Multidisciplinary Optimization of Hydrogen Fuel Distribution System Architectures for Conceptual Aircraft Design

Sparsh Garg*, Diogo Neves†, Tim Burschyk‡, Luca Boggero§, and Björn Nagel¶

DLR (German Aerospace Center), Institute of System Architectures in Aeronautics, Hamburg, Germany

The transition toward sustainable aviation has intensified the exploration of alternative propulsion technologies, with hydrogen fuel cells emerging as a promising candidate. This study addresses existing knowledge gaps in the design and integration of hydrogen fuel systems for aircraft, aiming to support informed decision-making during early conceptual design stages. A system architecture optimization (SAO) framework is employed to investigate the design space of the hydrogen fuel system for a fuel-cell-powered regional airliner. The work leverages the German Aerospace Center's (DLR) collaborative engineering ecosystem, comprising the ADORE, MDAx, and RCE platforms, which collectively enable the integration of model-based systems engineering (MBSE) and multidisciplinary design analysis and optimization (MDAO) for automated architecture exploration. The Common Parametric Aircraft Configuration Schema (CPACS) serves as the central data model, ensuring consistent information exchange between tools and disciplines. The optimization problem is formulated to minimize both system mass and electrical power consumption, with several architectural design choices treated as decision variables. The performance of the NSGA-II evolutionary algorithm is benchmarked against a surrogate-assisted Bayesian optimization approach to evaluate their respective efficiencies in navigating the complex design space. Furthermore, the advantages of employing an automated architecting methodology are quantified through comparison with traditional, expert-driven approaches. This research not only demonstrates the applicability of SAO in a realistic aerospace engineering context but also establishes a foundation for future investigations into hydrogen fuel system architectures. The framework can be extended to incorporate broader system boundaries and more comprehensive design studies, thereby contributing to the development of next-generation sustainable aircraft propulsion systems.

I. Introduction

Climate change has become a pressing global concern in the past decade, due to adverse impact of anthropogenic emissions on ecosystems, human health, and socio-economic systems [1]. To reduce the contribution of commercial aviation to these emissions, significant efforts have been made over the past years to develop technologies with lower impact on the environment. To that end, hydrogen has shown promise as an aviation fuel since it yields non-carbon emissions when combusted. However, hydrogen combustion still leaves NOx emissins to be addressed which can be further negated by the use of fuel-cells instead[2]. The feasibility of fuel-cell based aircraft is an active area of research which has yielded detailed analyses on hydrogen fuel tank design and integration, as well as on advanced fuel cell technologies [3]. However, a comprehensive knowledge on the hydrogen fuel distribution system, connecting the fuel tank to the fuel cell, is still lacking. The current research attempts to take initial steps in closing this knowledge gap, in order to assist in the early stages of design of fuel-cell-based aircraft.

The early design stages of an aircraft consist of a sequence of activities ranging from requirements definition and functional decomposition to concept evaluation. One fundamental task among them is system architecture definition, which establishes the preliminary structure of the overall system. It defines the architecture choices and components that comprise the system, which have a significant influence on the system performance [4]. However, architecture design spaces expand drastically as a function of the number of architectural decisions involved[5]. For complex systems, this makes it infeasible to exhaustively and manually probe for the best solutions [6]. The traditional workaround to this

*Researcher, DDP Group, Department of Digital Methods for System Architecting, sparsh.garg@dlr.de

†MSc. Thesis Student, diogo.m.neves@hotmail.com

‡Researcher, Department of Aviation System Concepts and Evaluation, tim.burschyk@dlr.de

§Head of DDP Group, Department of Digital Methods for System Architecting, luca.boggero@dlr.de

¶Institute Director, DDP Group, Institute of System Architectures in Aeronautics, bjoern.nagel@dlr.de

problem has been the filtering of select architectures for further development based on expert opinion [7], exposing the design process to bias, subjectivity and conservatism, hindering disruptive innovation [6].

System architecture optimization (SAO) [8, 9] can be used to mitigate the aforementioned issues, by converting system architecting into a numerical optimization problem. Model-based systems engineering (MBSE) methods are leveraged to generate candidate architectures and multidisciplinary design analysis and optimization (MDAO) [10, 11] techniques are used to evaluate the respective architectures in search for the optimal configuration. Therefore, SAO constitutes a systematic, automated and thus unbiased method of design space exploration [8].

A SAO problem is essentially a very specialized type of MDAO problem. SAO problems can be described as mixed-discrete, hierarchical, multi-objective and black-box in nature [12]. This poses significant constraints on the possible optimization algorithms that can be employed for SAO, essentially excluding gradient-based optimization. Furthermore, the platforms used to formulate and execute these problems, herein referred to as MDAO platforms, have to face significant challenges [13]. The main challenge is related to the fact that different architectures have different components with different couplings between them. This leads to design variables, constraints and even the involved disciplines to vary depending on the architecture. Thus, MDAO platforms meant to be used in SAO problems should be capable of automatically readjusting the MDAO problem during the optimization process, depending on the architecture being analyzed. This requirement is embodied in the concept of Dynamic MDAO [14], which facilitates the adaptive execution of SAOstudies across varying configurations.

Recently, Dynamic MDAO capabilities have been integrated into the back-end of MDAx [15], a collaborative MDAO workflow environment developed at DLR. Consequently, the combined framework of MDAx and RCE, an open source application for setup and execution of analysis workflows [16], now satisfies the functional requirements for conducting SAO studies. The present work leverages these enhanced capabilities to explore the design space of a hydrogen fuel distribution system, herein referred to as the hydrogen fuel system, for a fuel-cell-powered regional airliner. In doing so, it also seeks to demonstrate the practical applicability of the proposed framework to realistic engineering scenarios.

The paper is structured as follows: Section II presents the fundamentals of the relevant engineering design methods used. Section III describes the implementation of the SAO problem. The employed framework is introduced and the architecture design space is defined, including the establishment of the reference aircraft. Additionally, the disciplines used to design the various components of the fuel system are introduced and the optimization problem is formulated. Having conducted the design space exploration, the results are presented and discussed in Section IV. Section V provides the major conclusions and future scope of the research.

II. Methodology

This section offers a brief introduction to two topics that are central to the presented work. First, the concept of SAO is discussed and the two main elements of an SAO problem are presented. Lastly, Dynamic MDAO is introduced and the architectural influences that it deals with are outlined. The high-level strategy used in SAO problems with MDAx and RCE is also described.

A. System Architecture Optimization

The process of system architecting, also referred to as concept development, is typically subject to bias and conservatism [6]. This is mostly due to the reliance on expert opinion for the down-selection of configurations to pursue in further detail. SAO mitigates these issues by converting system architecting into a numerical optimization problem. It thus provides a systematized, automated and unbiased method of design space exploration [8].

The concept of SAO is depicted in Figure 1. Initially, the design space is formalized and modeled in an MBSE environment through the mapping of function to form (components) and the identification of architectural design choices. Once fully defined, architecture instances are automatically generated by an exploration algorithm and quantitatively evaluated, typically using MDAO techniques and by employing physics-based models. The performance metrics resulting from the evaluation can be used to compare architectures and make an informed decision on the optimal solution [17].

SAO problems consist of two main elements [6]:

1) An **architecture generator**, suggesting architecture instances to be evaluated.
2) An **architecture evaluator**, evaluating the performance of a given architecture instance.

The architecture generator has the task of generating architecture instances from an architecture design space. This design space models architectural choices and constraints. It is then through the resolution of these choices that

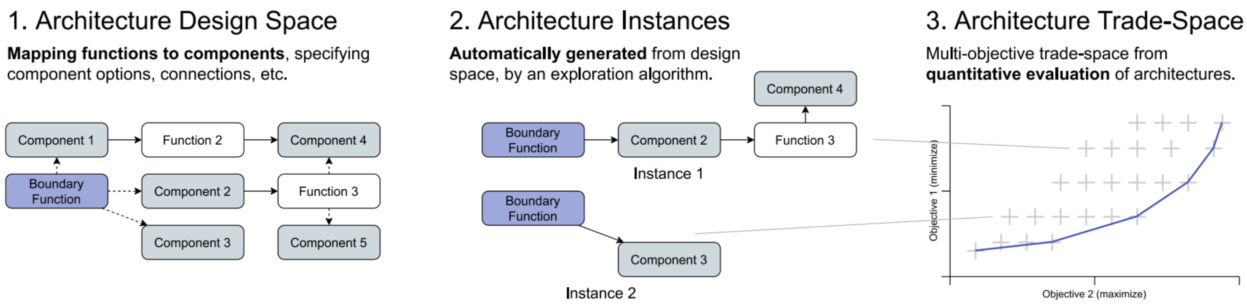


Fig. 1 Systematic architecture design space exploration concept: Architecture instances are automatically generated from a previously modeled and formalized architecture design space and quantitatively evaluated through multidisciplinary analysis methods. The results are used to discern optimal architectures with respect to objective functions. Reproduced from [17].

architecture instantiation is carried out. The architectural design space must be formalized to a degree that enables automated computational processing, while still allowing its description through conventional system architecting terminology, such as function-to-form mappings [18]. The architecture design space graph (ADSG) [12], one of the existing methods for design space modeling, satisfies these requirements. It can be encoded in the form of design variables and is compatible with the use of optimization algorithms, which enables the systematic exploration of the design space. Simultaneously, it allows users to model the architecture design space using common MBSE processes [12].

Apart from the formalized representation of the design space and automatic creation of architectures, the other main enabler of SAOis the automatic quantitative evaluation of proposed designs. An optimizer proposes a design to the architecture generator and receives feedback on the validity of said architecture. If an architecture is valid, it gets evaluated and performance metrics are extracted and fed back to the optimization algorithm, such that architectures can be compared and their feasibility (violation of constraints) assessed. The architecture evaluation step is typically performed in a multidisciplinary analysis (MDA) context, which in turn makes the total loop an MDAO problem.

B. Dynamic MDAO

Within the design space of a system architecture, different architectures exist. These can be made up of components with completely distinct working principles or in a different orientation and thus inducing different interactions between the system constituents. The particular architecture to be analyzed has influence on the design variables, disciplines and data connections present in the MDAO problem formulation [14]. Apart from very small design spaces, it quickly becomes impractical to manually formulate different problems for each candidate solution. This problem is particularly enhanced when dealing with complex aeronautical systems where the system design space can easily contain thousands, if not millions, of different system architectures [19]. This calls for automation of the MDAO problem formulation process, which is the essence of *Dynamic MDAO* [14].

Dynamic MDAO consists of the set of capabilities that allow for the dynamic and automatic formulation of MDAO workflows to accommodate for different architectures, within an architecture design space, during a SAO loop. In order for an MDAO platform to have the capability for Dynamic MDAO, it must be able to accommodate a few different factors that affect the formulation and execution of the problem called *architectural influences*. A total of four architectural influences have been identified that induce modifications to the MDAO problem formulation [20]:

1) **Conditional Variables**: The design variables that make up an MDAO problem can vary depending on the architecture to be evaluated. This is because different components are defined by different variables and each system architecture comprises different components. Any variable whose existence in the problem is dependent on an architectural decision is referred to as a conditional variable.
2) **Data Connection**: In some cases, the routing of variables can change as a result of an architectural decision. In other words, it is possible that the set of disciplines involved in the exchange of a certain variable is different according to the architecture at hand.
3) **Discipline Repetition**: It can occur that a discipline must be repeated. However, the number of repetitions can be the consequence of an architectural decision. This should be automatically adjusted, as each iteration of the

discipline then involves different input and output vectors.

4) **Discipline Activation**: The inclusion of a discipline in the MDAO problem may be subject to an architectural decision. This occurs when two or more technologies are available to perform a certain function, which require different computational tools for their assessment.

Four high-level strategies exist for the use of MDAO in architecture evaluation [14]. Out of these, the *single dynamic* approach (illustrated in Figure 2) is considered to be the most useful for collaborative MDAO while being feasible for implementation in current software solutions.

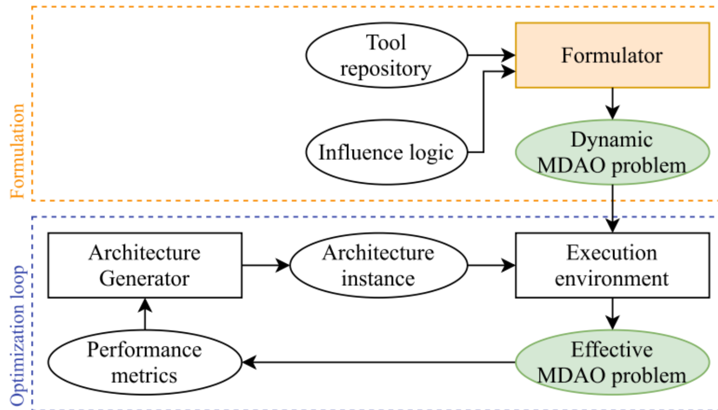


Fig. 2 The "Single dynamic" strategy: a high-level strategy for dealing with architectural influences in MDAO problems. The formulation phase is executed before the optimization loop, which is carried out without user interaction. MDAx is an example of a "formulator", whereas RCE can be used as the execution environment. Adapted from [14].

In a single Dynamic MDAO problem, tools are selected from a previously defined repository and the influence logic is specified. The influence logic consists of the problem's architectural influences and information on how the workflow behavior should be altered based on these influences. Contingent on these two things, a formulator generates a single Dynamic MDAO problem which, when executed in an appropriate environment, automatically modifies its behavior based on the given architecture instance. The result is an effective problem for each architecture assessed.

The capabilities of the MDAx [15] have recently been expanded to support the architectural influences presented above. MDAx is an application developed by the German Aerospace Center (DLR) for collaborative MDAO workflow modeling that enables the creation, inspection, and exploration of components and their relationships. It also enables the export of workflows for execution in Process Integration and Design Optimization (PIDO) environments, such as RCE [16]. Also developed by the DLR, RCE is an open-source application that enables the setup and execution of MDAO problems. Because of the new capabilities of MDAx, the joint framework of MDAx and RCE fulfills all the requirements for use as architecture evaluator in SAO problems.

The extension of MDAx to support architectural influences was done based on the single dynamic strategy. In this way, the exported RCE workflow contains all the logic necessary for the dynamic modification of its execution behavior. The way in which each architectural influence is dealt with in MDAx is not presented herein, for which the reader is directed to [20].

III. Implementation

Automatic exploration of the design space for hydrogen fuel system architectures constitutes a SAO problem. It should be reiterated that the system of interest for this study is the hydrogen fuel distribution system, which is referred to a hydrogen fuel system for simplicity. Such SAO studies are made possible by the use of Dynamic MDAO. The following section presents the conceptualization and implementation of the SAO problem at hand.

First, the SAO framework used is introduced. The framework is then applied to the fuel SAO problem. Then, the main steps required for its implementation are presented sequentially. This consists of the definition of the architecture design space, which includes the selection of a reference aircraft, the creation of the design and analysis disciplines and the formulation of the Dynamic MDAO problem.

A. System Architecture Optimization Framework

The applied SAO framework is illustrated in Figure 3, with reference to the platforms and data interfaces used. To employ such a framework, the first step is usually the creation of the architecture design space, in the form of an ADSG. The tool that facilitates the generation of ADSGs is called ADORE (Architecture Design and Optimization Reasoning Environment) [12]. Developed at the DLR, ADORE is a platform used to support the implementation of SAO problems. To do so, it provides an architecture design space modeling GUI, as well as various interfaces for connecting to evaluation code and to optimization algorithms [21]. It is also within ADORE that the user selects the optimization algorithm, objectives and constraints. When the SAO loop has to be executed, ADORE acts both as the optimizer and architecture generator.

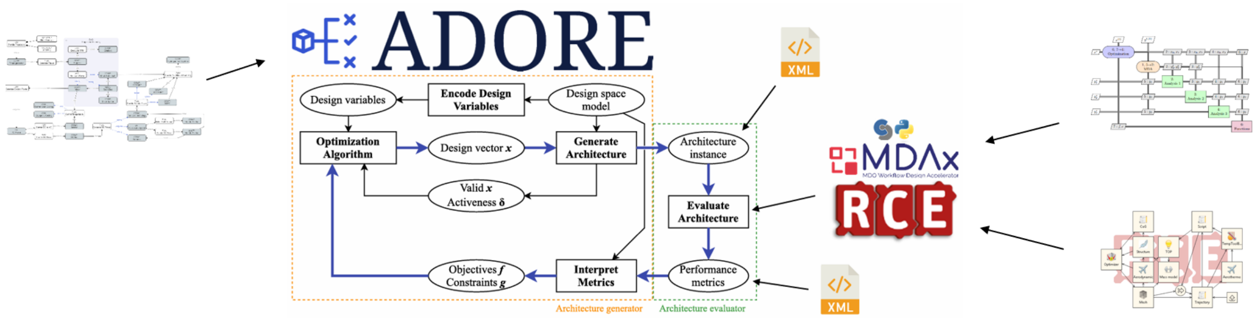


Fig. 3 The SAO framework used at the DLR Institute of System Architectures in Aeronautics. ADORE retains the functions of optimizer and architecture generator. MDAx is used to create the Dynamic MDAO problem, which is then exported and executed in RCE. The evaluation disciplines themselves are Python-based tools and CPACS [22] is used as an XML-based central data schema. Adapted from [21].

After creating the design space, the Dynamic MDAO workflow is defined in MDAx. Recall that this consists of a single workflow capable of analyzing all of the different architectures in the design space. The majority of the process is just like any other MDAO problem creation, with the definition of the disciplines to be included and their inputs and outputs. MDAx then establishes discipline connections automatically, made possible by the use of a central data schema, which in this case is CPACS [22]. The main difference with Dynamic MDAO lies in the accommodation of architectural influences. In MDAx, this is dealt by defining assertions that dictate how the workflow behaves depending on the architecture being analyzed. The implementation of said assertions for the problem at hand is described in [23]. The workflow is represented in the form of an eXtended Design Structure Matrix (XDSM) [24]. Once fully defined in MDAx, it is exported to RCE, where the complete workflow is executed.

B. Reference Aircraft

The chosen reference aircraft for the study is the ESBEF-CP1 (Figure 4), a hydrogen-powered regional concept aircraft. The ATR-72 inspired concept was initially developed by the DLR Institute of System Architectures in Aeronautics for the internal DLR project EXACT [3]. Table 1 compiles the aircraft's most relevant Top-Level Aircraft Requirements (TLARs).

As can be seen in Figure 4a, the aircraft has a distributed propulsion arrangement, a high-wing and a T-tail configuration. It has ten propulsion units which are referred to as pods. Each pod contains a hybrid fuel cell system, a liquid cooling system, an air supply system and an electric powertrain. Fuel is stored in liquid form in two CFRP tanks located in the aft fuselage, behind the cabin deck (see Figure 4b). The hydrogen is then transported, also in liquid form, in triple-walled pipes routed through the pressurized area of the aircraft.

C. Fuel System Architecture Design Space

The hydrogen fuel system design space is presented in Figure 5 in the form of an ADSG. Slightly transparent (gray) elements signify that they are not part of the optimization problem, but are included in the graph for the sake of completeness in the description of the fuel system and its possible architectures.

The boundary function "Provide GH2 to Fuel Cell", where GH2 stands for gaseous hydrogen, is associated with two active performance metrics: mass and electric power consumption, both of which should be minimized. Two main

(a) CPACS geometry of the aircraft

(b) Architecture of the hydrogen storage and distribution system.

Fig. 4 ESBEF-CP1: a hydrogen-powered concept aircraft developed by the German Aerospace Center (DLR). Reproduced from [25].

Table 1 TLARs of the ESBEF-CP1 reference aircraft. Adapted from [25].

Characteristic	**Value**
Design Range [NM]	1000
Cruise Speed [Ma]	0.55
Cruise Altitude [ft]	27000
Max. PAX number [-]	70

types of fuel system emerge at the first architectural decision: liquid and gaseous. The type of fuel storage is not subject to an architectural decision, as liquid storage is seen as the sole viable option. For the liquid system, the type of drive constitutes another architectural choice. It emerges in the fulfillment of the "Move Fuel" function, calling for selection between the concepts of a pressure driven and pump driven system. On the other hand, the fuel lines component, which fulfills the function of transporting the fuel, is subject to an architectural decision at the attribute level, as can be seen in Figure 6. Line insulation can be foam-based or vacuum-jacketed.

For a pump driven system, four possible types of pump are represented, as well as the respective drive types. However, only the centrifugal and piston pump variants are modeled and incorporated in the design study, since they are considered to be the most likely to be integrated in the first generation of passenger hydrogen aircraft [26]. Both liquid and gaseous transport systems require the tank pressurization function to be fulfilled. In both cases, the vaporization of the fuel can be carried out using either an electric heater or a heat exchanger.

Lastly, the fuel needs to be at the right thermodynamic state for it to be fed to the fuel cell. This is referred to as Fuel conditioning, which can essentially be broken down into two functions: the vaporization of the fuel and the further heating necessary to reach the required fuel cell inlet temperatures. In the case of the liquid fuel system, these two functions can either be performed separately, using different components, or together in a single component. In the latter case, the two functions are substituted by a single function, combined vaporization and heating. In any case, the choice is always between an electric heater and a heat exchanger. The red lines in the graph connect incompatible components and are thus denominated incompatibility constraints. For a more detailed explanation of these, the reader is directed to [23].

In the gaseous fuel system, vaporization is carried out directly at the tank outlet. For this reason, assuming that further heating is only done inside the propulsion pod, both functions cannot be performed by the same component. It should be noted, that in the gaseous fuel system, the vaporization of fuel is required for fulfilling two functions, tank pressurization and fuel conditioning. These can be performed with the same component, assuming that the necessary mass flow is routed back into the tank in a separate line.

D. Design and Analysis Disciplines

In order to design the fuel system, various disciplinary sizing models are needed. As a starting point, a preexisting, internal DLR, liquid fuel system sizing tool, developed for a specific architecture, was taken [27]. From this tool, models

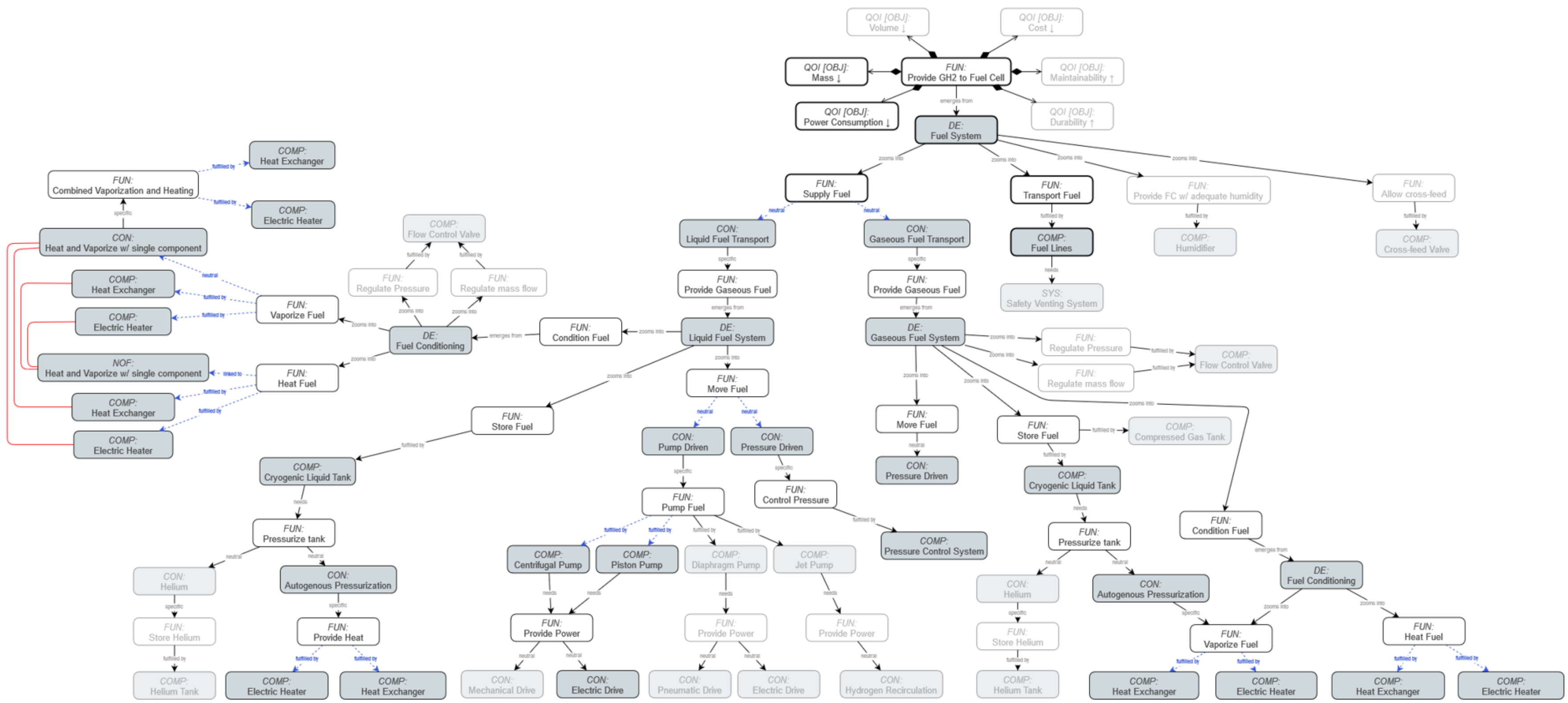


Fig. 5 Architecture Design Space Graph (ADSG) for a hydrogen fuel system, modeled in ADORE. Elements with reduced visibility are not part of the optimization problem but are kept for completeness.

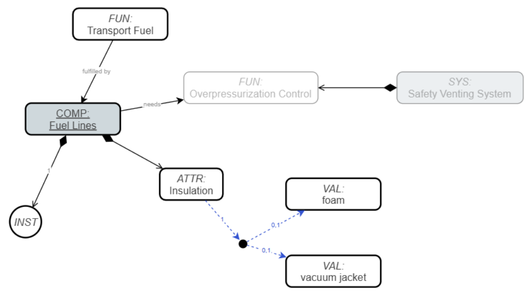


Fig. 6 The attribute "Insulation" of the "Fuel Lines" component can take two values: foam and vacuum jacket. This is subject to an architectural decision.

for the sizing of a heat exchanger, electric heater, fuel lines and centrifugal boost pump were extracted and transformed into individual component sizing tools. Additionally, a piston pump sizing tool was developed in its entirety and the functionality of using vacuum jacketed insulation was added to the fuel lines tool, which previously only included foam insulation. Several smaller alterations were also made to the previously existing models, for example to accommodate for the fact that both liquid or gaseous fuel systems are a possibility.

The previously mentioned disciplines are introduced next, with reference to inputs and outputs.

1. Centrifugal Boost Pump

The centrifugal boost pump discipline sizes a three-stage, variable-speed centrifugal pump driven by a 270-V DC electric motor, based on a reference pump [28, p. 105]. The discipline takes as input the fuel mass flow, the tank pressure, the required fuel cell inlet pressure and, if available, the pressure loss along the fuel lines. Pump parameters such as efficiency and rotational speed (rpm) are obtained from pump characteristic curves like the one of Figure 7 and affinity laws as presented by [29]. Based on these, the effective pressure rise provided by the pump is calculated.

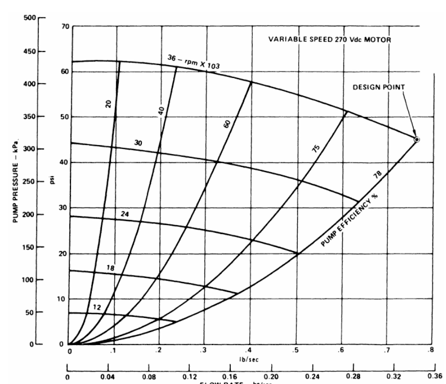


Fig. 7 Boost pump characteristics. Reproduced from [28].

As output, the discipline provides the state of the fuel at pump exit (pressure, temperature and enthalpy), as well as the total mass, including electric motor and frequency converter, and electric power consumption. The pump's mass is calculated on the basis of its dimensions and the employed material, whereas the power consumption is a function of volumetric fuel flow, pressure rise and pump efficiency.

2. Piston Boost Pump

The piston pump discipline uses as reference a low-speed, 5 cylinder "bucket-type" piston pump designed to handle boiling hydrogen, first presented by [30]. The performance of the pump is further detailed by [31]. Its design specifications are shown in Figure 8. Based on the performance of the reference pump, a conservative overall efficiency of 0.8 is assumed for the sized pump. The design speed is fixed to that of the reference, at 240 rpm. The inputs to the discipline are the same as those of the centrifugal pump discipline.

Bore and stroke, in.	3 × 1.5
Total displacement, cu. in.	53.03
Design speed, rpm	240
Displacement at design speed, gal/min	55.1
Design inlet conditions	Saturated liquid with zero head
Discharge pressure, lb/sq in. gage	135
Average piston speed, ft/sec	1.0
Lubrication	Entire pump submerged in pumped fluid
Total piston clearance, diametrical, in.	0.002
Operating temperature, °F	-430

Fig. 8 Reference piston pump design specifications. Reproduced from [30].

The complete dimensioning of the pump, necessary for mass estimation, is then done by maintaining proportionality, using the ratio between the obtained cylinder radius and that of the reference pump. Its mass is then determined by the total volume and material density. The electric power consumption is computed by dividing the brake power by the efficiencies of the pump and electric motor.

Apart from mass, power consumption and pump design specifications, the discipline also outputs the fuel state at pump exit, which is then used as an input for the next executed tool.

3. Fuel Lines

This discipline sizes the main fuel line and what is referred to as the recirculation line. This line exists such that more fuel is always provided than is needed, to prevent situations of possible fuel starvation. To ensure this, it circulates the excess fuel back to the tank. Additionally, the mass flow required for the pressurization line is also calculated. This is the line that extracts liquid fuel from the tank to vaporize for tank pressurization. This line is not sized, however, as it is assumed to be very short and thus the mass is assumed to be negligible when compared to that of the other piping.

The inputs to this disciplinary tool include the type of insulation used for the given architecture, the fuel mass flow, an array of flight altitudes taken from the aircraft mission trajectory, the thermodynamic state of the fuel at the entry to the line, the type of fuel system (liquid or gaseous), and the geometric positions of engines and tank from the aircraft model.

It is worth mentioning that the calculated pressure loss of the fuel line, which is the major output of the discipline, is used as an input to the pump sizing disciplines, creating a feedback that then requires a convergence loop to resolve.

4. Electric Heater

The electric heater discipline takes as input the thermodynamic state of the fuel at entry, the fuel mass flow, and the intended function of the heater. The intended function depicts whether the heater is meant to vaporize the fuel, heat it (further heating after vaporization) or both, referred to as conditioning. Depending on the function, the required increase in enthalpy is obtained, with which the electric power consumption (P) of the heater is calculated.

The sizing and subsequent mass calculations are performed through the scaling of a reference heater. Furthermore, the discipline's outputs are the fuel exit state, as well as the mass, volume and electric power consumption of the electric heater.

5. Heat Exchanger

The present discipline sizes a "shell and tube" type heat exchanger using the mean temperature difference (MTD) method [32, p. 186-190, 291-298]. The hydrogen fuel flows in the tubes, whereas the shell is occupied by a 50% volume ethylene glycol solution. This coolant fluid is assumed to carry excess heat extracted either from a fuel cell or a different aircraft system. Several other assumptions are made in the implementation of this relatively complex model, the most relevant of which are stated below.

- Steady-state flow.
- Constant fluid and material properties.
- No heat is lost to the surroundings.
- Thin-walled tubes (no thermal resistance).

Inputs to the discipline are the function of the heater, the design driving fuel mass flow, as in the maximum mass flow expected in the aircraft mission, and the thermodynamic state of the fuel at the inlet. Depending on the function of the heat exchanger (vaporization, heating or conditioning), the required exit state of the fuel is determined. The heat exchanger is sized and its mass is estimated in accordance with the dimensions of the shell, tubes and baffles, and with the material used, which in this case is aluminum. The main outputs of the discipline are the pressure losses within the heat exchanger, its mass and volume, as well as the fuel exit state, namely temperature, pressure, and enthalpy.

6. Objective Function Disciplines

Two disciplines are included in the problem, which quantify the performance metrics of the system. These are the *System Mass* and *Power Consumption* disciplines. They constitute the objective functions of the optimization problem. The system mass discipline receives as input the masses of each individual component in the fuel system and outputs the total system mass, whereas the power consumption discipline evaluates, in an analogous manner, the total electric power consumption of the fuel system.

For further details on the empirical models and methods employed for the generation of the different disciplinary tools for the aforementioned components, the reader is referred to [23]

E. MDAO Problem Formulation

Formally described, the SAO problem consists of the minimization of two objective functions: mass and electric power consumption for a given aircraft geometric configuration, mission and performance information. This is done with respect to ten architectural decisions encoded as discrete design variables and an additional design variable, the initial tank pressure. The value of the initial tank pressure is dependent on the "pump vs pressure driven" architectural decision. Problem can be defined in a formal MDAO notation as follows:

$$
\begin{aligned}
\text{minimize} \quad & \text{Mass}, \text{ElectricPowerConsumption} \\
\text{w.r.t.} \quad & \text{initialTankPressure} \in \{1.6, 3.5\} \\
& \text{fuelSystemType} \in \{\text{Liquid}, \text{Gaseous}\} \\
& \text{insulation} \in \{\text{Foam}, \text{VacuumJacket}\} \\
& \text{tankPressurization} \in \{\text{EH}, \text{HE}\} \\
& \text{if fuelSystemType} = \text{Liquid}: \\
& \quad \text{drive} \in \{\text{Pump}, \text{Pressure}\} \\
& \quad \text{if drive} = \text{Pump}: \\
& \quad\quad \text{type}_{\text{pump}} \in \{\text{Centrifugal}, \text{Piston}\} \\
& \quad \text{fuelConditioning} \in \{\text{Distributed}, \text{Combined}\} \\
& \quad \text{if fuelConditioning} = \text{Distributed}: \\
& \quad\quad \text{vaporization}_{\text{liq}} \in \{\text{EH}, \text{HE}\} \\
& \quad\quad \text{heating}_{\text{liq}} \in \{\text{EH}, \text{HE}\} \\
& \quad \text{if fuelConditioning} = \text{Combined}: \\
& \quad\quad \text{comboConditioning} \in \{\text{EH}, \text{HE}\} \\
& \text{if fuelSystemType} = \text{Gaseous}: \\
& \quad \text{heating}_{\text{gas}} \in \{\text{EH}, \text{HE}\}
\end{aligned}
$$

where, EH stands for 'Electric Heater' component and HE stands for 'Heat Exchanger' component. The definition involves all the architecture design choices described in Section III.C in form of design variables.

The corresponding XDSM is shown in Figure 9. The employed XDSM notation, which was introduced in [14], is slightly different from a conventional XDSM. It is adapted to Dynamic MDAO problems in order to represent architectural influences.

The execution of the first four disciplines in the workflow is mutually exclusive, which explains why they all have the same block numbering in the XDSM (Figure 9). The first two are associated with a liquid, pump-driven fuel system, whereas the last two are associated with a gaseous fuel system. Additionally, if the proposed system architecture is a liquid, pressure-driven system, then none of the disciplines numbered 1.1 are executed. Under the discipline name is the condition for its activation, referring the XML node identifying the component. So, the discipline is only executed if the

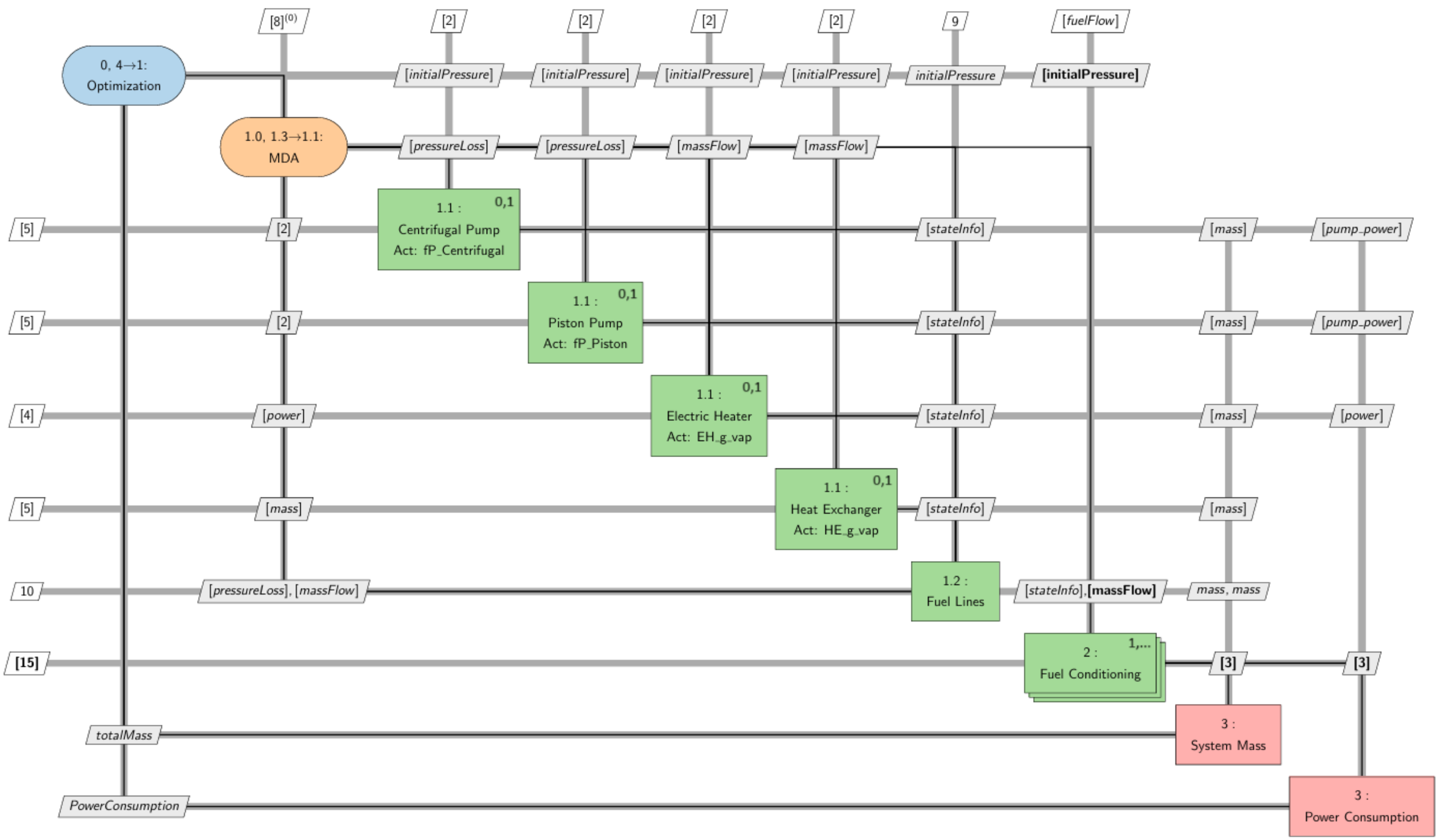


Fig. 9 **XDSM of the hydrogen fuel SAO problem. The extended notation [14] allows for the representation of the four architectural influences. If the number of executions of a discipline is dependent on an architectural decision, this is indicated in the top right corner of the block. *Conditional variables* are indicated in square brackets, whereas variables involved in *data connection* are expressed in bold and italic. Disciplines subject to *discipline activation* have the activation condition expressed in an additional row in the block. Finally, a stack of disciplinary blocks signifies *discipline repetition*.**

corresponding component is present in the architecture being analyzed.

The fuel lines discipline (1.2) is not associated with any architectural influences that affect its execution, being necessary for all architectures. Some of its outputs are, however, required as inputs to upstream tools. Because of this, a feedback coupling ensues, calling for a convergence loop to ensure consistency. For this, an MDA converger coordinates iterative analysis loops between these disciplines until convergence of the coupling variables is achieved.

After the MDA, the "Fuel Conditioning" block (2.0) is executed. This block does not represent a discipline, but rather what is referred to as a sub-workflow or nested workflow. In other words, it consists of a smaller workflow contained within the main workflow. Illustrated in Figure 10, the *Fuel Conditioning* sub-workflow is composed of two blocks, the electric heater and heat exchanger disciplines. These are never executed simultaneously within the same architecture evaluation. This workflow is subject to the architectural influence of discipline repetition. The number of repetitions is associated with the number of heating components in the system architecture, with exception to those in the 1.1 blocks since they belong to the gaseous fuel system case. Heating components are the functions of vaporization and pressurization. As discussed in Section II.B, whenever discipline repetition is used, different inputs are used for each iteration. Thus, for each heating component in the architecture, the necessary information for its sizing is given as input to the nested workflow. Then, depending on whether the component in question is an electric heater or a heat exchanger, the corresponding discipline is activated.

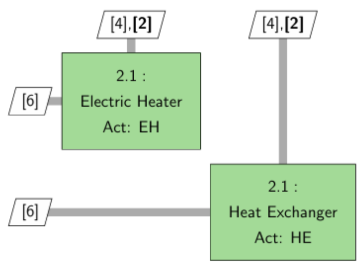


Fig. 10 The "Fuel Conditioning" sub-workflow. Only one discipline is executed in each repetition. The activation condition is the existence of the respective component node in the XML file given as input to the nested workflow.

Finally, attention is directed to the objective function disciplines: System Mass and Power Consumption. These are not affected by any architectural influence. They are also independent of each other and thus can be executed simultaneously. Consequently the optimizer receives the resultant values of the performance metric variables that constitute the objectives of the optimization problem: the total mass and electric power consumption of the proposed hydrogen fuel system architecture.

A more exhaustive explanation of the MDAO problem formulation and the corresponding XDSM workflows and their generation in MDAx, can be found in [23].

IV. Results & Discussion

In this section, the previously presented SAO framework is applied to the design of a hydrogen fuel system for a regional short-range aircraft with distributed propulsion. The results are presented and discussed, including the analysis of the optimal architecture. As the design space is small and evaluation times are short, it was possible to run a design of experiments (DOE) that covers all feasible architectures. This is presented in Section IV.A, accompanied by a discussion of the conclusions drawn. Section IV.B then compares the performance of two different optimization strategies, one based on an evolutionary algorithm and another based on the use of surrogate models. In Section IV.C, the efficiency of the employed methodology is evaluated by comparing it with two different approaches with lower degrees of automation.

A. Design of Experiments

The architecture design space is made up of 80 valid architectures. The combination of this relatively small design space and the relatively short evaluation time for each architecture allows for the conduction of a DOE. The results are shown in Figure 11. It should be noted that the results obtained are for one side of the aircraft. The total values for mass and electric power consumption would then be double of what is shown.

One notable aspect is the lack of a Pareto front, for the given boundaries of the problem and the assumptions under

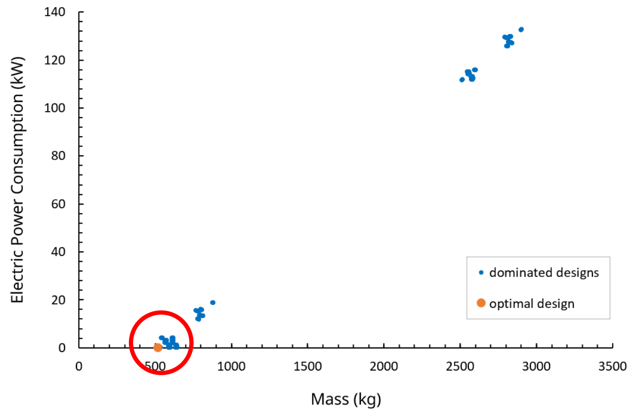


Fig. 11 Results of the DOE. Each point represents a valid and evaluated architecture, which is associated with a certain mass (x-axis) and electric power consumption (y-axis). The optimal design is shown in orange. The best performing group circled in red, worthy of a deeper investigation

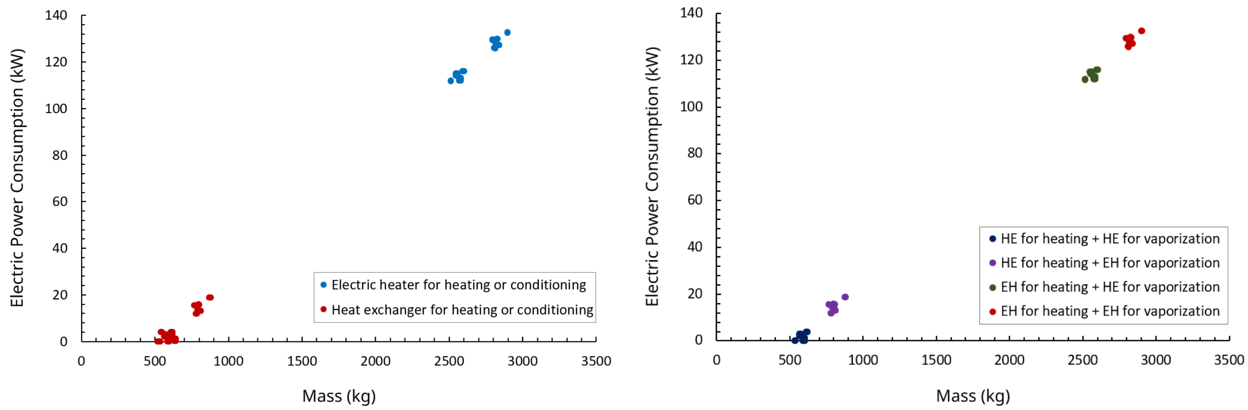
consideration. It is expected that an expansion of the system boundaries and the use of different assumptions could result in a Pareto front of architectures.

In Figure 11, there are two main point groups, each divided into two secondary groups. Out of these, the best performing group is highlighted with a red circle and will be investigated in detail later in this section. As shown in Figure 12a, the main clusters relate directly to the choice between a heat exchanger or an electric heater for the functions of heating or conditioning. Recall that three main functions exist: vaporization, associated with latent heat transfer to vaporize the fuel; heating, associated with sensible heat transfer to increase the fuel's temperature to the required fuel cell entry temperature; and conditioning, consisting of the fulfilling of both vaporization and heating functions in a single component. So, an architecture is associated either with the vaporization and heating functions, with a separate heater component for each, or with the conditioning function with one heater fulfilling both simultaneously. Furthermore, the heating function elevates the fuel temperature from its boiling point of around 20 K to the fuel cell entry temperature, generally above 0° C (273 K). This requires significantly more energy than the vaporization. Additionally, there is another function which is decoupled from the three main ones, referred to as *pressurization*. Pressurization is defined as the vaporization of part of the fuel in the tank in order to maintain adequate tank pressures. In liquid systems, pressurization requires an additional heater, whereas in gaseous systems it is performed in the same heater used for the vaporization function.

The discrepancy in electric power consumption between the two types of heaters is explained by the fact that heat exchangers do not directly consume electric power. The higher mass associated with electric heaters is related to the assumptions within the pre-existing sizing models used. Essentially, based on these models, the electric heater has a significantly lower specific power (heating power per unit mass), thus being heavier for the same amount of required energy output. Therefore, regarding the component mass, the results appear to be quite sensitive to the assumptions made for the specific power of both component types.

Figure 12b shows only those architectures where vaporization and heating are carried out in different components, thus excluding conditioning. The type of heater used for vaporization is the cause for the secondary clusters within each main grouping. Whenever a heat exchanger is used, lighter architectures with lower power consumption are achieved. The reasoning is the same as for the previous case, with heat exchangers having no direct power consumption and with the assumption of a higher specific power. As mentioned previously, the further heating of the fuel after vaporization requires significantly more energy than the vaporization itself. This is why it is a more dominant function, influencing the two main clusters, whereas vaporization has a secondary influence. Essentially, in the context of this problem, and for the reasons given previously, a heat exchanger heavily outperforms an electric heater with respect to both metrics. This also explains the lack of a Pareto front. It can be assumed, that the expansion of the system boundary to include the whole heat exchanger ecosystem especially the source providing the cooling or acting as a heat sink, might eliminate the significant contrast with respect to the energy consumption of heat exchanger and electric heaters. More accurate mass estimation and assumptions for electric heater sizing might also influence the results achieved in this study.

With the choice on the type of heater for the three main functions being so decisive on the performance of the architecture, the influence of other architectural decisions becomes significantly less prominent. To be able to draw any



(a) The choice between an electric heater and a heat exchanger for the heating or conditioning of the fuel has the single biggest influence on the performance of the architecture.

(b) The choice between an electric heater and a heat exchanger for the vaporization of the fuel is what creates the two sub-groups within the two main clusters. To shorten the legend, abbreviations are used: HE stands for Heat Exchanger and EH stands for Electric Heater.

Fig. 12 Results of the DOE with respect to different architectural choices

conclusions from them, one of the four clusters has to be analyzed independently. By zooming into one cluster, the differences within it are exacerbated. Figure 11 shows the group selected for this task.

In Figure 13, the architectures in this cluster are differentiated on the basis of the type of heater used for pressurization, the type of insulation, the number of heaters used for heating and vaporization, the type of drive, the type of pump and the type of fuel system.

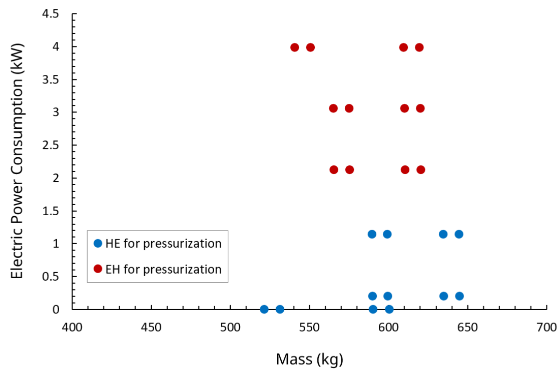
As the function of pressurization only exists explicitly in liquid fuel systems, Figure 13a only exhibits liquid fuel system architectures. Among these, once again, the type of heater used has a significant influence on the architecture. The 50% of the designs with the highest power consumption use electric heaters. However, in these smaller scales, the mass of the heater does not appear to be as noteworthy. Some electric heater architectures outperform those with heat exchangers, suggesting that other decisions also have a significant effect.

Regarding the type of insulation, depicted in Figure 13b, in otherwise identical architectures, using vacuum jacket over foam generates a lighter design. This is due to the difference in the density and thickness of the materials used between the inner and outer metal layers, as explained in Section III.D.3. However, the difference in weight is not large, especially when compared to other architectural decisions. Additionally, vacuum jacket insulation has disadvantages that are not quantified in the study, such as higher costs and structural reliability issues [28]. Thus, given the not so significant mass advantage, foam insulation could constitute a simpler option.

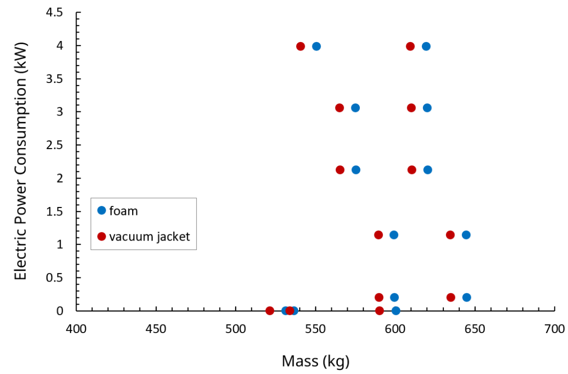
As expected, using two separate heaters or a single one does not affect the electric power consumption of the architecture (Figure 13c). However, considering Figures 13c and 13d together, it can be concluded that the use of a single heat exchanger for the vaporization and heating of the fuel produces lighter architectures in pressure driven systems. In contrast, for pump driven architectures, the use of two separate heaters is beneficial. An explanation for this could be that for pump driven systems, the energy transferred to the fuel by the pump allows for a reduction in the scale of the heater used for vaporization, which does not transfer in the same way when a single component is used.

Comparing the type of drive (Figure 13d), pressure driven systems are the only ones capable of zero power consumption. Within the boundaries of this study, a pump adds weight and power consumption with no contrary drawbacks for the pressure driven system. However, a number of factors are not taken into account which would indeed be detrimental to the adoption of pressure drive. One such factor is that in a pressure driven system, the tank pressure would have to be higher. This has to be taken into account in the tank sizing, as the tank must be able to withstand said pressures, potentially increasing its mass. As the tank is outside the scope of the analysis, this is not reflected in the results. The lack of a pump would also require a more sophisticated pressure and flow control system, adding additional weight which is not accounted for in the present study.

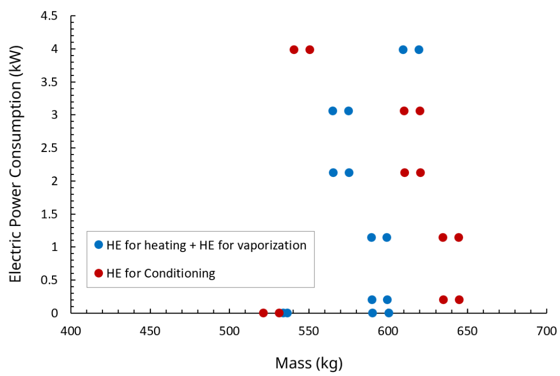
The type of fuel pump is another architectural decision. As can be seen in Figure 13d, no discernible differences in mass appear between architectures with centrifugal or piston pumps. When it comes to power consumption, piston



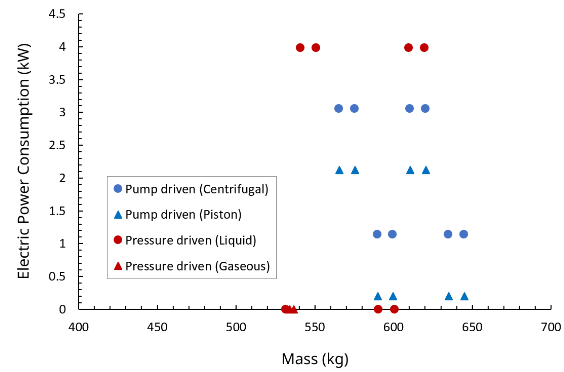
(a) Type of heater used for pressurization



(b) Type of insulation



(c) Comparison between the use of 2 separate heaters or a single one



(d) Type of drive, pump and fuel state

Fig. 13 The best performing cluster is magnified, so that less dominant architectural decisions can be analyzed.

pump configurations consume significantly less. This is mostly related to the models used for the sizing of both pumps. The piston pump is exactly sized for the required pressure rise. In the case of the centrifugal pump model, predefined design points exist and the point closest to the required application is taken. Therefore, in reality, if a centrifugal pump were to be designed specifically for this application, such a large discrepancy in power consumption would not exist.

Finally, the optimal architecture that was achieved in the study is presented in Figure 14. It consists of a liquid fuel, pressure driven system. The functions of vaporization and heating are fulfilled by a single component, a heat exchanger. Tank pressurization is also ensured by a heat exchanger and the fuel lines have a vacuum jacket insulation. As explained previously, the exclusive use of heat exchangers in a pressure driven system allow for the architecture to have no electric power consumption. The mass of the architecture is 521.55 kg for one side of the aircraft, which corresponds to 1043.10 kg for the total system.

It should be emphasized once again that these results, naturally including the optimal architecture, are significantly influenced by the definition of the system boundary and thus by what is and is not taken into account. For the design of a fuel system at the level of detail required in industry, it would be recommended to expand the design space to include at least the tank design and the fuel cell BOP, namely the thermal management system. Furthermore, additional quantities of interest should be analyzed, such as cost, reliability and maintenance, among others.

Another important point is that there are several different architectures in the vicinity of the optimal architecture, as can be seen in Figure 13, with similar values of mass and electric power consumption. The performance of these architectures is so similar that, given the uncertainties stemming from the limited system boundaries and the assumptions mentioned, the optimal architecture might not be the most desirable. Like stated above, by taking additional performance metrics into account, it is possible that other architectures could prove to have stronger arguments for their implementation.

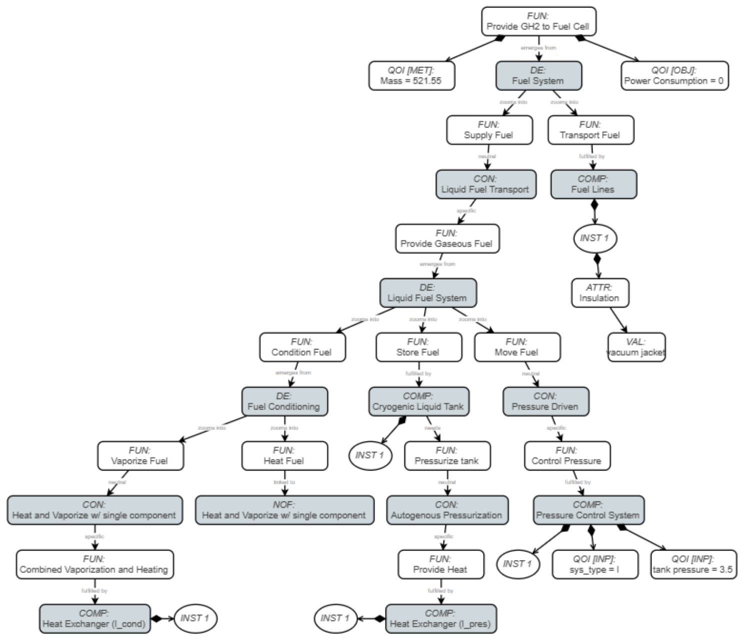


Fig. 14 The optimal architecture consists of a liquid fuel, pressure driven system. It exclusively uses heat exchangers and the fuel lines are insulated by a vacuum jacket.

B. Optimization Studies

Having analyzed the DOE and the best performing architecture in the design space, the effectiveness of various optimization strategies was assessed. Two approaches were studied: evolutionary optimization and surrogate-based optimization (SBO). In the first case, the algorithm used was the NSGA-II [33], an elitist multiobjective genetic algorithm. Several optimizations were performed with progressively decreasing number of generations and population size, and therefore decreasing number of evaluations. An additional optimization was conducted using Bayesian Optimization [34]. This is a surrogate-based optimization algorithm that builds a surrogate model of the design space and uses additional infill points to further explore the design space and refine the model. The results are displayed in Table 2.

These results show, on a very small scale, the benefits of surrogate-based optimization. Compared to the NSGA-II algorithm, the surrogate-based approach is capable of evaluating more architectures faster, while simultaneously being more effective in finding the optimum. In this case, the global optimum was actually obtained, with only 37.5 % of the evaluations of the total DOE and 28.8 % of the time.

Table 2 Optimization results of the different approaches to the SAO problem.

ID	1	2	3	4	5
Type	DOE	NSGA-II	NSGA-II	NSGA-II	SBO
generations	-	5	5	4	-
population size	-	8	6	6	-
initial DOE size	-	-	-	-	15
infill points	-	-	-	-	15
total evaluations	80	40 (-50 %)	30 (-62.5 %)	24 (-70 %)	30 (-62.5 %)
runtime (h:mm)	4:48	2:18 (-52 %)	1:41 (-65 %)	1:24 (-71 %)	1:23 (-71 %)
opt. mass (kg)	521.55	534.09	540.78	534.09	521.55
opt. power (W)	0	0	3058.5	0	0
mass dev. (%)	-	2.4	3.7	2.4	0
power dev. (%)	-	0	∞	0	0

C. Comparison to Conventional Approach

In addition to the SAO study for the hydrogen fuel system, the utility of the employed SAO framework is analyzed. The purpose is to quantify the time savings potential of such an automated procedure. For this, three approaches to the analysis of the complete design space (80 architectures) are compared. The difference between them lies in the level of automation, going from a completely manual method to the automated SAO methodology used in this study. Between the two, a semi-automatic approach is also considered. The details of said analysis are not presented herein (the interested reader is directed to [23]), but the main outcome is presented in Table 3. Even in a relatively small design problem such as the one presented, the advantage of the use of an automated procedure is clear. Repetitive manual tasks are eliminated, resulting in significant time savings. It is also straightforward that the larger the design problem, the more worthwhile this approach is. This is because the total time it takes to implement is much less sensitive to the size of the problem when compared to the other two approaches.

Table 3 Comparison of the different approaches based on total duration.

Approach	Duration (hh:mm)
Manual	61:20
Semi-automatic	31:40 (- 48 %)
Automatic	13:48 (- 77%)

Taking into account the necessary time for training on the used SAO framework, the approach is still considered valuable for any industry relevant design case. The required training time is estimated at around 30 hours [23], including introductions to ADORE, MDAx, RCE and the full implementation of a benchmark problem. In practical application, design spaces are generally much larger than that of the current problem. Therefore, this training time is less significant when compared to the time required in a fully manual approach. The semi-automatic approach requires some of the training mentioned, excluding that of the creation of a benchmark problem.

Naturally, the non-automated approaches presented would not be feasible in industry relevant cases. Traditionally, only a small number of architectures would be selected for analysis based on their potential, as perceived by expert opinion [7]. The use of SAO thus allows for a much more thorough exploration of the design space, while being also free of subjectivity and bias [6].

V. Conclusion and Outlook

This research aimed to study the design space of a hydrogen fuel system for a fuel-cell-based regional airliner with specific focus on the fuel distribution system architectures. This goal has been pursued through the use of system architecture optimization (SAO), where particularly promising architectures are discovered by formalizing and solving an optimization problem. For this purpose, the SAO framework developed at the DLR Institute of System Architectures in Aeronautics is employed. ADORE, the architecture design space modeler, retains the functions of optimizer and architecture generator. MDAx, the MDAO problem formulator, is used to create the MDAO problem, which is then exported and executed in RCE, a PIDO environment. Additionally, CPACS is used as an XML-based central data schema.

Recent developments in MDAx have equipped it with capabilities that allow the dynamic and automatic formulation of MDAO workflows to accommodate different architectures within an optimization study. These constitute the concept of Dynamic MDAO and enable the execution of SAO. Therefore, this study also aimed to demonstrate that the employed framework can be used for realistic application cases in aeronautical engineering.

The results of the design space exploration show that the fuel system's performance, in terms of mass and electric power consumption, is strongly dependent on the type of heater used for the various heating functions of the system. These are vaporization, heating, conditioning and pressurization. Architectures that favor the use of heat exchangers in detriment of electric heaters significantly outperform their counterparts. This appears to suggest that heat exchangers are favorable, at least in part due to the presupposed reuse of expelled heat from other aircraft system. In contrast to the direct consumption of electric power from electric heaters, this constitutes a more efficient and synergistic solution. Furthermore, significant differences also arise between the mass of the two types of systems. This is related to the assumptions made about the specific power of both heater types.

For the reasons stated above, it is intuitively reasonable that heat exchangers could generally constitute a better solution. However, such a stark difference suggests that the system boundaries and assumptions may also have a significant influence. The fuel cell balance of plant consumes electric power. It will also interact directly with a heat exchanger used in the fuel system. Thus, the inclusion of the BOP in the analysis is expected to reduce the differences in power consumption between heat exchanger and electric heater architectures. Regarding the system mass, a sensitivity analysis of the assumptions about the specific power of the components would be a relevant topic of future work.

Given the strong dominance of the type of heater in the results, other architectural decisions become less prominent. A vacuum jacket insulation provides a marginal weight saving compared to foam insulation. Since the difference is not large, other factors such as cost, reliability and manufacturing could be more decisive. These are not taken into account in the study. The type of pump is also not a driving architectural choice with the performance of the two pump types addressed in this study, not influencing the architectures significantly. Finally, the optimal architecture is pressure driven. However, pressure driven systems require higher tank pressures. In turn, this should be taken into account in the tank sizing, potentially increasing its mass. As the tank is outside the scope of the analysis, this is not reflected in the results.

In summary, the results obtained allow for the identification of trends. However, they are also influenced by the definition of the system boundary and the assumptions made. Thus, the optimal architecture should not be seen as a recommendation. For the design of a fuel system at the level of detail required in industry, the design space should be expanded to include at least the fuel cell BOP and the tank design. Additionally, humidifiers and the venting system could be added to the analysis. The option for helium pressurization should be studied, as well as additional pump types and respective drives. The inactive elements in the fuel system ADSG (Figure 5) can provide guidance on potential directions of design space expansion. Furthermore, additional quantities of interest should be accounted for, such as maintenance, cost, reliability, among others. It is foreseeable that just by adding these metrics, the apparent value of architectures could shift.

Through the implementation of this SAO problem, a solid foundation now exists for the systematic exploration of hydrogen fuel system architectures. Further developments are now possible, in order to conduct more comprehensive studies, consisting of additional disciplines, thus expanding the system boundary and/or providing additional architectural alternatives.

Finally, this research has demonstrated the use of SAO in a realistic engineering application. Particularly, it has demonstrated the capabilities of the employed collaborative framework. A comparison of different optimization approaches highlights the potential of surrogate-based optimization. The advantages of using an automated approach in the system architecting phase have been quantified in terms of time-saving potential, compared to a fully manual and a semi-automatic approach. Additionally, it is emphasized that such an approach allows for a much larger exploration of the design space, while also eliminating expert bias and subjectivity.

References

[1] IPCC, *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.*, Intergovernmental Panel on Climate Change, 2023.

[2] Adler, E. J., and Martins, J. R., "Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts," *Progress in Aerospace Sciences*, Vol. 141, 2023, p. 100922. https://doi.org/10.1016/j.paerosci.2023.100922.

[3] Atanasov, G., and Silberhorn, D., "EXACT Sustainable Aircraft Concepts Results and Comparison." *Deutsche Gesellschaft für Luft- und Raumfahrt - Lilienthal-Oberth e.V.*, 2025. https://doi.org/10.25967/630388.

[4] Bussemaker, J., and Boggero, L., "Technologies for Enabling System Architecture Optimization," ONERA-DLR Aerospace Symposium (ODAS), 2022.

[5] Iacobucci, J. V., "Rapid architecture alternative modeling (RAAM): A framework for capability-based analysis of system of systems architectures," Ph.D. thesis, Georgia Institute of Technology, 2012.

[6] Bussemaker, J. H., Ciampa, P. D., and Nagel, B., "System Architecture Design Space Exploration: An Approach to Modeling and Optimization," *AIAA AVIATION 2020 FORUM*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2020. https://doi.org/10.2514/6.2020-3172.

[7] Roelofs, M., and Vos, R., "Uncertainty-Based Design Optimization and Technology Evaluation: A Review," *2018 AIAA Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, 2018. https://doi.org/10.2514/6.2018-2029.

[8] Bussemaker, J. H., and Ciampa, P. D., "MBSE in Architecture Design Space Exploration," *Handbook of Model-Based Systems Engineering*, edited by A. M. Madni, N. Augustine, and M. Sievers, Springer International Publishing, Cham, 2022, pp. 1–41. https://doi.org/10.1007/978-3-030-27486-3{_}36-1.

[9] Crawley, E. F., Cameron, B., and Selva, D., *System Architecture: Strategy and Product Development for Complex Systems*, Pearson, Boston, 2016.

[10] Martins, J. R. R. A., and Lambe, A. B., "Multidisciplinary Design Optimization: A Survey of Architectures," *AIAA Journal*, Vol. 51, No. 9, 2013, pp. 2049–2075. https://doi.org/10.2514/1.J051895.

[11] Sobieszczanski-Sobieski, J., Morris, A., van Tooren, M. J., La Rocca, G., and Yao, W., *Multidisciplinary Design Optimization Supported by Knowledge Based Engineering*, Wiley, 2015. https://doi.org/10.1002/9781118897072.

[12] Bussemaker, J. H., Boggero, L., and Nagel, B., "System Architecture Design Space Exploration: Integration With Computational Environments and Efficient Optimization," *AIAA AVIATION FORUM AND ASCEND 2024*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2024. https://doi.org/10.2514/6.2024-4647.

[13] van Gent, I., and La Rocca, G., "Formulation and integration of MDAO systems for collaborative design: A graph-based methodological approach," *Aerospace Science and Technology*, Vol. 90, 2019, pp. 410–433. https://doi.org/10.1016/j.ast.2019.04.039.

[14] Garg, S., Garcia Sanchez, R., Bussemaker, J. H., Boggero, L., and Nagel, B., "Dynamic Formulation and Execution of MDAO Workflows for Architecture Optimization," *AIAA AVIATION FORUM AND ASCEND 2024*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2024. https://doi.org/10.2514/6.2024-4402.

[15] Garg, S., Bussemaker, J., Boggero, L., and Nagel, B., "MDAX : ENHANCEMENTS IN A COLLABORATIVE MDAO WORKFLOW FORMULATION TOOL," *34th Congress of the International Council of the Aeronautical Sciences, ICAS 2024*, 2024. URL https://elib.dlr.de/206786/.

[16] Boden, B., Flink, J., Först, N., Mischke, R., Schaffert, K., Weinert, A., Wohlan, A., and Schreiber, A., "RCE: An Integration Environment for Engineering and Science," *SoftwareX*, Vol. 15, 2021, p. 100759. https://doi.org/10.1016/j.softx.2021.100759.

[17] Bussemaker, J., Garg, S., and Boggero, L., "The Influence of Architectural Design Decisions on the Formulation of MDAO Problems," 2022.

[18] Menshenin, Y., Mordecai, Y., Crawley, E. F., and Cameron, B. G., "Model-Based System Architecting and Decision-Making," *Handbook of Model-Based Systems Engineering*, edited by A. M. Madni, N. Augustine, and M. Sievers, Springer International Publishing, Cham, 2020, pp. 1–42. https://doi.org/10.1007/978-3-030-27486-3{_}17-1.

[19] Cabaleiro de la Hoz, C., "Definition, Design and Optimization of Aircraft On-Board System Architectures Considering Multiple Life Cycle Stages," Dissertation, Politecnico di Torino, 2025.

[20] García Sánchez, R., "Adaptation of an MDO platform for system architecture optimization," Master's thesis, Delft University of Technology, 2024.

[21] Bussemaker, J., "ADORE Documentation," , 2024. URL https://adore.mbse-env.com/docs/#adore-v151-documentation.

[22] Alder, M., Moerland, E., Jepsen, J., and Nagel, B., "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," 2020.

[23] Neves, D., "Multidisciplinary Optimization of Hydrogen Fuel System Architectures for Conceptual Aircraft Design," Master's thesis, Technical University of Munich, 2025.

[24] Lambe, A. B., and Martins, J. R. R. A., "Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes," *Structural and Multidisciplinary Optimization*, Vol. 46, No. 2, 2012, pp. 273–284. https://doi.org/10.1007/s00158-012-0763-y.

[25] Bielsky, T., Thielecke, F., Atanasov, G., Burschyk, T., and Nagel, B., "Collaborative parametric overall aircraft and systems design to evaluate hydrogen-powered regional aircraft," Deutsche Gesellschaft für Luft- und Raumfahrt - Lilienthal-Oberth e.V., 2024.

[26] Turner, J., Contaut, S., Tarantino, A., and Masson, A., "Cryogenic Hydrogen Fuel System and Storage - Roadmap Report," , 2022.

[27] Burschyk, T., Haemisch, J., and Villada Quiceno, V., "Liquid Hydrogen Fuel System: Architecture and Modelling Approach," *DLR Achitecting Future Aircraft Symposium*, 2025. URL https://elib.dlr.de/213419/.

[28] Brewer, G. D., *Hydrogen aircraft technology*, CRC Press, Boca Raton, 1991.

[29] Moran, S., "Pump Sizing: Bridging the Gap Between Theory and Practice," *Chemical Engineering Progress*, 2016.

[30] Biermann, A. E., and Kohl, R. C., "Preliminary Study of a Piston Pump for Cryogenic Fluids," *NASA MEMO 3-6-59E*, 1959.

[31] Biermann, A. E., and Shinko, W. G., "Performance Study of a Piston-type Pump for Liquid Hydrogen," *NASA Technical Note D-276*, 1960.

[32] Shah, R. K., and Sekulić, D. P., *Fundamentals of Heat Exchanger Design*, Wiley, 2003. https://doi.org/10.1002/9780470172605.

[33] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 2, 2002, pp. 182–197. https://doi.org/10.1109/4235.996017.

[34] Bussemaker, J. H., Saves, P., Bartoli, N., Lefebvre, T., and Nagel, B., "Surrogate-Based Optimization of System Architectures Subject to Hidden Constraints," *AIAA AVIATION FORUM AND ASCEND 2024*, American Institute of Aeronautics and Astronautics, 2024b. https://doi.org/10.2514/6.2024-4401.