Parametric modeling of the aircraft electrical supply system for overall conceptual systems design

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Abstract

Owing to the ongoing endeavor to gradually improve aircraft operational efficiency with the use of electrified on-board system concepts, computational modeling of the electric power supply system (EPSS) is becoming an even more important element of the system design process. The rising complexity innate to the early decision for an optimal system layout of such a More Electric Aircraft makes it necessary to use integrated and physics-based system models to study most promising concepts from an overall systems and aircraft level perspective. In this paper, a parametric model of the EPSS is presented, which is implemented into the overall systems design environment GeneSys. The parametric approach of the proposed method not only allows to evaluate promising architecture variants but also has the flexibility to study the effect of topological design decisions (positioning, routing) on system-level metrics. This includes routines for knowledge-based and automated generation of the EPSS topology based on parametric geometry information of the aircraft. In addition, a component-based system sizing and steady-state simulation process is used to estimate mass and electric load profile of the system for a given flight trajectory. To demonstrate the implemented model, the result of three exemplary topology studies are discussed.

1. INTRODUCTION

The benefits and drawbacks of an electrified on-board systems architecture for future aircraft has been discussed for decades [1]. However, literature still draws a disagreeing picture on which extent the further electrification might contribute to the reduction of cost factors like assembly, maintenance, or fuel burn during aircraft operations. This stems, among others, from an increased level of interdependence between systems and a growing significance of coupling effects with other aircraft design disciplines like engine, aerodynamics, structures, or production. The rising complexity innate to the design of such More Electric Aircraft (MEA) makes it necessary to use integrated and physics-based system models for concept studies on an overall systems and aircraft level.

To this end, the Institute of Aircraft Systems Engineering (FST) at Hamburg University of Technology (TUHH) has developed the *GeneSys* framework. It supports overall systems design (OSD) studies based on a parametric and component-based system modeling approach [2, 3, 4]. *GeneSys* comprises a set of sizing and steady-state simulation modules for several aircraft systems which have a relevant impact on aircraft level metrics like mission fuel burn. These systems are both consumer systems (e.g. environmental control, flight control) and their respective power supply networks (electric, hydraulic, pneumatic).

With the trend towards an increased on-board electrification, specifically the design of the electric power supply system (EPSS) is becoming more complex, because the number of (safety-critical) electric consumers connected to the EPSS and their range of electric power demand will further increase [5]. A respective component-based network model for the EPSS that covers the required design complexity of electrified architectures has, however, not been implemented into *GeneSys* so far.

To find a suitable layout for the EPSS, early concept studies using physics-based sizing and simulation models for such complex supply networks have to be performed. In essence, two questions are answered by these studies:

1. Which power sources (Engine, Fuel Cell, Battery, etc.) should be deployed to provide electrical power under all relevant operating conditions and how is the power share defined during these scenarios?

2. How should the supply networks be specified with respect to the number of redundant networks, type of power (AC, DC), grid structure (centralized, decentralized) and topology (positioning, routing)?

The first question is closely related to the design and selection of propulsion concepts and the overall (primary and secondary) power supply layout in general.

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The second question is more specific as it aims at architectural decisions on overall systems level, namely the layout of the electrical generation and distribution system to supply power for electric consumer aboard the aircraft. To answer the first question, it is necessary to initially integrate methods that can answer the second question.

In this paper, the integration of an EPSS model for OSD is presented, which is suitable to perform studies related to the second question. It constitutes the basis for a future model extension for more complex studies pertaining to both issues. To this end, a parametric model of the EPSS is integrated into *GeneSys* which has the flexibility to perform automated topological layout studies on system level based on predefined network specifications. This includes an algorithm for knowledge-based and automated generation of the EPSS topology based on parametric geometry information of the aircraft. The generation of a topology is proceeded by a component-based system sizing and steady-state simulation process.

The paper is structured as followed. In section 2, the general layout of modern EPSS is described. The parametric model of the EPSS is elaborated in section 3. The *GeneSys* framework and the integration of the EPSS model is described in section 4. The sizing process and three exemplary topology studies are presented in section 5.

2. LAYOUT OF A MODERN ELECTRIC POWER SUPPLY SYSTEM

The architecture of an aircraft EPSS typically consists of power generation units, power distribution units, and the wiring harnesses. These cables and components are used to distribute the electric power to all on-board consumer systems. In addition, some of these components include converters to adapt the voltage level and voltage type of individual power lines or networks.

Older EPSS architectures were arranged in a centralized manner, which is also one of the most significant differences from more modern architectures [6]. Within these conventional architectures, the generated power is transported to the primary power distribution center (PEPDC) which is located in the electronic bay in the front of the fuselage [6]. From there, the electric power is distributed to all electrical consumer systems in the aircraft. Before the electric power is supplied to each consumer system, it passes circuit breaker panels (CBP) which are typically located in the front and in the rear of the aircraft [6]. Circuit breakers are protection devices to avoid an electrical overload. In case of an overload, the circuit breaker opens the circuit mechanically [5].

In larger passenger airplanes, the voltage is generated as a three-phase electric current [7]. Some consumer systems require a supply of a single-phase electric current or a direct current. This applies for instance to cockpit systems and lights. Components such as transformer rectifier units (TRUs) which are part of the PEPDC, are used to adapt the voltage type and voltage level from alternating current to direct current [8].

The difference to a more decentralized architecture of a modern EPSS essentially applies for consumer systems which are both non-critical for flight and do not require high electrical loads [9]. The motivation to replace the centralized system by a decentralized system is a decrease of the total cable length and a more efficient power management system [6]. An example of a modern EPSS architecture is displayed in Figure 1. The generators at the main engines and at the auxiliary power unit (APU) which is located in the aft fuselage are directly connected to the PEPDC. The PEPDC supplies electric power to the secondary power distribution boxes (SPDBs) which are located in the cabin area. The SPDBs supply the consumer components in the cabin and cargo area which are located closest to the particular SPDB [6, 10].

The secondary power distribution center (SEPDC), which supplies safety-uncritical consumer systems with reduced power requirements [6, 10], and the SPDB were introduced in the Airbus A380 [9] and continued to be developed in modern system architecture layouts such as in the Boeing 787 and Airbus A350 [8, 11]. The SEPDC and SPDBs contain solid-state power controllers (SSPC) that replace the mechanically triggered CBPs [8]. The SSPCs provide a digital and automatic load protection and switching functionality [5]. The PEPDC is also directly connected to the SEPDC.

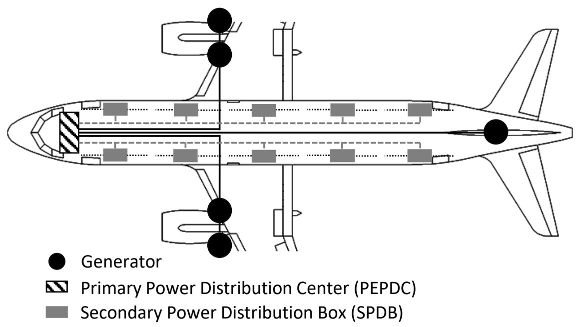


FIGURE 1. EPSS architecture of MEA

A decentralized arrangement of the EPSS system opens up the design space for number and location of distribution units. It is therefore necessary to optimize these topological degrees of freedom with the objective to reduce system mass.

Proposals for newer EPSS architectures for all electric aircraft (AEA) include the usage of high voltage direct current (HVDC) to supply consumer systems with electric power [11, 12, 13]. Because some AEA concepts include, for example, fuel cells and batteries as direct current power sources to supply aircraft on-board systems, the voltage does not need to be transformed into alternating current for an HVDC network. For electrical consumers, which use alternating current, DC power is converted to AC with locally installed inverters at the respective consumer. This may apply to consumer systems such as motors [11].

3. PARAMETRIC MODELING OF THE EPSS

The methodology, which is applied to perform EPSS sizing, is presented in the following. It is based on the approach for conceptual sizing of aircraft systems using physics-based system models, which has been proposed by Koeppen [2] and Liscouet-Hanke [14]. The underlying pattern of this sizing approach is to perform the system sizing by propagating power requirements from power sinks (here: electric consumers) to power sources (here: generators, batteries). In addition, different operation modes, such as *normal operations* or *one engine inoperative* (OEI), are analyzed. For example, in the system architecture shown in Figure 1, the connection to the Auxiliary Power Unit (APU) would not be considered by only assessing the operation mode *normal operations* because during this mode, the electric power is supplied by the main engine generators (cf. Table 4). Moreover, the available power is decreased in emergency situations such as OEI without available backup systems such as the APU. If in this case the power requirements surpass the available power, the load of non-essential systems, such as Galleys or cabin lights, can be partly or fully shed to be able to supply at least all essential systems with the remaining power sources [2, 14].

The first step of the system sizing process is to perform electrical load analyzes (ELA) for different operation modes to determine the electrical loads of consumer systems. The ELA includes information about the voltage level, the voltage type, the load requirements over a flight mission, and the maximum required load for every consumer system [6].

Furthermore, consumer systems which are supplied by alternating current can create an inductive or a capacitive current which leads to a phase shift within the distribution network. Because of such phase shifts, reactive power requirements are added to the effective power requirements of the system, which increases the total power requirements at the generators. These phase shifts are also included in the ELA to determine possibilities to connect these systems within the distribution network to minimize the total phase shift. So far, average values for phase shift are included in the power requirements as a simplistic representation of the power calculation of alternating current consumer systems. Approaches to optimize the system by actively changing the respective phase conductor to minimize the total phase shift (cf. [8]) are not part of the approach of the EPSS sizing in this paper and will be part of future implementations.

Based on the data of the ELA, the distribution network is sized. The transmitted power is propagated from consumer systems via distribution components to the generators to select required cables. The type and diameter of a cable segment is selected based on the requirement that a certain connection must not exceed a specified voltage drop. This voltage drop depends on the resistance of the cable that is largely influenced by the length, diameter, and material of a particular cable connection. The voltage drop requirement depends on the nominal voltage level of the particular connection [15]. Table 1 shows some examples of the allowed voltage drop, which are dependent on the voltage level defined by the Society of Automotive Engineers (SAE) in the guideline ARD50055 [15]. The voltage drop for other voltage levels is extrapolated from the given values in Table 1.

TAB 1. Allowed voltage drop dependent on the nominal voltage [15]

Nominal System Voltage [V]	Allowable voltage drop (continuous operation) [V]
28	1
115	4
200	7

The voltage drop is calculated according to Equation 1 and Equation 2, which are based on calculation rules for electrical series circuits and Ohm's law [16, 17]. The calculation of the cable resistance consists of two parts. The first part is the calculation of the specific resistance of the cable $R_{\text{cable,spec}}$ which is the resistance per unit of length given by the manufacturer multiplied by the length of the cable, which is known from the system topology. The second part of the calculation of the cable resistance is the consideration of the temperature dependency of the resistance. This is considered by the difference of an assumed maximum temperature of the cable T and the ambient temperature T_0. The difference is multiplied with the temperature coefficient α which depends on the material of the cable. The calculation of the voltage drop U_{drop} in Equation 1 considers the maximum electric current $I_{\max}$ which is calculated in Equation 2. The maximum electric current results from the maximum propagated electric power flow $P_{\text{consumer,max}}$ and the nominal voltage U_{consumer}, that is available for the consumer system after considering the voltage drop U_{drop}. Both parameters are an output of the ELA.

(1) $U_{\text{drop}} = R_{\text{cable,spec}} \cdot l_{\text{cable}} \cdot (1 + \alpha\,(T - T_0)) \cdot I_{\text{max}}$

(2) $I_{\text{max}} = \dfrac{P_{\text{consumer,max}}}{U_{\text{consumer}}} = \dfrac{P_{\text{consumer,max}}}{U_{\text{spec}} - U_{\text{drop}}}$

In this approach, the specific parameters of the cables are obtained from a database containing commercial off-the-shelf cables [18]. The database is searched for cables that fulfill the voltage drop requirements according to cable resistance, the applied voltage type and voltage level, and the maximum required power. At the same time, the considered cables should be as lightweight as possible. If a cable conforms to these conditions, it is chosen and selected for the considered cable segment. The calculation of the voltage drop is repeated for each connection between a distribution unit and a consumer system and for connections between distribution units. The cables between the generators and the PEPDC are calculated based on the constraint that the voltage drop should not exceed two percent of the voltage level [15].

This approach of selecting cables allows to determine both the mass of the cable and the power losses due to the voltage drop. It is assumed that connections of all voltage types share the same return current path via the aircraft fuselage or the electrical structure network (ESN) [8]. Furthermore, modern EPSS architectures are supplied by a variable frequency (VF) varying between $360\,\text{Hz}$ and $760\,\text{Hz}$ [5]. This provokes effects on the cable selection such as the skin effect, which needs to be considered as well [19]. However, this effect is neglected in the presented approach and is part of future implementations.

As shown in Equation 3, the mass of all considered cables of the EPSS is the sum of the length of the respective cable l_{cable} and the specific mass $m_{\text{cable,spec}}$ of the cable selected from the database.

(3) $m_{\text{cables}} = \sum_{i=1}^{N_{\text{cables}}} l_{\text{cable},i} \cdot m_{\text{cable,spec},i}$

The mass of the components with a significant effect on the total mass are the units for changing the voltage type and voltage level, such as TRUs or inverters, power distribution units, such as the PEPDC or SPDBs, and power generation units. The mass of the power converters is calculated by power-to-weight ratios [13, 12] and are displayed exemplary in Table 2.

TAB 2. Power-to-weight ratio of on-board aircraft converters and switches [13, 12, 20]

Component type	Power-to-weight ratio
TRU	$0.4\,\frac{\text{kg}}{\text{kW}}$
DC converter	$0.3\,\frac{\text{kg}}{\text{kW}}$
AC converter	$0.35\,\frac{\text{kg}}{\text{kW}}$
SSPC	$2\,\frac{\text{kg}}{\text{kW}}$

According to Equation 4, the mass of the PEPDC is the sum of all power converters that are located in the PEPDC. The calculation of the mass depends on the maximum power $P_{\text{conv,max}}$ for each converter, and on an empirical calibration factor Ψ_{PEPDC} to account for materials and other electric components within the PEPDC. A further correction factor $\Psi_{\text{P,offset}}$ is added to the PEPDC to compensate for consumer systems which are not considered in the EPSS sizing during the conceptual design phase. According to Koeppen, an offset value of $\Psi_{\text{P,offset}} = 1.1$ is a reasonable assumption [2].

(4)

$$m_{\text{PEPDC}} = \Psi_{\text{PEPDC}} \cdot \Psi_{\text{P,offset}} \cdot \sum_{i=1}^{N_{\text{Converter}}} P_{\text{conv,max},i} \cdot m_{\text{conv,spec},i}$$

The mass of the SPDBs is calculated in Equation 5. This equation also considers the integrated SSPC unit which is sized according to the maximum power $P_{\text{SPDB,max}}$ and the power-to-weight ratio of the SSPC as shown in Table 2. An empricial correction factor Ψ_{SPDB} is also considered, taking into account for materials and other electric components within the SPDB. The mass of the SEPDC can also be calculated according to Equation 5 as well, since the mode of operation of the SEPDC is similar to the one of the SPDBs [5].

(5) $m_{\text{SPDB}} = \Psi_{\text{SPDB}} \cdot P_{\text{SPDB,max}} \cdot m_{\text{SSPC,spec}}$

The mass of the power generation units can be estimated with empirical formulas such as Equation 6 for the mass of a generator that provides a three-phase alternating current at a voltage level of $200/115\,V$. Equation 7 can be applied to calculate the mass of a generator that provides a voltage level of $400/230\,V$ [17]. Table 3 displays the constant values for the mass calculation as presented in Equation 6 and Equation 7.

(6) $m_{\text{gen,115V}} = P_{\text{gen,115V}} \cdot k_1 + k_2$

(7) $m_{\text{gen,230V}} = P_{\text{gen,230V}} \cdot k_3 + k_4$

TAB 3. Empiric values for calculating the generator masses [17]

Constant type	Value
k_1	$3.16 \cdot 10^{-4}\,\frac{\text{kg}}{\text{VA}}$
k_2	$29.53\,\text{kg}$
k_3	$2.55 \cdot 10^{-4}\,\frac{\text{kg}}{\text{VA}}$
k_4	$30.14\,\text{kg}$

The last step of the sizing process is to calculate the total mass m_{EPSS} of the system. As shown in Equation 8, the total mass is the sum of the mass of the selected cables and of the mass of the components such as the generators and distribution units. Furthermore, an additional factor $\Psi_{\text{cable,offset}}$ is added to compensate for the mass of the cable connections of consumer systems which are not considered in the conceptual design phase. This offset is calculated based on an empirical function, which depends on the assumed share of the total power requirements of the included consumer systems.

(8) $m_{\text{EPSS}} = m_{\text{components}} + \Psi_{\text{cable,offset}} \cdot m_{\text{cable}}$

After completing the sizing process, a steady-state simulation is performed based on the designed system and a given flight trajectory. During the steady-state simulation, the system variables (power, voltage, current) do not change over time and are calculated for each discrete mission point based on the designed system. The outcome of the steady-state simulation is the total electrical load profile for the given flight trajectory. The electrical load profile at the generators represent the electric power requirements for the given flight trajectory. This can be used to calculate the power-off-takes during the mission which is an input, for instance, to perform an overall aircraft assessment. Further outcomes of the steady-state simulation are the effects on load shedding strategies during emergency situations. With the total load profile, it is possible to check whether the required system power exceeds the available power. If this is the case, the load shedding strategy has to be adapted to decrease the number of supplied non-critical aircraft systems.

4. OVERALL CONCEPTUAL DESIGN OF ON-BOARD SYSTEMS

During conceptual design phase, the fidelity of on-board system models increases gradually throughout the design process. Typically, the process starts with an initial aircraft layout provided by overall aircraft design (OAD). To obtain first estimates of the parameters which are relevant for OAD iterations like system mass and secondary power demand, simple regression functions are used. As maturity of the aircraft concept progresses, detailed system design (DSD) of relevant aircraft on-board systems is conducted by dynamic simulations of system behavior and use of other high-fidelity analysis methods. The set-up of these detailed models, however, consumes development resources and requires the systems architecture to be already defined. Thus, architectural and topological trade-off studies with DSD models are considerably limited. It is necessary to conduct these type of studies on a specific level of model abstraction, namely on the Overall Systems Design (OSD) level, at which fidelity of system models and the complexity of architectural design choices from an overall systems and aircraft perspective are balanced.

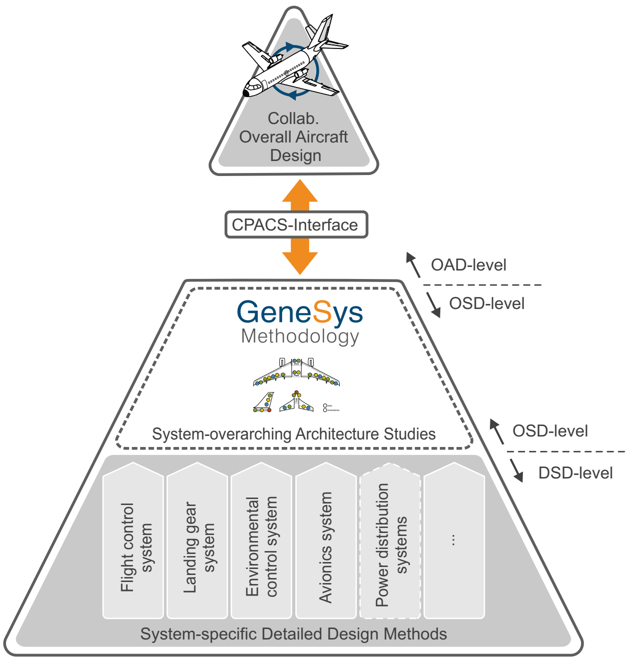


FIGURE 2. Stages of aircraft design from the perspective of a system engineer using *GeneSys*

The *GeneSys* software framework has been developed to support system engineers performing trade studies on OSD-level with a set of consistent and integrated system models. Knowledge-based positioning heuristics and parametric methods for sizing and simulation are used to rapidly evaluate competing sys-

tems architectures. The process is structured to be both flexible to perform integrated iteration loops with OAD-level and comprehensive to integrate physics-based sizing and steady-state simulation models derived from the DSD stage [4]. The related taxonomy of the described design stages is illustrated in Figure 2. Based on the initial aircraft lofting provided by OAD, the overall systems architecture and its topology can be defined to refine initial estimates for system parameters like mass or secondary power demand. To this end, parametric and component-based system models of relevant consumer systems (e.g. environmental control, flight control) and their respective power supply networks (electric, hydraulic, pneumatic) are used [2, 3]. Relevant data is communicated via standardized XML-interfaces. As shown in Figure 2, data is exchanged with the OAD process via the dedicated XML-standard "Common Language for Aircraft Design" (CPACS) [21]. The CPACS file contains a parametric geometry model and performance data from other disciplines like aerodynamics and propulsion design.
Figure 3 shows the generic sizing process of a representative system module in *GeneSys*. The process is divided into four consecutive steps: Pre-processing, topology generation, sizing and simulation, and post-processing.

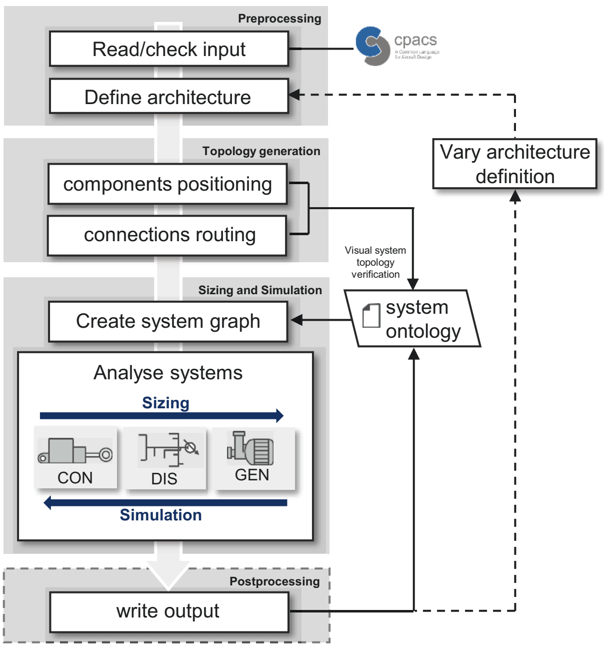


FIGURE 3. Process diagram of the design process of the EPSS based on the *GeneSys* framework

During pre-processing, system architecture and relevant boundary conditions for the sizing process are defined manually. These definitions are based on a functional description of the system layout and comprise, for instance, the type and number of components, the assignment to aircraft structural groups (e.g. wing, fuselage), and specifications about inputs and outputs of functional system components (e.g. power, data).

As a next step, knowledge-based algorithms exploit these configuration data and CPACS information to automatically generate a first layout of the system topology — that is, components are located and power conductors are routed according to predefined layouts (topology templates) by the algorithm. Topology information are saved in a dedicated XML file (*sysArchXML*) which is standardized according to a parametric ontology for conceptual design of aircraft on-board systems. Aircraft geometry and system topology can be visualized to check and adapt the initially generated topology (cf. Figure 5).

Having defined and generated the topology, the system is sized and its behavior is simulated. For systems that in any way transmit power or provide a mass flow between functional components, the system is modeled as a graph directed from power generators to power consumers. Based on predefined operational scenarios involving cases of failure, the required power or mass flow and respective state variables in network segments are propagated backwards from consumers to generators. Hereby, the most critical case that is relevant for sizing can be identified. Thereupon, system power consumption and required mass flows are simulated for a given aircraft mission trajectory using steady-state behavior models considering power losses in transmission lines and functional components.

To perform architectural or topological studies, the initial parametric definition of the architecture has to be changed systematically. This can be automated using a wrapper module that modifies the configuration file and executes the sizing process for each defined variant. Hereby, both the system architecture by, for example, changing the general layout of used components and the system topology by, for instance, changing number or location of a specific component can be object of study.

5. TOPOLOGY STUDIES FOR A MODERN EPSS

The system sizing process of the EPSS according to Figure 3 is presented in the following. This includes the description of the problem set-up and the consideration of boundary conditions of operational scenarios for system sizing. Afterwards, the results of a study on three different topological concepts are described.

5.1. Problem set-up

In the following, the problem set-up is described stating the reference aircraft and the reference system architecture which are used to perform the sizing process and the concept studies.

5.1.1. Reference aircraft

To perform the EPSS sizing process and concept studies, the reference aircraft architecture of the federal aviation research program (LuFo) AdVanced Aircraft CONcepts (AVACON) is used [22]. The AVACON reference aircraft is the research baseline 2028 (ARB2028) which is a mid-range aircraft designed for 285 passengers with a system architecture based on the design of a state-of-the-art MEA.

5.1.2. Reference systems architecture

The layout of the on-board systems of the ARB2028 is in general based on a modern more-electric systems architecture as part of the MEA concept [4]. This also applies to the EPSS architecture, which is comparable to the system layout of the Airbus A350. The engine generators provide three-phase alternating current with variable frequency (VF) at a voltage level of $400\,\mathrm{V}$ between two phases. Within the PEPDC, power is converted to a second three-phase alternating current with an AC-AC converter at a voltage level of $200\,\mathrm{V}$ between two phases with a constant frequency of $400\,\mathrm{Hz}$. All available voltage levels and voltage types are:

- $400/230\,\mathrm{V\,AC}$ / VF
- $200/115\,\mathrm{V\,AC}$ / $400\,\mathrm{Hz}$
- $28\,\mathrm{V\,DC}$

The ARB2028 is a twin-engine aircraft. Due to the regulations of extended operations (ETOPS) [23], the availability of system components has to be at a level to ensure safe operations during failure cases such as OEI. To ensure the required level of safe operations, 2 generators are located at each main engine and at the APU. Furthermore, the reference architecture contains 2 PEPDCs which are located in the electronic bay underneath the cockpit, 2 SEPDCs which are located next to the PEPDCs, 6 SPDBs which are distributed in the cabin, and 2 SPDBs which are distributed in the cargo area.
The simplified structure of the system architecture with the above-mentioned components of the EPSS is shown in Figure 4. All generators are connected to the PEPDC from where the electric power is distributed into the aircraft. At the PEPDC, the voltage type and voltage level is converted to the required voltage type and voltage level of the consumer systems. Consumer systems that need to be supplied by a single phase alternating current are connected to one phase of the particular three-phase alternating current network. The PEPDC supplies electrical loads to consumer systems which are either flight critical systems, require high loads with a maximum current above $15\,\mathrm{A}$ [8], or require a three-phase alternating current feed-in [8]. This includes the supply of the SPDBs and SEPDC, as shown in Figure 4.
As shown in Figure 4, the architecture of the ARB2028 contains a Ram Air Turbine (RAT) that would supply the essential electrical systems during an operation mode in which it is assumed that all other generators are inoperative [5]. All non-essential consumer systems are shed in this operation mode. Considering the selected operation modes for the system sizing process (cf. Table 4), all of them have an influence on the sizing of the network that is connected to the cabin consumer systems because the non-essential consumer systems are not fully shed. In the context of the concept studies presented, the operation mode in which only the RAT supplies the essential loads is neglected because it does not have a significant influence on the results.

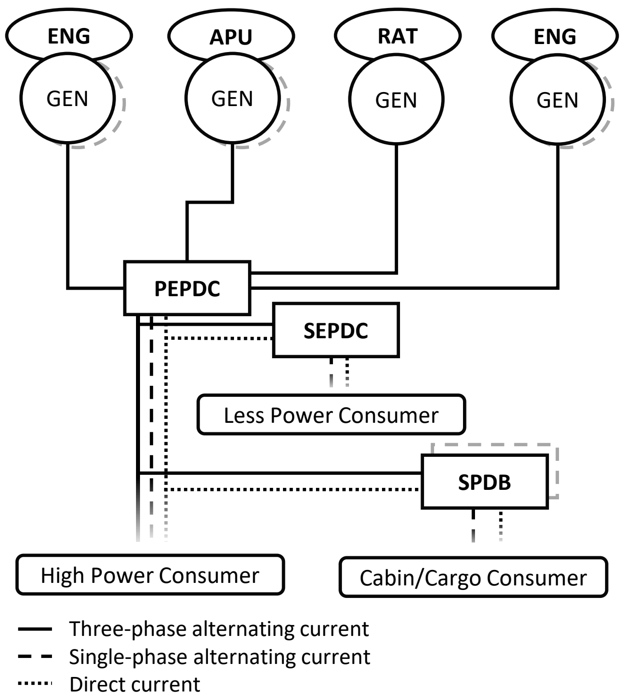


FIGURE 4. Schematic layout of a modern EPSS

5.2. Topology generation

To use the automated positioning and routing algorithms of the *GeneSys* framework, the EPSS ar-

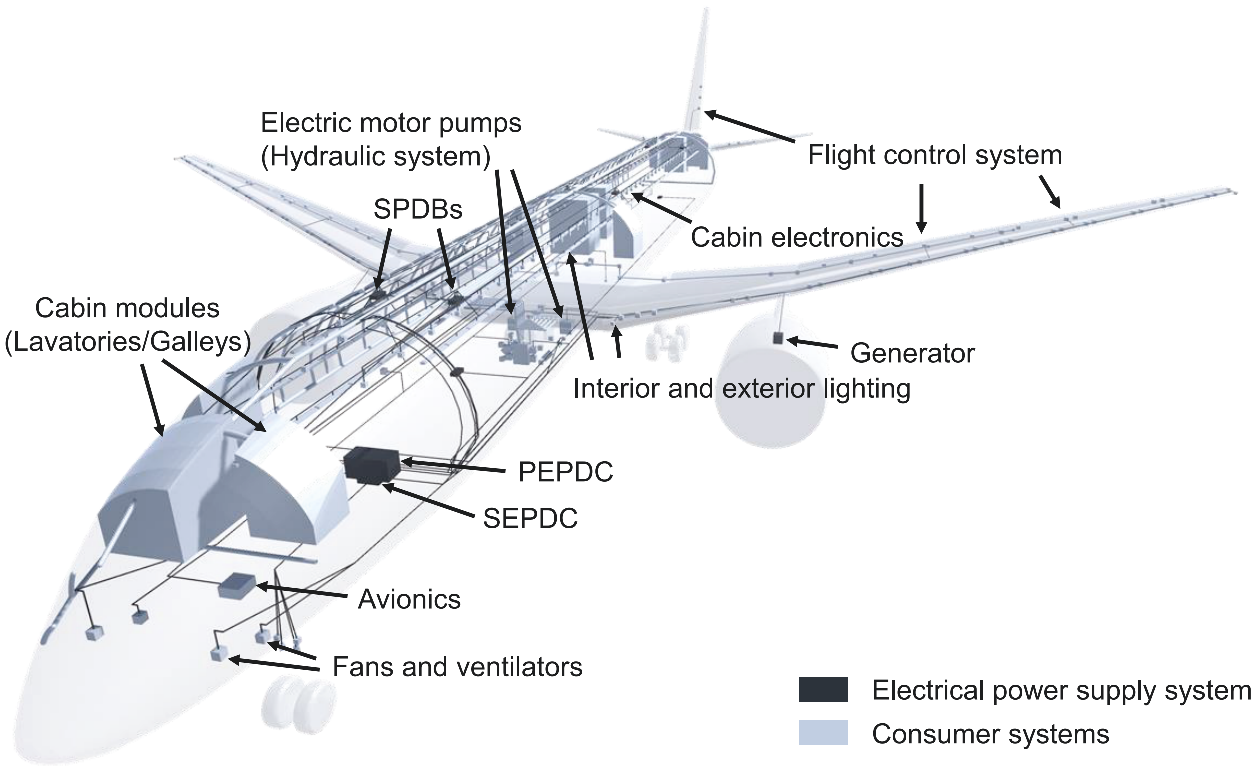


FIGURE 5. System topology of the electric power supply system and relevant consumer systems

chitecture for the ARB2028, which is described in subsection 5.1, must be predefined by the systems engineer in a configuration file. This file includes information about the number of components, the geometric information about each system component, and the information about the input and output parameters for each system component as it is elaborated in section 4. The required information for the configuration file with a definition of a system architecture are exemplified in Appendix A. In this example, the EPSS consists of 4 generators, 1 PEPDC, 2 SPDBs, and 2 galleys which represent the consumer systems. The generators are located at the aircraft engines, the location of the PEPDC is defined to be in the electronic bay in the front of the fuselage, and the SPDBs are located in the cabin. Each component is functionally assigned to an electrical network. The nominal voltage level and voltage type required by the respective consumer system is also specified.

To simplify the sizing process during the conceptual design phase, the consumer systems are limited to systems with a significant share in the total required electric power. It is assumed that these systems represent $90\,\%$ of the total required electric power. These consumer systems are the actuators of the flight control system, the galleys, the fans of the environmental control system, the ice and rain protection system, the electric motor pumps of the hydraulic power supply system, the fuel pumps, the avionic systems, the cabin electronics, and the interior and exterior lighting. Figure 5 shows the resulting system topology with the consumer systems that are connected to the EPSS within the ARB2028 systems architecture.

Based on the previously defined systems architecture, the system topology is generated based on information about the aircraft and on the positioning of system components and connections. Figure 5 also serves as visual verification of the positioning heuristics. The generators are located at the engines, the PEPDCs are located in the front area of the fuselage and the SPDBs are distributed in the cabin. The connection of the consumer systems to the EPSS are visualized by cables, which are routed along typical cable routing spaces in the aircraft. These cable routing spaces are among others in the triangle area underneath the cabin floor, above the cabin area, and along the wing spars.

5.3. System sizing

The sizing process of the EPSS is based on the approach presented in section 3. With the generated system topology, a graph of the EPSS is created. The graph is directed and indicates the power flow from the sources of the graph to its sinks. Following the description from section 3, the sources of the graph represent the power sources of the EPSS and the end nodes represent the power sinks. Hence, the direction of the graph is defined according to the power flow, while the system sizing is oriented in the opposite direction. Table 4 shows the list of considered operation modes to perform the EPSS sizing. These operation modes are chosen as the relevant sizing cases for the studies in subsection 5.4.

TAB 4. List of operation modes (sizing cases) and respective active power supply components which are considered during system sizing process.

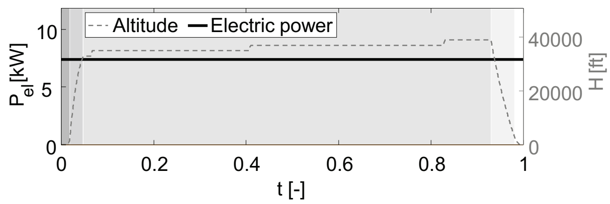
Operation Mode	Power Supply Components
Normal Operations	$\mathrm{GEN_L} \wedge \mathrm{GEN_R}$
OEI + APU avail.	$(\mathrm{GEN_L} \vee \mathrm{GEN_R}) \wedge \mathrm{GEN_{APU}}$
OEI	$\mathrm{GEN_L} \vee \mathrm{GEN_R}$

The first step is to generate the ELA of all considered consumer systems that are connected to the EPSS. The power requirements of the consumer systems are generated by executing system analysis modules of relevant consumer systems. The load profiles of the generated power requirements are classified into three different types, which differentiate themselves by the accuracy of the load profiles as displayed in Figure 6. The calculation of the required electric power of different systems depends on the level of detail of the system model. Furthermore, the power calculation also depends on the need to evaluate the system in high level of details. This is the case, when, for example, the share of the required power of a system compared to the overall provided power is significant.

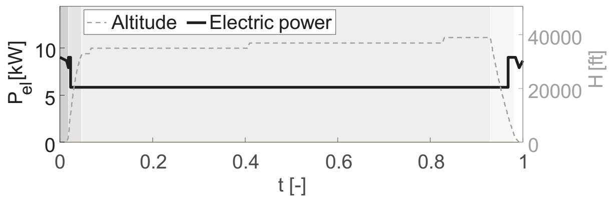
The first type of load model is a time-independent load representation, which is displayed in Figure 6a. This type of load profile represents consumer systems with an approximately constant load requirement during the flight mission, such as flight computers of the avionic systems.

Figure 6b shows a load profile which depends on the flight mission segment. This type of load profile comprises changes of power requirements at different flight phases. An example is the power consumption of the internal and external lights. For instance, the power peaks in the beginning and in the end of the flight mission are caused by the activation of the landing lights at altitudes below $10{,}000\,\mathrm{ft}$.

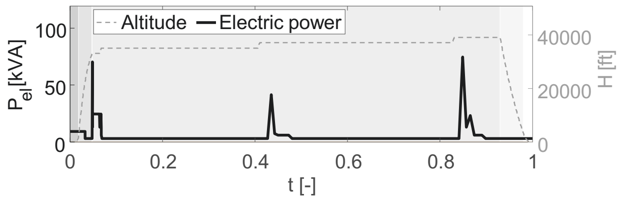
The third type of load profile is dependent on the flight mission and on the actual flight time. This type of load profile is displayed in Figure 6c and is typical for representing the required loads of the galleys. The galley loads are calculated with a system module that simulates the galleys based on parameters like the number of seats in the cabin, the cabin configuration, and the amount of meals served during the flight. As shown in Figure 6c, there are three power peaks during the flight mission. The first and last peak represent the required power for serving a meal and drinks to each passenger. The peak in the middle of the flight mission represents the required power for serving drinks only.



(a) Electrical load profile - time-independent



(b) Electrical load profile - mission segment resolution



(c) Electrical load profile - temporal resolution

FIGURE 6. Electrical load profiles of different consumer systems

After allocating the power requirements to each consumer system, the sizing parameters of the EPSS, which are the required power of each consumer system and the voltage type and voltage level, are propagated through the system graph of the distribution network. With the propagation of these parameters, the maximum power requirements are estimated in each network segment. The cables for each connection can then be selected from the database as described in section 3.

After analyzing the distribution system considering all consumer system loads and power losses over the cables and voltage transformer units, the total load profile of the EPSS is calculated. The total load profile represents the electric power which has to be supplied by all active power supply units. In case of the operation mode *normal operations*, the power is supplied by all engine generators. The resulting total load profile of the ARB2028 aircraft is displayed in Figure 7. It also shows the load profile of the OEI operation mode with two remaining operating generators. Non-essential consumer systems, such as the Galleys (cf. Figure 6c) are shed according to defined load shedding schemes.

In addition to the determination of the total electric required power of the EPSS, the mass needs to be calculated as a relevant evaluation metric for the preliminary sizing process. The mass is calculated according to the methods presented in section 3. To determine the usage of voltage converter units, it is assumed that a voltage converter unit is required, if the power specification of a functional component has different input and output voltage type and voltage level.

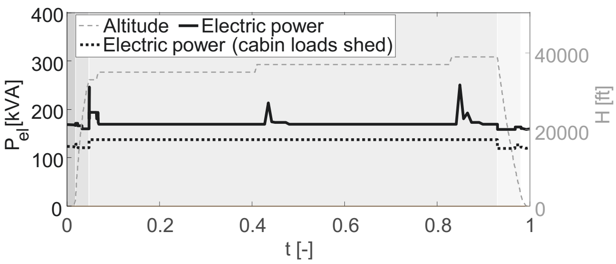


FIGURE 7. Total load profile of the EPSS

2 to 16. The position of SPDBs and their distance to each other is evenly distributed along the cabin by the positioning algorithm, as can be seen in Figure 8. The number of SPDBs is increased by 2 with each iteration step, because the positioning heuristic of *GeneSys* is designed to allocate the SPDBs symmetrically along the x-z-plane in the cabin.

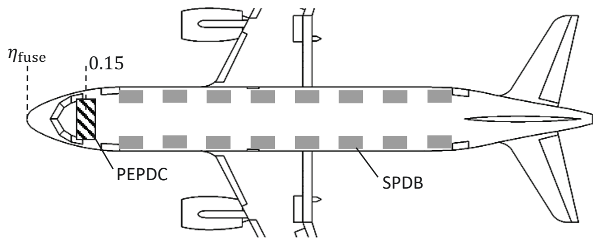


FIGURE 8. Positioning of relevant components of the EPSS that are part of study 1 (number of SPDBs)

5.4. Examples of possible topology studies

Through the integration of the EPSS sizing module in *GeneSys*, concept studies can be performed to find a suitable layout for the system architecture. To explore the topological sensitivities of the EPSS, three topology studies are conducted and discussed. An additional wrapper module changes the definition of the system architecture in the configuration file and executes the sizing process for each considered layout. In the presented study, number and location of several components are modified. The parameter system mass is used as the evaluation metric for all three studies. The three conducted topology studies are listed in the following.

1. Adaption of the electrical network of the cabin by varying the number of SPDBs
2. Variation of the PEPDC location and adaption of the electrical network of the cabin (study 1) for each PEPDC location
3. Adding a second PEPDC and varying its location while adapting the electrical network of the cabin (study 1) for each location of the second PEPDC

The topology studies are analyzed and discussed in detail in the following.

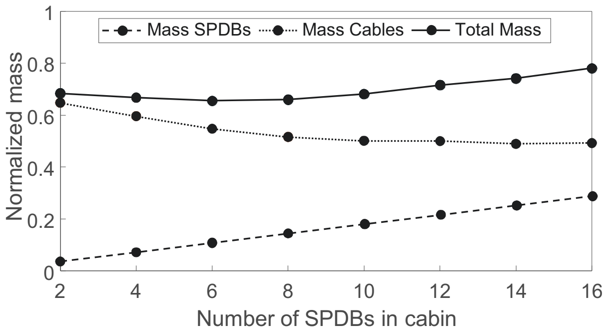
5.4.1. Study 1: Number of SPDBs

With the first study, the topological layout of power controllers for cabin electrical consumers is examined. To this end, the number of SPDBs is varied from

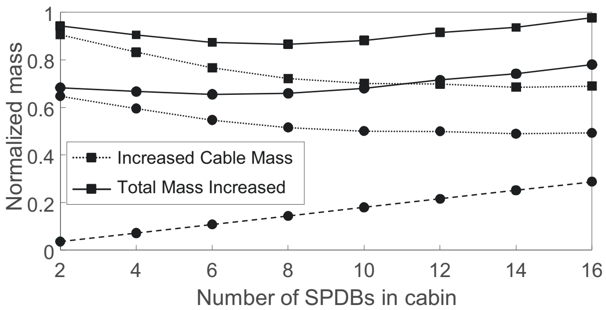
The results of the first study are shown in Figure 9. In Figure 9a, the mass of the electrical network of the cabin is depicted. The total mass is divided into the cable mass and the mass of the SPDBs. In the first step, a simplification of the model is assumed, which includes that the mass of the SPDBs is constant. Hence, the total mass of all SPDBs linearly increases with the number of SPDBs. The mass of the cables is decreasing with the number of SPDBs. This stems from the algorithmic routing of the cables between SPDBs and consumer systems. If the number of SPDBs increases, the total cable distance from the SPDBs to the consumer system components decreases. According to the total mass, the optimum is reached at 6 SPDBs.

However, the layout with the minimum mass in Figure 9a is not distinctive. The total mass of architectures with 2, 4, or 8 SPDBs lies in a similar range with a deviation of $4.7\,\%$, $2.5\,\%$, and $0.5\,\%$ from the calculated minimum, respectively. If one considers that uncertainty is inherent to this values due to model simplifications, a decision about the optimal number of SPDBs has to be substantiated with more detailed analyses. For the presented models, uncertainties are introduced by neglecting system components with minor contribution to the system mass.

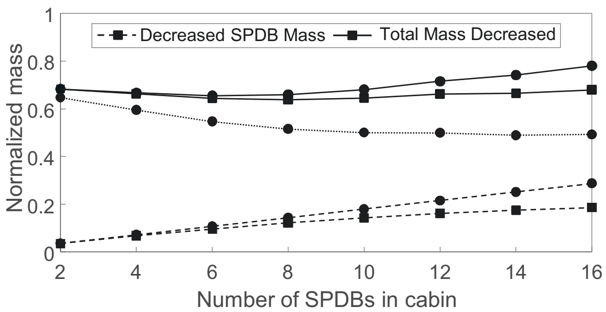
Moreover, the choice of the input parameter $\Psi_{\text{cable,offset}}$ according to Equation 8 affects the mass of the electrical network within the cabin significantly. This is illustrated by Figure 9b where the results of the study is shown, for which a constant offset of $20\,\%$ is added to the cable mass. In this case, the optimum number of SPDBs is calculated at $n_{\text{SPDB,opt}} = 8$.



(a) Mass of the cabin electronics with constant component mass of the SPDBs



(b) Correction of the mass of the cabin electronics due to possible neglect of cables



(c) Mass of the cabin electronics with varying component mass of the SPDBs

FIGURE 9. Results of study 1: Sensitivities when changing the number of SPDBs, their masses and the cable masses

Another source of uncertainty is the assumption that the mass of an SPDB is constant. An increment in the number of SPDBs can decrease the number of cabin consumer systems which are connected to one SPDB. It might be the case, that the mass of the SPDBs decreases due to reduced number of ports on each SPDB and due to a reduced maximum required power supply. According to Equation 5, a reduced maximum required power supply would have an influence on the sizing of the SSPCs inside the SPDBs. The decrease of the SSPC mass due to the reduced number of ports of each SPDB is illustrated in Figure 9c. In consideration of adapting the mass of the SSPCs, the optimum number of SPDBs in the cabin changes from $n_{\text{SPDB,opt}} = 6$ to $n_{\text{SPDB,opt}} = 8$ and the total mass decreases by $2\,\%$.

The results of the above presented cases about the sensitivity of the optimum mass of the electrical cabin network show that an optimum number of SPDBs cannot be clearly determined due to uncertainties during the early design stage. In the case of the presented EPSS of the ARB2028 aircraft, the optimum number range of SPDBs in the cabin is between 4 and 10. Because more SPDBs would significantly increase the total mass and enhance the system complexity, it is unlikely that more than 10 SPDBs are integrated.

5.4.2. Study 2: Number of SPDBs and location of PEPDC

The mass optimization of the EPSS by varying the location of all primary and secondary distribution network components is considered in the second study. Since the PEPDC is typically located in the front of the fuselage, long power lines have to be routed from the engine generators and the APU generators to the PEPDC. Also, the galley which is located in the aft fuselage is one of the consumer systems with the highest power requirements. Because galley feeder lines are heavy due to the high power requirements, it is examined, if the relocation of the PEPDC towards the aft fuselage might decrease the length of the cables and the total system mass. As illustrated in Figure 10, the PEPDC is iteratively moved backwards until it is located at $80\,\%$ of the fuselage length. In addition, the optimization described in subsubsection 5.4.1 for study 1 is performed for each location of the PEPDC.

The results of the second study are shown in Figure 11. Figure 11a displays the total mass of the EPSS for three selected locations of the PEPDC, which are at $15\,\%$, $50\,\%$, and $80\,\%$ of the fuselage length. The curve of the total mass of each PEPDC location depends on the number of SPDBs. While the total mass of the EPSS is similar when the PEPDC is located either in the front or rear of the fuselage, the total mass of the EPSS is lower when the PEPDC is located in the middle of the fuselage. This is caused by shorter cable distance to the generators or consumer systems with high power requirements, such as the galley in the aft cabin. The optimum number of SPDBs is 2 in this case. According to the design heuristics in *GeneSys*, these two SPDBs would be located in the center of the cabin above the PEPDC.

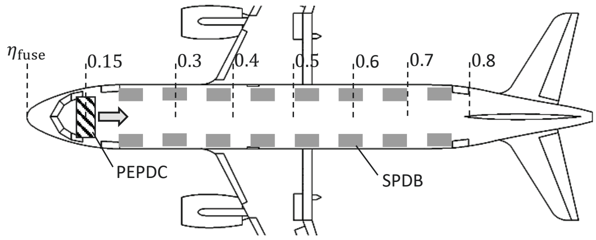
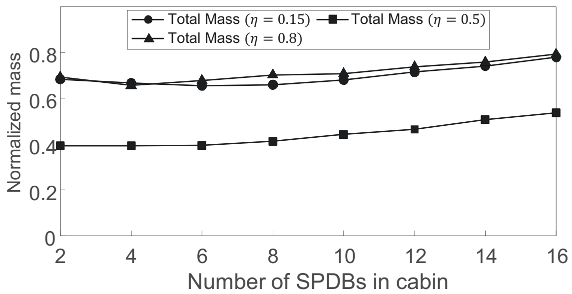
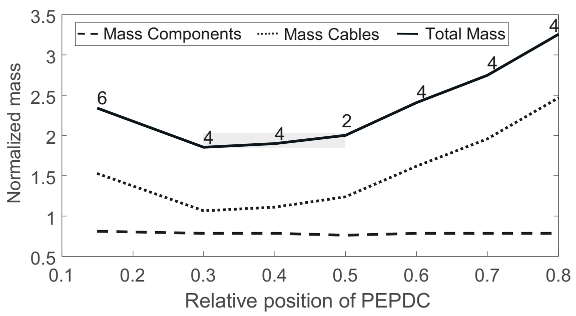


FIGURE 10. Positioning of relevant components of the EPSS including adaptions of the PEPDC locations for study 2 (number of SPDBs and location of PEPDC)



(a) Mass of the EPSS when changing the number of SPDBs and changing the location of the PEPDC (relative location of PEPDC in bracket)



(b) Total mass of the EPSS at different PEPDC locations with optimum number of SPDBs in each case

FIGURE 11. Sensitivities due to changes in the location of the PEPDC

The calculated masses of all analyzed PEPDC locations are shown in Figure 11b. The optimum number of SPDBs is stated at each location of the PEPDC. Again, a distinctive optimum is not evident. However, it can be concluded that reduction of the EPSS total mass can be expected, if the PEPDC is relocated in the range between $30\,\%$ and $50\,\%$ of the fuselage length.
Shifting the PEPDC towards the center of the fuselage seems advantageous if only the system mass is analyzed. For example, the air of the electronic bay is conditioned accordingly. To cool the components such as voltage transformers within the PEPDC, the air of the new location of the PEPDC needs to be conditioned as well. In addition, the relocation of the PEPDC might be constrained by the available installation space, which has not been considered for the presented study.
To sum up, the location of the PEPDC in front of the fuselage is advantageous because it is connected to many critical consumer systems, such as the flight computer and cockpit avionic systems, which are located in the electronic bay as well. In this case, the cable distances to these consumer systems are decreased. However, the location of the PEPDC in the center of the fuselage is also advantageous because the mass of the power lines from the generators and to the galley in the aft fuselage is decreased. To combine these effects, a second PEPDC is added to the system architecture in the following study.

5.4.3. Study 3: Adding a second PEPDC

A second PEPDC is added to the EPSS in this study. As shown in Figure 12, one PEPDC is located in the front of the fuselage and remains unchanged while the location of the second PEPDC is varied from $30\,\%$ to $80\,\%$ of the fuselage length. As presented in study 1, the number of SPDBs is also varied between 2 and 16 for each location of the second PEPDC. The generator cables and the consumer systems in the aft fuselage are supplied by the second PEPDC. The first PEPDC supplies the flight critical systems in the electronic bay and the consumer systems in the front of the fuselage. The advantage of this layout is the reduction of cable length for consumers with high power requirements.

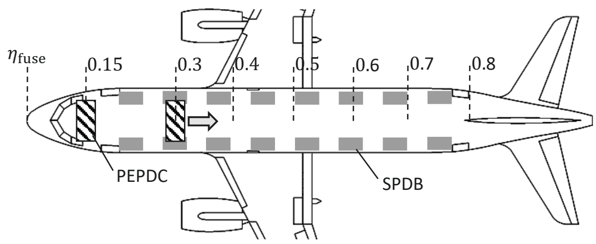
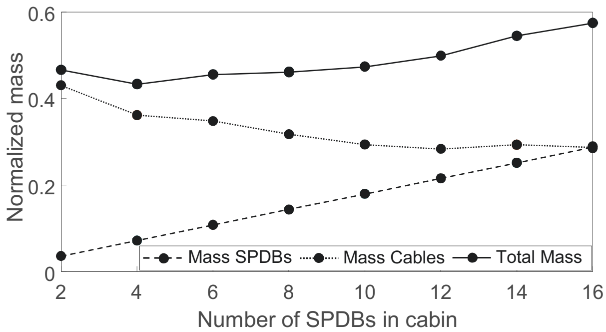
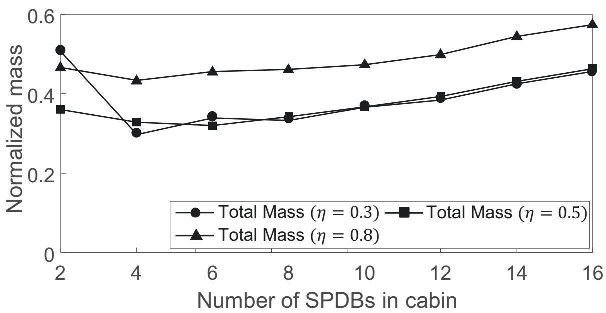


FIGURE 12. Positioning of relevant components of the EPSS including adaptions of the second PEPDC locations for study 3 (adding a second PEPDC)

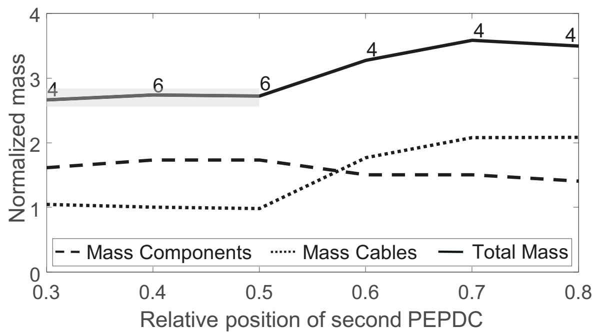
The results of this study are illustrated in Figure 13. The mass of the SPDBs and of the cables which connect the cabin consumer systems to the SPDBs if the second PEPDC is located at $30\,\%$ of the fuselage length is shown in Figure 13a. In this case, the optimum number of SPDBs in the cabin is 4, but the minimum is also not distinctive.



(a) Mass of the cabin electronics with constant component mass of the SPDBs having added a second PEPDC at 30 % of the fuselage length



(b) Mass of the EPSS when changing the number of SPDBs and changing the location of the second PEPDC



(c) Total mass of the EPSS at different locations of the second PEPDC with optimum number of SPDBs in each case

FIGURE 13. Sensitivities due to changes in the location of a second PEPDC

The total mass of the EPSS for three selected locations of the second PEPDC, which are at 30%, 50%, and 80% of the fuselage length is shown in Figure 13b. For each location of the second PEPDC, the number of SPDBs is varied. The result of the optimum mass is similar for the arrangement in which the second PEPDC is located at 30% and 50% of the fuselage length. If the second PEPDC is located in the aft fuselage, the total mass increases.

The total mass of all analyzed locations of the second PEPDC is shown in Figure 13c. The optimum number of SPDBs is stated at each analyzed location of the second PEPDC. In this case, the optimum location of the second PEPDC can be expected between 30% and 50% of the fuselage length, while the optimum amount of SPDBs varies between 4 and 6. However, the second PEPDC has a high impact on the total mass and leads to a higher total mass of the EPSS compared to the topology with one PEPDC. As shown in Figure 11b and Figure 13c, the mass of the optimum location of the second PEPDC lies in a similar range as the second-highest mass of the topology with one PEPDC ($\eta = 0.7$).

5.5. Discussion of results

Parametric topology studies were performed to identify the optimum number and location of components of the EPSS with the objective to decrease the total system mass. In general, the results of the performed topology studies have a rather small impact on the potential to optimize the EPSS. Because the uncertainties in earlier design stages are high, the results of early studies that do not show a dominant design solution should rather be grasped as tendencies and have to be further analyzed in a more detailed design stage. The second and third study have also shown that not only one parameter should be considered for optimizing the system. Changing the position of the PEPDC is affected by the available installation space and the availability of air conditioning to cool the electrical components of the PEPDC.

Nevertheless, the presented studies demonstrate, that the use of a parametric modeling framework like *GeneSys* allows a systematic and automated assessment of system architectures and their topological layouts. However, they also demonstrate that interdependencies between systems already exist in the scope of the presented simplified topology studies. To increase the significance of the presented results, an integrated assessment is necessary.

6. SUMMARY AND CONCLUSION

In this paper, a methodology for a component-based network model for the design of the electric power supply system has been presented. Apart from the capability to perform the sizing and simulation of the electric power supply system in the conceptual design phase, concept studies are conducted to find a suitable layout for the system architecture. The methodology is included in the *GeneSys* framework, which

comprises a set of sizing and steady-state simulation modules for aircraft on-board systems to perform overall systems design.
To this end, the integration of the electric power supply system into *GeneSys* includes the parametric definition of the system architecture and the implementation of positioning heuristics such as knowledge-based topology templates to generate the system topology. Also, the procedure for system sizing of the electrical network has been described. A graph-based representation of the system topology is created for the sizing process. This representation is used, according to the design process of the electric power supply system, to propagate system parameters through the network. The propagation of system parameters is performed for all defined operation modes (sizing cases).
The proposed approach for sizing of the electric power supply system within *GeneSys* opens up new functionalities, which have been exemplified. Among others, one of the functionalities is to perform automated topology studies with a given solution space. Thus, effects on the aircraft systems due to conceptual changes on aircraft level can directly be evaluated. In this paper, this was demonstrated by three simplistic topology studies in which the number and location of components of the electric power supply system were varied. However, it has been shown that no dominant topological layout can be identified with engineering models for the early design stage. In this case, more detailed models for the system sizing process are needed, which might be able to reduce the existing uncertainties in the model and in the assumptions of the parameters.

ACKNOWLEDGEMENT

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A. APPENDIX: EXEMPLIFIED DEFINITION OF A SYSTEM ARCHITECTURE

Name	Parent	Location	Network in	Network out	Voltage spec. in	Voltage spec. out
Generator 1	engine	left		E1		400/230 VAC
Generator 2	engine	left		E2		400/230 VAC
Generator 3	engine	right		E1		400/230 VAC
Generator 4	engine	right		E2		400/230 VAC
PEPDC	fuselage	eBayFwd	E1;E2	E1;E2	400/230 VAC	400/230 VAC; 200/115 VAC; 28 VDC
SPDB 1	fuselage	cabinLeft	E1	E1	200/115 VAC; 28 VDC	115 VAC; 28 VDC
SPDB 2	fuselage	cabinRight	E2	E2	200/115 VAC; 28 VDC	115 VAC; 28 VDC
Galley 1	fuselage	cabinFwd	E1		200/115 VAC	
Galley 2	fuselage	cabinAft	E2		200/115 VAC	
...	...	...	...	...	...	...