -more sophisticated propulsion control system needed [26]	-ICE and EM are not mechanically coupled -more sophisticated propulsion control system needed	-ICE and EM are not mechanically coupled	-ICE and EM are not mechanically coupled -more sophisticated propulsion control system needed	-extensively high development cost for new technology necessary -no mechanical coupling
	+	-	0	+	0	-
Flexibility (F)	-flexibility in design [12] and operational modes -upgrade to \`All electric´ is possible	-limited flexibility in design and operation -no possibility to run \`All electric´	-flexibility in design and operation -\`All electric´ would be possible with integrational changes	-no flexibility in design and operation -Upgrade to \`All electric´ is easily possible	-limited flexibility in design but no operational flexibility -upgrade to \`All electric´ is possible with changes	-no flexibility required -upgrade for new batterie technologies easily possible
	++	-	+	0	-	++

DOI: 10.13009/EUCASS2023-908

3.2 Evaluation results

In a last step for the evaluation procedure the overall, weighted evaluation result was computed. The weighting factors and the PT topology rating is summarized in Table 4.

Table 4: PT topology rating and weighting factors

Criterion	Serial hybrid electric	Parallel hybrid electric	Serial/parallel partial hybrid electric	Turboelectric	Partially turboelectric	All electric	Relative weighting factor
P	3	4	2	2	2	3	0.2333
I	3	2	1	3	1	4	0.1190
W	2	3	2	3	3	0	0.1952
S	3	3	4	1	2	1	0.2524
C	3	1	2	3	2	1	0.1286
F	4	1	3	2	1	4	0.0714
Result	0.7190	0.6786	0.6143	0.5476	0.5012	0.4607	

To compute the weighted evaluation results, equation (4) is used. The weighted evaluation result for each topology wR_i is the sum of the product of the individual score $m_{j,i}$ and the weighting factor for each criterion w_j divided by the step size of the scale for the topology rating with k being the number of criteria.

$$wR_i = \sum_{j=1}^{k} \frac{w_j \cdot m_{j,i}}{4} \qquad (4)$$

The weighted evaluation results are shown in the last row of Table 4. The `Serial hybrid electric´ PT topology received the highest rating. It is followed closely by the `Parallel hybrid electric´ PT topology in second place and then the `Serial/parallel partial hybrid electric´, the `Turboelectric´ and the `Partially turboelectric´ PT topology. In last place of the ranking of this evaluation is the `All electric´ PT topology. Since the difference between the first two PT topologies is small, the most promising options to consider for further detailed analysis and design are the `Serial hybrid electric´ and the `Parallel hybrid electric´ PT topology for the given aircraft and project requirements.

3.3 Vulnerability and sensitivity analysis

As stated by Feldhusen *et al.* [4] a lot of misjudgements can be made in the evaluation process, leading to non-representative result for the project and therefore, could be the reason for not being able to fulfil the original requirements in the end. First a vulnerability analysis was performed as described by Pahl *et al.* [6], in order to search for weak spots within the PT topology options. Weak characteristics within certain criteria could be concealed by the evaluation result if the corresponding weighting factor is low and so the influence on the evaluation result is minimal. As suggested in various sources [4–6] this analysis is performed in a visual manner - displaying the weighting factors and the rating for each criteria for the most promising PT topologies. The result is illustrated in Figure 12 for the two most promising PT topologies in bar diagrams, where the width of each bar corresponds with the relative weighting factor for each criterion. The abscissa displays the PT topology rating and the ordinate all six criteria labelled with the associated abbreviations. In general, the amount of grey area represents the weighted evaluation result for both PT topologies.

Investigating the vulnerability for the `Serial hybrid electric´ PT topology, the lowest score for this PT topology is two for the criterion `Weight´. For all other criteria, this PT topology was rated with three or higher. For the `Parallel hybrid electric´ PT topology, the lowest score is one for the criteria `Flexibility´ and `Development and operational costs´. All other ratings for this PT topology assigned a value of two or even higher. The characteristics with low rating should be investigated in more detail when choosing one of these PT topologies because there could be a potential risk for weak characteristics.

Furthermore, a sensitivity analysis was performed as recommend by Feldhusen *et al.* [4] and Lindemann [5] by varying each weighting factor independently and considering an evaluation with the weighting factors of a specific aspect (e.g. technical or economic related).

DOI: 10.13009/EUCASS2023-908

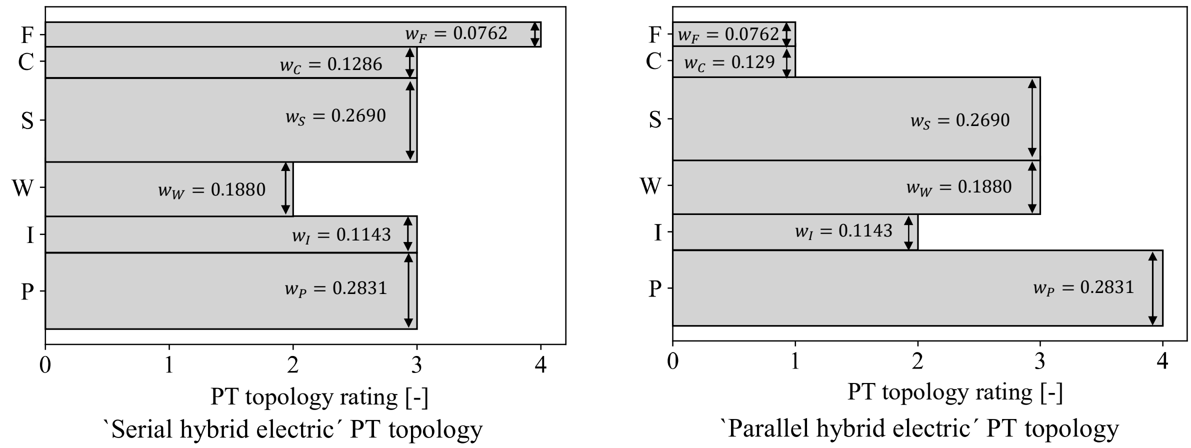
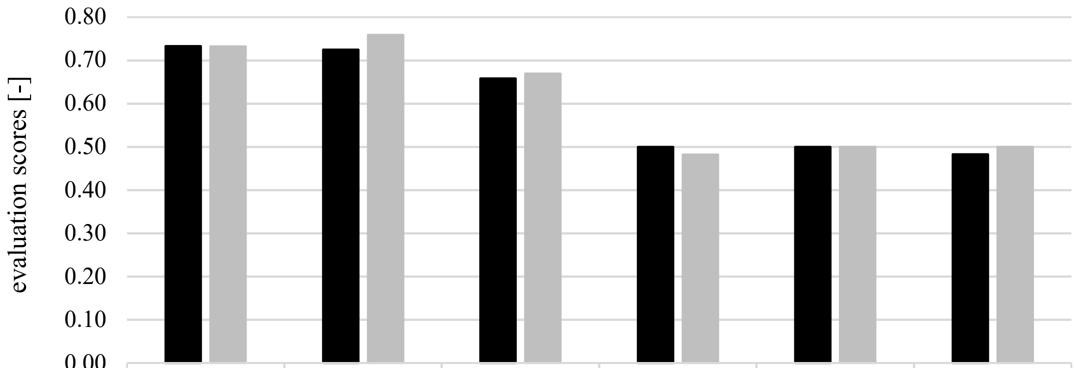


Figure 12: Value profiles with corresponding weighting factors

By only considering weighting factors related to technical characteristics – meaning an evaluation without criterion C – the ranking of the two best PT topologies changes, while the rank of all other PT topologies remains as shown in Figure 13.



	Serial hybrid electric	Parallel hybrid electric	Serial/parallel partial hybrid electric	Turboelectric	Partially turboelectric	All electric
■ Baseline Evaluation	0.7333	0.7250	0.6583	0.5000	0.5000	0.4833
■ Technical Evaluation	0.7321	0.7589	0.6696	0.4821	0.5000	0.5000

PT topologies

■ Baseline Evaluation ■ Technical Evaluation

Figure 13: Comparison of technical evaluation with overall weighted evaluation

Investigating the influence of the weighting factors on the evaluation result, all criteria were investigated independently. While varying one weighting factor within a range of +/-20 % for one criterion, the ratio between the other criteria was remained constant. The results for the criterion `Safety´ is shown as an example in Figure 14. These investigations were performed for all criteria, but is only presented for the most important criterion, since the greatest changes were observed for that particular case.
The evaluation result of the top two PT topologies and the `Partially turboelectric´ PT topology remains nearly constant for the investigated range, while the remaining three PT topologies show minor changes for the evaluation score, but no changes in the ranking of the PT topologies.
With the sensitivity and vulnerability analysis, the evaluation can be seen as robust against small fluctuations in the criteria overall weighting as omitting selected criteria or varying each weighting factor did not lead to significant changes in the evaluation results.

DOI: 10.13009/EUCASS2023-908

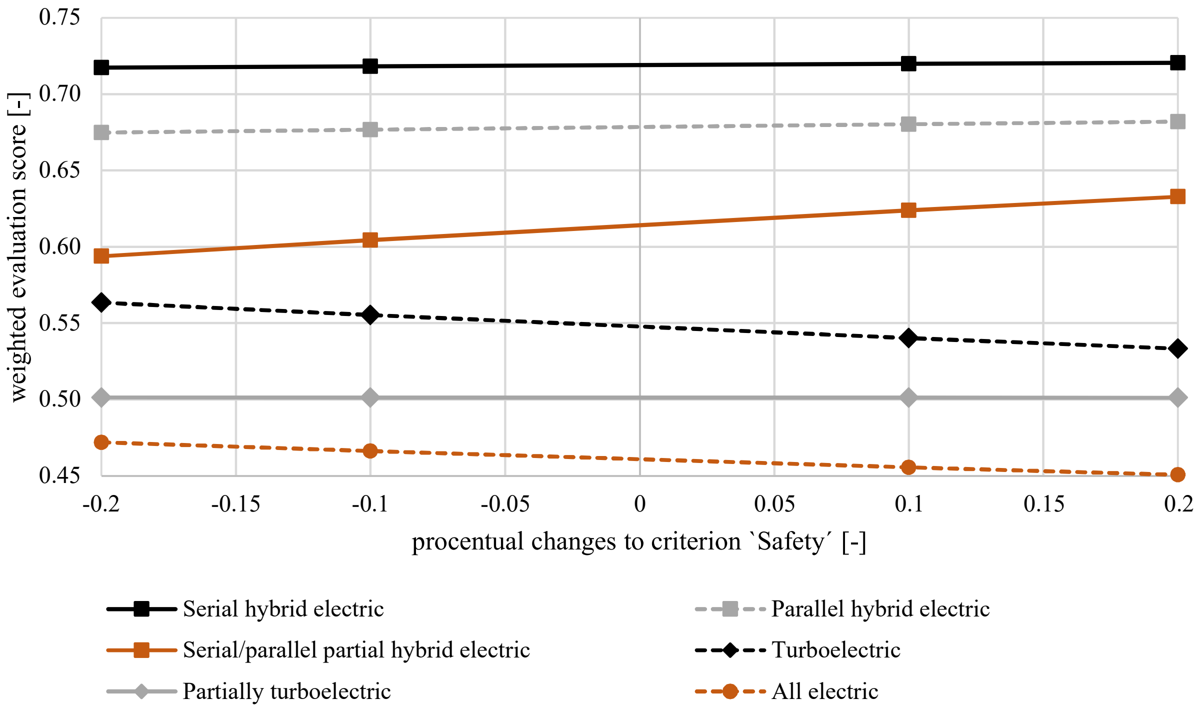


Figure 14: Sensitivity analysis for criterion `Safety´

4. Integration of powertrain topology in an aircraft concept

Since the most promising PT topologies have been identified now, they can be applied on to the aircraft concepts from the conceptual design. Through this, a more detailed topology can be built, including all necessary components to implement the topology in the airframe. According to Will *et al.* [9], the high wing aircraft concept 4 with 10 propulsors as a DEP is a promising option. This aircraft concept was selected to apply the `Serial hybrid electric´ PT topology. Table 5 lists more information about the specific aircraft concept.

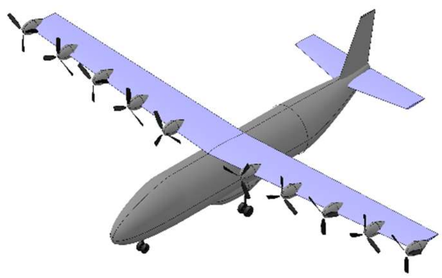


Figure 15: Aircraft concept 4

Table 5: Preliminary specifications to concept 4

Parameter	Value
wing span, m	15
fuselage length, m	12
MTOM, kg	4120
cruise speed, m/s	133

Since the aircraft concept has not been finalized yet, some minor changes are possible to the aircraft concept e.g. the number of engines. Smaller changes to the airframe e.g. the position of the wing or the exact fuselage length will not influence the PT topology at the current investigated level of detail.

The schematic overview of a first integration concept for a `Serial hybrid electric´ PT topology to the aircraft concept 4 is depicted in Figure 16. A second integration concept was done for the `Parallel hybrid electric´ PT topology but only one concept is presented here. The battery pack as well as the ICE are connected to a PMDS. Using one turbine engine as the ICE is one possible solution, however the decision on which type of ICE will be utilized in this project has not been made yet. A generator connected on to the shaft of the ICE is used to converted the mechanical power to electrical power. This electrical power is transferred to direct current via a suitable converter. The PMDS feeds the HV DC bus via multiple converters to ensure necessary degrees of redundancy. For each electric motor a separate inverter is necessary to feed the motors with the conditioned alternate current. These inverters are connected to the HV DC Bus directly in this design. It is expected that the battery system needs a thermal management system to establish and maintain ideal operating conditions in the environment of the battery system in an aircraft.

DOI: 10.13009/EUCASS2023-908

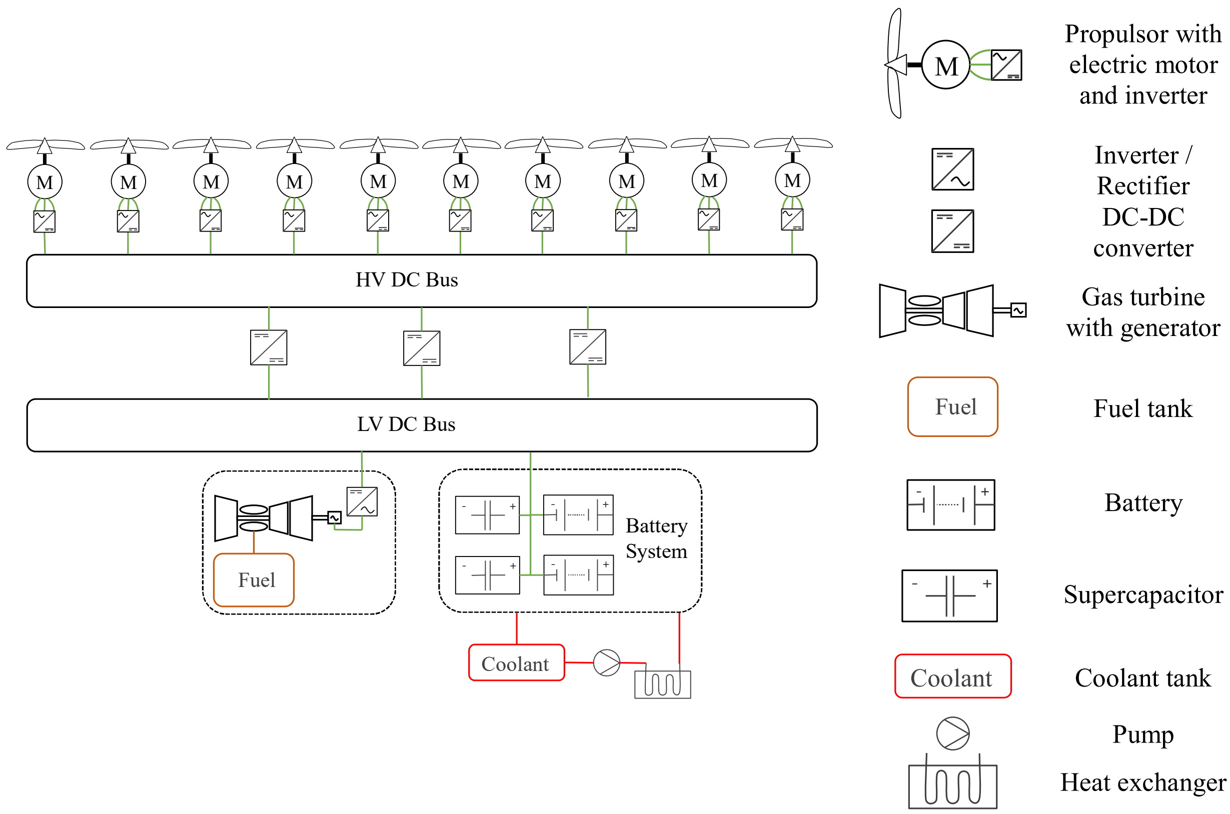


Figure 16: Schematic overview for a `Serial hybrid electric´ PT topology in aircraft concept 4

5. Conclusion and Outlook

The most prominent options for electric and hybrid electric PT topologies have been presented in this work and their specific characteristics were analysed. Furthermore, one possible qualitative evaluation methodology was presented with the goal to reduce the number of possible options of novel PT topologies to be investigated in more detail during later stages of the development. This methodology was applied to a nine-seater general aviation aircraft concept and resulted in a ranking of the presented PT topologies. The weighted points rating was carried out considering the specific requirements of the aircraft concept at hand. After the evaluation, a vulnerability analysis to detect significant weaknesses in top ranked PT topologies was conducted, revealing no such weaknesses in the evaluation process. In addition, a sensitivity analysis to investigate the influence of the small deviations in the weighting factors on the overall result was performed. For a range of +/-20 % difference for each weighting factor, no changes in the top ranked PT topologies could be observed. Finally, a schematic illustration of applying a `Serial hybrid electric´ PT topology to an exemplary aircraft concept was presented.

With these schematic overviews of the most promising PT topologies applied to a few promising aircraft concepts, a more detailed, quantitative investigation of the overall best solution can be performed. Therefore, tools for the overall aircraft design as well as tools for modelling the PT are applied together in one workflow to analyse and size the required aircraft and the PT components based on various flight missions and performance requirements.

By further developing such novel power and propulsion system architectures, future sustainable aviation can be enabled. In order to provide first proof of concept, the implementation in the general aviation sector is deemed to be a suitable application.

References

[1] European Union, “Flightpath 2050 Europe`s Vision for Aviation,”.

[2] Air Transport Action Group (ATAG), “Waypoint 2050: An AIr Transport Action Group Project,”.

[3] Martin Hepperle, “Electric Flight - Potential and Limitations,” 1 Jan. 2016.

[4] Feldhusen, J., and Grote, K.-H., *Pahl/Beitz Konstruktionslehre. Methoden und Anwendung erfolgreicher Produktentwicklung,* Springer-Verlag, Berlin/Heidelberg, 1 Jan. 2005, 883.

[5] Lindemann, U., *Methodische Entwicklung technischer Produkte,* Springer-Verlag, Berlin/Heidelberg, 1 Jan. 2005, 347.

DOI: 10.13009/EUCASS2023-908

[6] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H. (eds.), *Engineering Design A Systematic Approach*.

[7] Kazula, S., “Konzeptstudie bezüglich variabler Pitot-Triebwerkseinlässe für kommerzielle Überschallflugzeuge mittels eines Entwicklungsansatzes für sichere Produkte,”.

[8] Will, F., Flüthmann, N., and Eschmann, C., “Derivation of Top-Level Aircraft Requirements for Small Aircraft Transport by Modelling Demand in Europe,”.

[9] Will, F., Ladwein, F., and Zill, T., “Design and evaluation of novel general aviation aircraft concepts with a fully integrated powertrain for regional air mobility,”.

[10] Mangold, J., Lang, M., Stober, J., Ladwein, F., and Will, F., “NASA/DLR Design Challenge 2019 HyBird Aircraft Concept,”.

[11] Melvin H. Snyder Jr., “Effects of a wingtip-mounted propeller on wing lift, induced drag, and shed vortex pattern,”.

[12] D. Felix Finger, “Methodology for Multidisciplinary Aircraft Design under Consideration of Hybrid-Electric Propulsion Technology,” 1 Sep. 2020.

[13] Gkoutzamanis, V., “HECARRUS Project Hybrid Electric Small Commuter Aircraft Conceptual Design,” 1 Jan. 2020.

[14] Delbecq, S., “Knowledge-Based Multidisciplinary Sizing and Optimization of Embedded Mechatronic Systems - Application to Aerospace Electro-Mechanical Actuation Systems,”.

[15] Gray, J. S., Kenway, G. K., Mader, C. A., and Martins, J. R. R. A., “Aero-propulsive Design Optimization of a Turboelectric Boundary Layer Ingestion Propulsion System,” *2018 Aviation Technology, Integration, and Operations Conference,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2018.

[16] Kenway, G. K., and Kiris, C. C., “Aerodynamic Shape Optimization of the STARC-ABL Concept for Minimal Inlet Distortion,” *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2018.

[17] Welstead, J., and Felder, J. L., “Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion,” *54th AIAA Aerospace Sciences Meeting,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2016.

[18] Felder, J., Kim, H., and Brown, G., “Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid-Wing-Body Aircraft,” *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition,* American Institute of Aeronautics and Astronautics, Reston, Virigina, 1 Jan. 2009.

[19] Zunum Aero, “Zunum Aero Aircraft,” URL: https://zunum.aero/aircraft/ [retrieved 1 July 2023].

[20] Eviation, “Eviation Alice,” URL: https://www.eviation.com/aircraft/ [retrieved 1 July 2023].

[21] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Bevirt, J., et al., “Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator,” *16th AIAA Aviation Technology, Integration, and Operations Conference,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2016.

[22] Hall, D., Chin, J., Anderson, A., Smith, A., Edwards, R., et al., “Development of a Maxwell X-57 High Lift Motor Reference Design,” *AIAA Propulsion and Energy 2019 Forum,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2019.

[23] Antcliff, K. R., and Capristan, F. M., “Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept,” *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference,* American Institute of Aeronautics and Astronautics, Reston, Virginia, 1 Jan. 2017.

[24] Francisco M. Capristan, and Nathaniel J. Bleaesser, “Analysis of the Parallel Electric GAs Architecture with Synergistic Utilization Scheme (PEGASUS) Concept,”.

[25] Kazula, S., Graaf, S. de, and Enghardt, L., “Review of Fuel Cell Technologies and Evaluation of their Potential and Challenges for Electrified Propulsion Systems in Commercial Aviation,” *Journal of the global Power and Propulsion Society*, 7: 43-57.

[26] Rendón, M. A., Sánchez R., C. D., Gallo M., J., and Anzai, A. H., “Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities,” *Journal of Control, Automation and Electrical Systems*, 1 Jan. 2021.
doi: 10.1007/s40313-021-00740-x.

[27] Haran, *Electrified Aircraft Propulsion*, 1 Jan. 2022, 299.

[28] Patrick Christoph Vratny, “Conceptual Design Methods of Electric Power Architectures for Hybrid Energy Aircraft,” 1 Jan. 2018.