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Towards a seamless simulation of the air transport system

Erwin Moerland[1], Andrea Mancini[1] and Björn Nagel[1]

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

Abstract

To create revolutionary solutions answering the increasing demands on the air transport system of the future, a systematic and integrative consideration of all disciplines across the complete product lifecycle is needed. Through the development and utilization of a well-balanced mix of design process digitalization and the development of a corresponding design process methodology, actively involving the heterogeneous disciplinary specialists, the German Aerospace Center (DLR) has fostered effective collaboration between the multitude of disciplines involved over the past decade. The combined effort has led to the maturation of a framework for the seamless connection of disciplinary knowledge in a highly-scalable distributed multidisciplinary collaboration framework for air vehicle design. This paper describes the components of the developed distributed collaboration framework and provides an overview of the broad range of air vehicle design initiatives in which the framework has been successfully applied. On the basis of this, an outlook in future enhancements of the overall design methodology is presented, ultimately targeting to obtain an air vehicle architecture optimization framework capable of seamlessly covering the entire design lifecycle of revolutionary air transport systems.

Keywords: Collaborative Design, Multidisciplinary Design optimization (MDO), Knowledge Digitization, Digital Continuity

Nomenclature

Abbreviations

COTS = Commercial Off-The-Shelf
DLR = German Aerospace Center
DSM = Design Structure Matrix
MBSE = Model-Based Systems Engineering
MDAO = Multidisciplinary Design Analysis and Optimization
SOA = Service-Oriented Architecture
xDSM = eXtended Design Structure Matrix
XML = eXtensible Markup Language

Data standard and software titles

CPACS = Common Parametric Aircraft Configuration Schema
MDAx = MDAO workflow Design Accelerator
RCE = Remote Component Environment

1. Introduction

In 2012, the question whether a common language for aircraft design can be established was raised by Nagel [1]. The proposition was made, that the usage of a standardized data model could have a significant impact on the efficiency of collaborative design efforts. Furthermore, establishing the capability to build complex simulation workflows incorporating the multitude of tools was identified as a prerequisite to enable the collaborative design in teams. This paper discusses how the digital methods supporting distributed collaborative engineering have been continuously developed and implemented, nowadays fostering the effective collaboration between the heterogeneous group of engineers within air vehicle design. Having the Common Parametric Aircraft Configuration Schema (CPACS) as central data exchange format at its center, the efforts have led to the maturation of the CPACS-based simulation framework for air vehicle design. The framework enables the structured creation and execution of multidisciplinary simulation workflows, incorporating a steadily increasing number of disciplinary analysis tools. Within the dedicated, decentralized network of competences, these tools can stem from both within and across company borders and cover a wide spectrum of analysis capabilities - mainly targeting the conceptual and preliminary product design phases. In recent applications, the design process covers considerations from multiple product lifecycle phases. Next to advancing the physics-based vehicle design process itself, tools for assessing the impact of design choices on an ecological and economical level, as well as production considerations are incorporated – targeting the creation of a seamless simulation of the air transport system across the complete lifecycle. Through the utilization of the combined capabilities available in the framework, this ultimately enables the team of engineers to make well-informed decisions on which combinations of technologies provide the highest potential for the future air transport system.

This paper starts by introducing the CPACS-based simulation framework for air vehicle design. Thereafter, a representative selection of implementations of the collaborative simulation framework in air vehicle design studies including the major lessons-learned is presented. After comparing the with the presented framework to a selection of similar initiatives, the paper ends by providing an insight in the planned enhancements of the framework and provides a conclusion and outlook in its future applications.

2. The CPACS-based simulation framework for air vehicle design

To enable the interconnection of established software tools of the heterogeneous specialists within the design process, these are wrapped to a central data exchange format and made available within a large network of competences. The DLR-established data format “Common Parametric Aircraft Configuration Schema (CPACS)” [2, 3] provides the common language for standardized parameter exchange between these tools. As depicted in Figure 1, CPACS provides a hierarchical structure in which the different components making up an air vehicle configuration can be described at multiple levels of fidelity and be combined into overall future air vehicle concepts. Next to parametric vehicle concepts, CPACS allows combining multiple concepts up to the fleet level, ultimately allowing considerations on the overall air transport system. Next to considerably reducing the amount of interfaces between the multitude of tools involved in the process when compared to ad-hoc solutions (see the insert on the bottom-right of Figure 1), the continuous development and application of this XML-based central data format has led to a common language for conceptual to advanced preliminary air vehicle design, used by an increasing community of aerospace engineers. Experience learns that – next to using the language for standardizing the parameter exchange between tools – it also provides a common denominator for the involved specialists to communicate through. The hierarchical schema provides the syntax for the digital data exchange, the documentation describes the underlying semantics on how to interpret the information. The application and collaborative development of the data format by an increased community has led to extensions of the syntax, but moreover to convergence of the common semantic interpretation of the individual structures and nodes of CPACS data files.

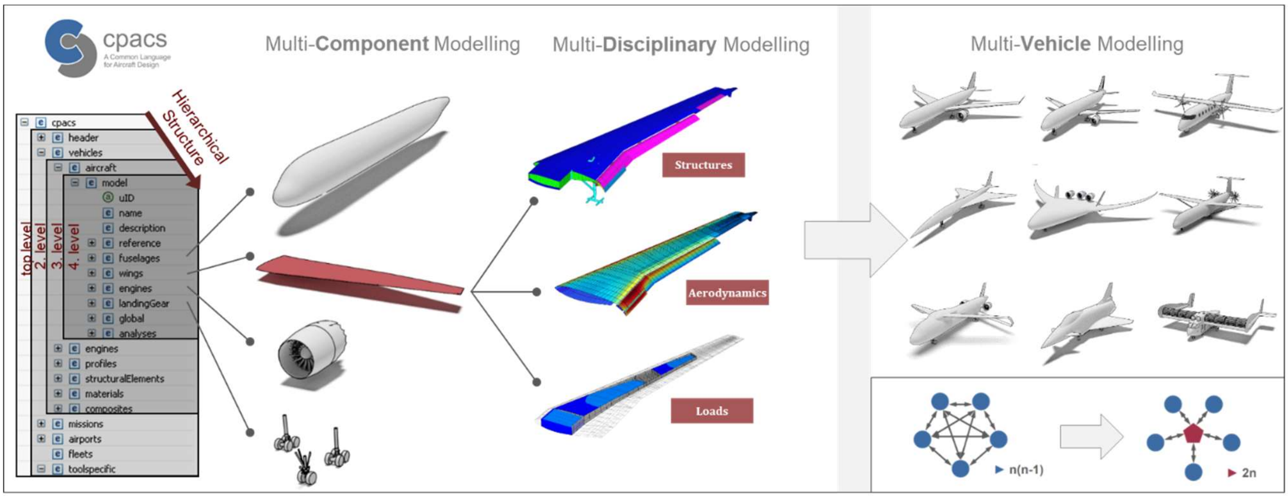


Figure 1 - The common parametric aircraft configuration scheme (CPACS) as central data format for effective integration of components and disciplines for air vehicle modelling

Wrapping a new or existing tool to the CPACS central data format is purposefully non-intrusive in a sense that the source code does not necessarily have to be adjusted. Functional libraries support in retrieving the required information from the data format and converting it to the native tool input format as well as in converting tool outputs to the central CPACS data format. Using the libraries for acquiring geometric information as well as for data interpolation has as major advantage that the semantically correct interpretation can be guaranteed. By hosting the automated tools at dedicated servers at the respective organizations and interconnecting these within a network of competences, these are made available as engineering services [4]. In this way, the engineering services are shared in a network, without having to share the corresponding intellectual property in the form of source code or compiled versions of a tool. Since wrapping a tool and hosting it as engineering services on individual dedicated servers is non-intrusive, these can be used to perform individual analyses by the respective specialists according to their experience as well and the tool owners stay in full control of when and how their knowledge is applied.

The provision of engineering services into a network of competences allows for the creation of simulation workflows, linking the competences into an overall system for multidisciplinary analysis and optimization. The DLR-developed process integration and design optimization software Remote Component Environment (RCE) is dedicated to enable the creation and execution of such workflows [3]. Figure 2 shows a workflow for the design and analysis of a strut-braced wing configuration, in which over 24 tools of 11 institutes distributed across Germany are combined into a single, seamless multi-fidelity analysis system.

Through the implementation of such digital workflows, it became apparent that common understanding of the different roles and responsibilities of the engineers within the network as well as creating awareness of the contribution and dependencies of each of the specialists within the design process significantly increases the quality of the outcome of the combined design effort. On top of a general consensus on how the underlying design process is organized, ensuring a clear alignment of individual and overall design targets is required for all participants to maximize the outcome of the team efforts. Finally, it is important to note that the applied design methodology should ensure the engineers are kept ‘in the loop’. Even if the complete simulation workflow is automated, the various specialists should have a regular look at the intermediate stages of execution to confirm the quality of the results produced [5]. In the end, all specialists and the workflow operators are required to post-process the generally vast amount of design points considered to effectively combine knowledge on the disciplinary and overall vehicle concept design level in the decision-making process.

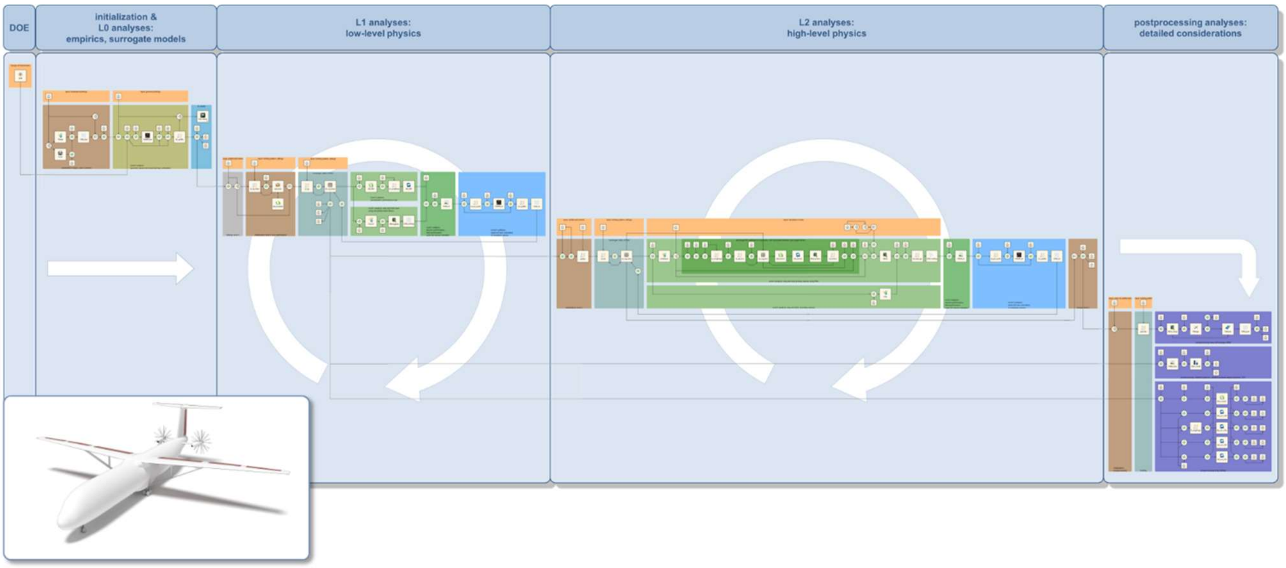


Figure 2 - A multi-fidelity simulation workflow for the design of strut-braced wing configurations, combining over 24 engineering services of 11 institutes across Germany in a single, executable workflow [4]. The square blocks represent the engineering services, which are interconnected into a logical system in which the data exchange is managed through the usage of central data exchange format CPACS and its libraries.

To streamline the setup and execution of digital simulation workflows, five types of agents - each having their role and responsibility within the collaborative design process - have been identified [6-8]:

- *Customer*: the main beneficiary. (S)he defines the design task, sets the boundary conditions concerning time and resources available and revokes design iterations until (s)he is satisfied with the results.
- *Architect*: specifies the design case by translating the customer's needs into a formalized problem, connecting the design task to the available network of competences and defining the required design phases and dimensionality of the design space.
- *Integrator*: translates the formalized design problem into executable simulation workflows utilizing the capabilities available in the network of competences
- *Collaborative engineer*: supports the competence specialists in making their tools available as engineering service and ensures the stable and secure connection of the dedicated servers within the network of competences
- *Competence specialist*: provides the required design competences as engineering services. These can be disciplinary capabilities (e.g.: structural sizing or noise analysis) or services supporting the process (e.g.: visualization of overall results)

Providing the basis for all collaborative design or analysis studies, an analysis or design team generally consists of a multitude of competence specialists, supported by a handful of members representing the other roles.

To assist setting-up the complex simulation workflows, methods from the field of systems engineering were applied. One of the most prominent and helpful methods is the creation of design structure matrices to identify engineering service dependencies and to cluster and structure these accordingly. In recent design efforts, the workflow creation is fully automated using the MDAO workflow Design Accelerator software (MDAx), utilizing techniques for obtaining an efficient routing of parameters through the engineering services [9]. Figure 3 provides an insight in the extended design structure matrices (xDSM), which principle is at the basis of visualizing dependencies within the MDAO simulation workflows [10]. The large diagram shows a competence overview linking ecological and economic impact assessment capabilities within the EXACT project, elaborated in section 3.4 of this paper. The insert of Figure 3 shows an xDSM diagram of a conceptual design initiation workflow for different engine technologies, consisting of engineering services for initiating engine and vehicle configurations (openAD_engine), aircraft mission calculation (AMC) and synthesis. The xDSM logic can be automatically exported and consecutively executed using the process integration software RCE.

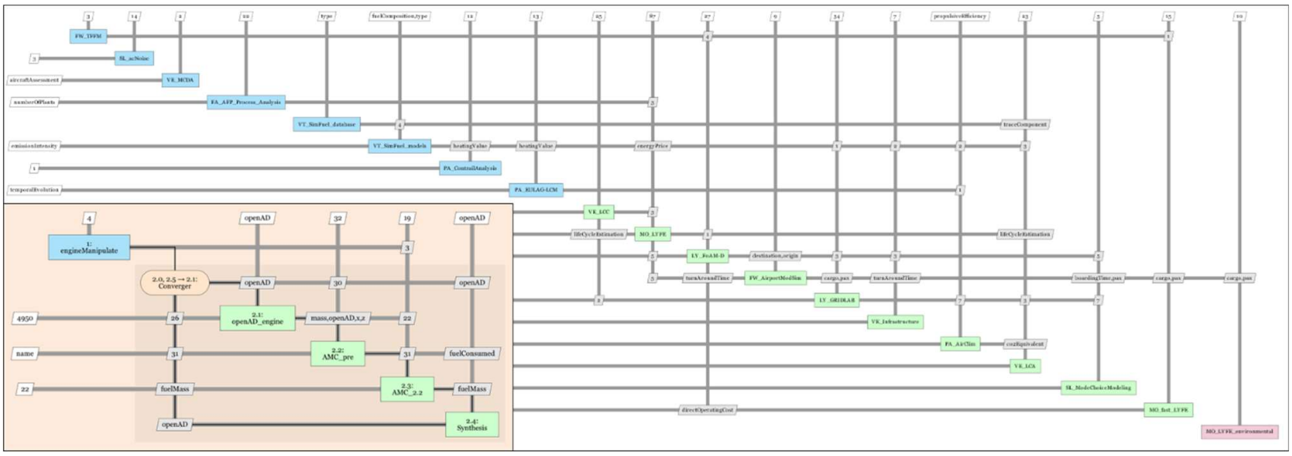
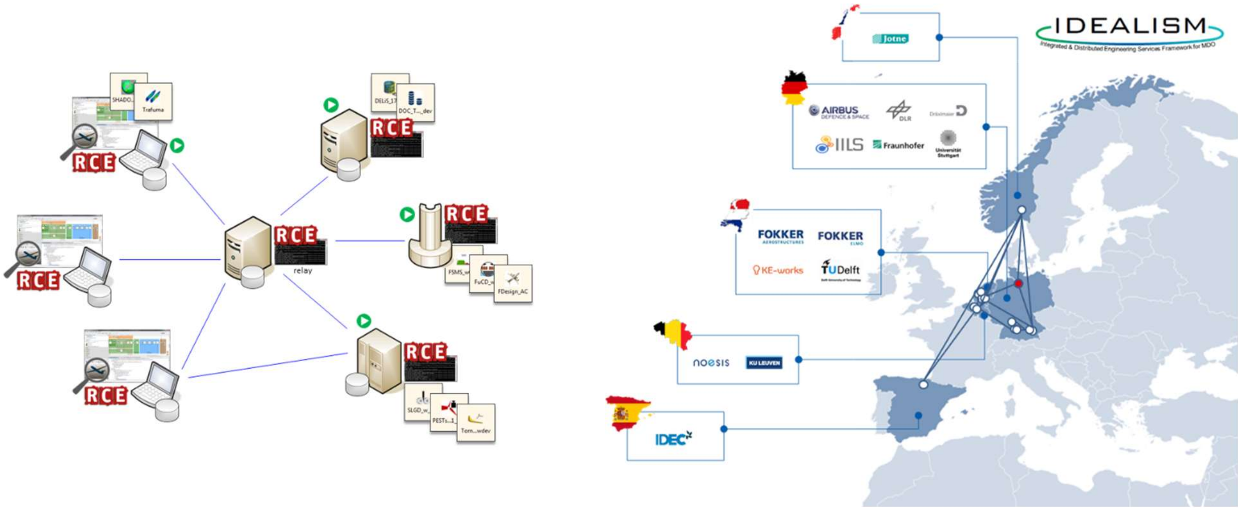


Figure 3 - utilizing extended design structure matrices (xDSM) to create an insight in the dependencies between competences. The large diagram shows a competence overview linking ecological and economic impact assessment, the insert provides an xDSM of a conceptual design initiation workflow, which is automatically exported into the process integration software RCE (see Figure 2).

Within a series of European research & development projects, the network of competences has been considerably extended by enabling the automated, cross-company exchange of information within the aircraft design community. Currently, multi-tier design processes, in which knowledge models are either shared as black-boxes or in the form of response surface models, are established to create and analyze promising technologies to be embedded in future aircraft system architectures, see Figure 4. The simulation of future air vehicle configurations using well-organized simulation workflow orchestration techniques is at the heart of the design studies performed.



(a) DLR Software Remote Component Environment (RCE) enables the efficient remote connection of models in simulation workflows, whilst these are hosted on dedicated servers at the full control of the model owners [11].

(b) schematic of the multi-tier cross-company integration of competencies for the design of a vertical tail plane within the IDEaliSM project

Figure 4 - A methodology for cross-company and cross-nation integration of competencies has been established within EU projects IDEaliSM (ITEA) [12] and AGILE (Horizon 2020) [6].

The CPACS-based simulation framework for air vehicle design is being developed with an extendible collaborative engineering setting in mind. It aims at providing a low-threshold for actors having developed digital analysis capabilities - often over multiple years - to provide these as engineering services within a network of competences. Due to the loose-coupling of these services, they can be easily omitted or included according to the design question at hand, exchanged with lower- or higher-fidelity counterparts according to the information and resources available. The provided flexibility and extensibility of the system however comes at a cost: due to the inherent complexity and multitude of disciplines involved, performing design studies and interpreting their results cannot be done by individuals anymore and requires organizing the collaboration of all team members involved. To be able to cope with this, increasing the experience in the application of the framework, such as described in section 3 of this paper needs to go hand-in-hand with the continued development and application of design process digitalization methods as described in section 5. Thereby, with the system being successfully utilized in a series of projects of increasing size and complexity, the focus of developments is shifting towards the completion of the simulation framework ecosystem by adding intuitive user interfaces and standardized visualization dashboards for the ease of operation.

3. Implementations of the simulation framework to collaborative air vehicle design

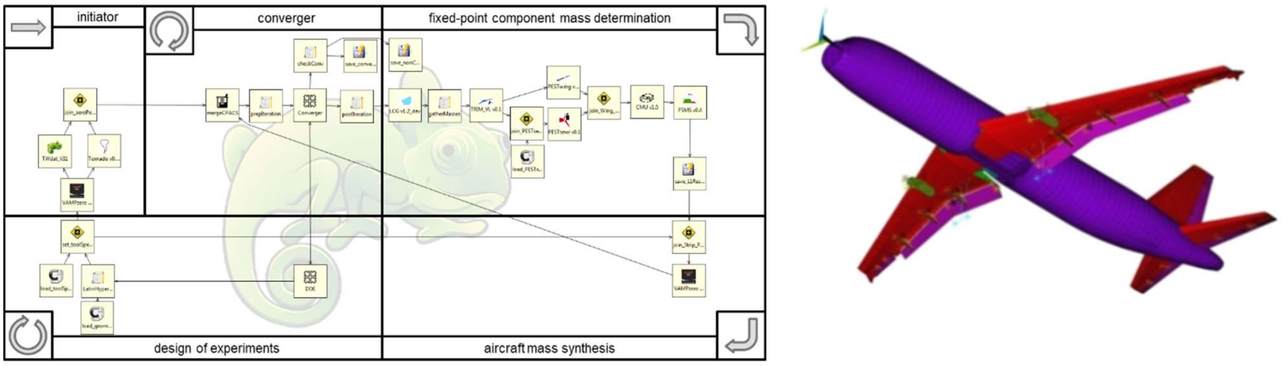
Within this chapter, a selected set of applications of the simulation framework for collaborative air vehicle design are presented, showing how the framework evolved over time presenting the three major lessons-learned per implementation phase. It shows how digital simulation capabilities develop at a high pace, providing a promising opportunity to cope with the complexity of modern air vehicle design.

3.1 Creating the simulation technology for the assessment of conventional aircraft configurations

After initial efforts aimed at developing technologies for the interconnection of analysis software within simulation workflows starting in 2005, a virtual aircraft multidisciplinary analysis and design process is created, incorporating the competencies of twenty-five participants, located at eleven departments across six sites of the German Aerospace Center (DLR) [13].

Figure 5(a) represents a simulation workflow as modelled in the process integration environment RCE. To gain trust in the usage of the simulation framework and the results produced, existing short- to medium and long-range tube and wing configurations are re-designed and its outcome compared to data available in literature. Whilst adhering to the early versions of the CPACS data schema, the models are mainly built-up through manual labor using basic aircraft data obtained from literature. Due to the required bookkeeping, this is a time-consuming effort and underlines the need for (more) automated configuration initiation methods. To learn how to approach the knowledge transfer and interpretation within the geometry-centric approach, trade studies are performed for a set of major aircraft design parameters such as wing area and aspect ratio. By comparing the analysis results on overall aircraft configuration level to the expected trends as well as extensively discussing the results on individual discipline and component level, initial interpretation discrepancies could be resolved.

To investigate new technologies not covered by empirics or for which simplified physical considerations do not yet exist, the results higher-fidelity engineering services need to be incorporated in the vehicle design process. Figure 5(b) shows a global finite element method (FEM) model of the low- to medium-range tube and wing configuration considered. Based on the CPACS model obtained by the classical aircraft design workflow, this FEM model is automatically built up and combines the results of a fuselage structure and wing structure modeler whilst using explicit information on the fuselage-wing interface from the data format. The results of the corresponding structural sizing routines can be fed-back to the simulation workflow presented.



(a) Simulation workflow for D150 (short- to medium-range) and D250 (long-range) classical aircraft design

(b) Detailed global structural model including movables built-up to learn coupling results of low- and high-fidelity tools. Reproduced from [13].

Figure 5 - Basic simulation workflow for classical tube and wing aircraft design and corresponding global structural FEM model of the resulting short- to medium-range configuration

Three main lessons-learned:

- Especially within teams including a multitude of competence specialists having heterogeneous backgrounds, the overlap of knowledge can be relatively small. This can cause difficulties in understanding one another. Finding a common denominator between the differing perspectives, language and conventions used by each of the specialists is one of the major targets of the CPACS data exchange format. To cover the exchange of implicit or even tacit knowledge, this needs to go hand-in-hand with regular meetings having a long-enough duration such that a) there is plenty of room for dialogues and b) there is ample time to align individual interests of the specialists involved with the overall targets of the following design iteration.
- Difference between syntax and semantics: although a common syntax is used, obtaining a common semantic interpretation of the exchanged data proves to be less straightforward. Using the experiences in the data exchange, at the end of this phase CPACS is updated to version 2.0, a process in which more than 250 identified issues have been processed focusing both on updating the syntax and providing clear information on the semantical interpretation of the schema format.
- Tool-owners having their tools connected to the CPACS-system in the form of engineering services learned what it entails to provide a generally applicable batch-executable tool. By creating pre-processing scripts catching the problems regularly occurring and providing suggestions for improvements – even before tool execution, the provided service becomes more robust and time is freed to focus on creative tasks.

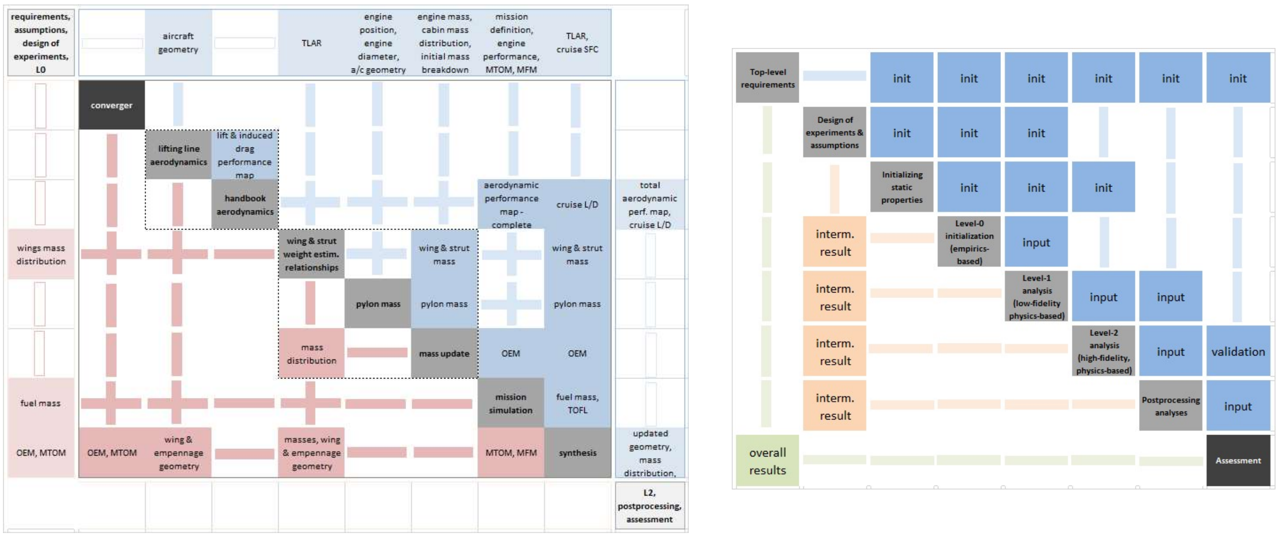
3.2 Towards the consideration of less-conventional designs

After building up the basic technology supporting the distributed design framework, the focus of design tasks shifts to investigate enhanced short- to medium-range configurations having the potential to provide a significant reduction in cost (25-30% in direct operating costs). The introduction of counter-rotating open rotor engines, featuring a significantly lower thrust specific fuel consumption compared to modern turbofan engines, as well as investigations into a thin high-aspect ratio strut-braced wing lead to the result shown in Figure 6(b). Next to this, flight mechanical considerations and handling quality assessments are performed for a Blended-Wing Body configuration [14], including a connection of the resulting configuration and flight control system to the in-flight air vehicle simulator AVES.

The introduction of design camps – three-day gatherings having a character similar to sprints in the scrum framework - proves very valuable in coping with the complexity of the design exercise. At the start of the design process, the *competence specialists* share their view on technology options in a qualitative manner during these design camps, aiding in the identification of promising technologies, categorizing these as well as in the selection of the most promising configurations within the generally vast amount of options. Targeting the numerical comparison of the promising configuration options, in a following design camp parametric design spaces are defined and corresponding simulation processes are sketched using the combined knowledge of the design team. This is the phase, where *architects* (see section 2) play an important role in structuring the inputs of all competence specialist involved and in guiding the process. Whilst the *collaborative engineers* ensure the network of competences required for the analyses is completed and available, the *integrator* uses the simulation process sketch to translate the formalized design problem into executable simulation workflows. During the final stages of a design cycle, the design camps focus on collaborative decision making, involving all participants of the design team. Especially during these gatherings, it is of large importance to combine the knowledge of all team members in weighing the different configuration options. Understanding how considerations of ones' discipline influences the outcome of other disciplines as well as the overall vehicle design and vice versa provides invaluable integration knowledge.

By utilizing methods from the field of systems engineering, the process methodology is extended towards more collaborative and less ad-hoc simulation workflow structuring. Especially the creation and utilization of design structure matrices proves very helpful. As depicted in Figure 6(a), design structure matrices provide valuable insight in which information is required and obtained by the individual engineering services available and allow clustering engineering services according to their level of fidelity, discipline and components covered. The figure shows how the engineering services on the diagonal are coupled and which kind of data is exchanged between these. The required input from lower-levels of fidelity as well as information and configuration updates provided by the coupled set of engineering services is shown on the upper row, respectively rightmost column. The top-level design structure matrix, representing the overall logic of the multi-fidelty design process, is shown in Figure 6(b). After setting-up the design space, designs of experiments of steadily increasing level of fidelity are conducted. Within the Level-0 initialization, the configuration is initiated using a set of empirical methods, extended by pre-calculated response surface models for the phenomena not covered by historical data. An example of the latter is the weight estimation of wing-strut combinations, stemming from a set of pre-executed finite element method simulations. To obtain a proper balance between the fidelity of the physics represented by the models and overall simulation execution times, the part of the workflow incorporating the low-level physics-based engineering services (the level-1 analyses) is at the center of the performed analysis and provide the major part of the results. To increase the confidence in the results, engineering services of high level of detail are used to confirm and, where needed, to correct results of the converged medium fidelity physics-based simulation workflows.

An unforeseen benefit of providing tools as engineering services in a network of competences, combined with extensive exchanges between the team members involved is found in tools classically used to perform (manual) analyses for predetermined configurations, to be enhanced and used more broadly. Following the application to investigate strut-braced wing configurations for example, the configuration implies a statically overdetermined structural system as loads are transferred through the wing root as well as the root of the strut to the fuselage. Furthermore, the structural relief comes at the cost of an increase in aerodynamic drag. Classically, the wing and fuselage components of aircraft as well as structural and aerodynamic design are treated as relatively separate disciplines, now having to interact more intensively. The corresponding aerodynamic and structural engineering services were extended to be able to cope with the new phenomena occurring. With the capability extensions in pace, the effort to consider the effect of adding juries - extra supports which allow considering truss-braced wing configurations - did not require much extra effort.

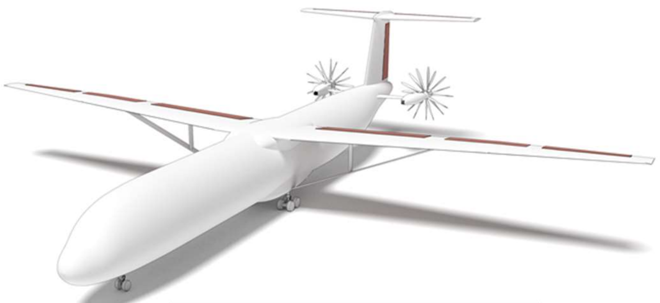


(a) Selection of design structure matrix representing the aerodynamic coefficients and structural mass calculations, mission simulation and configuration synthesis using level-1 engineering services

(b) Top-level design structure matrix (DSM) representing the overall multi-fidelity logic of the simulation workflow depicted in Figure 2.

Figure 6 - Consideration of less-conventional designs within the established collaborative design environment based on a combination of simulation workflow results and expert knowledge. For a detailed discussion on the results and lessons-learned, the reader is referred to [15]

Parameter	Unit	Range
Main wing		
wing aspect ratio	-	15 - 20
wing $t/c_{average}$	-	0.08 – 0.12
wing loading	kg/m²	460 – 540
Strut		
strut η_{wing}	-	0.25 – 0.75
strut depth (* c_{wing})	-	0.2 – 0.5
strut $t/c_{average}$	-	0.08 – 0.14
strut $\#_{juries}$	-	0, 1, 2
Operational		
initial cruise altitude	km	11 - 13
flow laminarity (wing upper side & strut)	-	0% , 50%



Parameter	Unit	Resulting value
Geometry		
strut η_{wing}	-	**0.52**
strut depth	-	**0.15**
# juries	-	**1 (2)**

Figure 7 - Parameter variations (left) and impression of the resulting strut-braced wing configuration (right). For a detailed discussion on the results, the reader is referred to [15].

Three main lessons-learned:

- The introduction of design camps – three-day, full-time gatherings having a character similar to sprints in the scrum framework - prove very valuable in coping with the complexity of the system established aid significantly in collaborative decision making.
- Formalizing the design process using design structure matrices largely aids in understanding the mutual influence of engineering services and their effect on the overall vehicle configurations studied. Furthermore, being aware of the contribution of one’s discipline and the sensitivities to the configuration studies motivates competence specialists in providing their knowledge during the entire design cycle.
- Engineering services available in a network of competences tend to get enhanced and be used more broadly as a result of experiences gained in performing integrated design studies.

3.3 Formalizing the product development process and extending the system towards usage across companies and borders

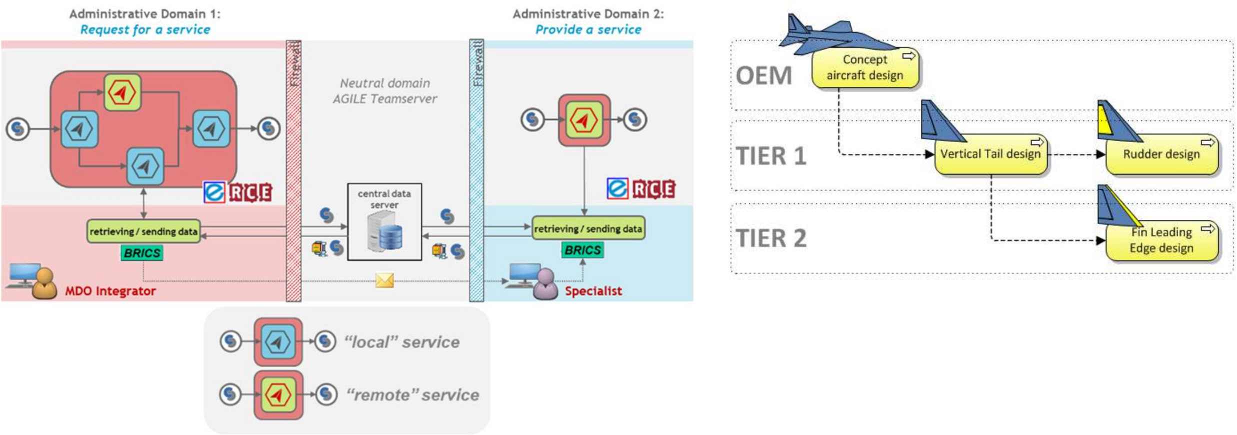
Creating a formalized tier supply chain, capable of performing design analyses within semi-automated simulation frameworks crossing company borders is the next major development (see Figure 4(b)). Within a series of EU-projects, multiple partners provide their expertise as engineering services due which the palette of available competences and the number of configurations investigated is increased considerably.

Featuring a set of interchangeable commercial off-the-shelf (COTS) and open-source software solutions, a flexible system for connecting simulation workflow capabilities across company and country borders is implemented. At the basis of this capability is the Collaborative Architecture, in which the principles of service-oriented architectures (SOA) originating from the field of software engineering are transferred to the engineering design domain. As shown in Figure 8(a), using a central data server taking care of all the data interactions between the different sub-workflows of the partners involved, a loosely-coupled system of engineering services is successfully implemented and utilized for the execution of multiple design challenges - involving different constellations of engineering services [7]. Utilizing the modularity and scalability of the developed cross-company service-oriented product development process has two major advantages. First, the complexity of future air vehicle configuration studies can be mastered by incorporating the required specific engineering knowledge generally spread across a large amount of companies. Second, a vehicle design team has the ability to take considerations based on the experience available in its tier-supplier network already during initial design considerations into account (see Figure 8(b)). This has the potential to aid in obtaining more efficient vehicles as well as in spreading the risk of novel vehicle developments across multiple parties.

For implementing the process within an industrial context, three sequential stages for process automatization within the service-oriented process methodology are identified [16]:

1. The creation of engineering services to automate repetitive manual design tasks, reducing the time required for performing design tasks, making these less error-prone and more generally applicable.
2. The integration of a multitude of engineering services in business- and simulation workflows, integrating both manual and automated engineering competences in a single, continuous process. This allows substantiating the effects of design decisions on overall product level and provides the prerequisites to perform full product optimization.
3. Transition to a front-loaded multidisciplinary product development process. This entails adopting a strategy where increased performance and reduced time-to-market is obtained by shifting the identification and solving of design problems to early design phases.

Through its implementation, all the non-creative, often time-consuming repetitive tasks such as data management and exchange, data conversion, tool execution, gathering and combining analysis results are automated using the formalized design system. This has two major advantages: it saves a tremendous amount of time and resources to conduct design iterations and it makes the process less error-prone. As described in [6], a speed-up of over 40% in setting-up and execution realistic MDAO simulations for air vehicle configurations compared to the state-of-the-art methods for air vehicle design can be achieved.



(a) data is exchanged between the engineering services across companies through a central data server in a neutral domain [17]

(b) component subdivision in tier-supplier network of competences [12]

Figure 8 - Extending the system across company borders

Three main lessons-learned:

- Through standardization, automation and process formalization, a speed-up of over 40% in setting-up and execution realistic MDAO simulations for air vehicle configurations compared to the state-of-the-art methods for air vehicle design can be achieved.
- Not every part of the product development process can or should completely be automated. Before effort is spent in digitizing a process step, an investment-benefit analysis should be performed. For example, when deciding on whether it makes sense to automate a task, it should be identified how repetitive the task actually is. Next to this, the right balance of flexibility and complexity of engineering services should be defined up front. Combining business- and simulation workflows - in which manual and automated design tasks are well-balanced and coupled - allows for the formalization of the entire product development process.
- Coping with the IT-requirements across companies forms a bottleneck in setting-up the distributed network of competences. The connection of the dedicated analysis servers at each company to a central data server in a neutral domain, through which data can only be pulled and pushed upon allowance of the involved employees, seems the option preferred by the majority of IT-managers.

3.4 *Utilizing and extending the system for future air vehicle design*

Current applications of the simulation framework for air vehicle design focus on the identification and assessment of aircraft concepts and technologies for achieving more sustainable air mobility solutions [18]. Based on the outcome of market analyses, targeting the maximization of the impact of climate-neutral technologies considering future demand for air mobility and expert knowledge on promising propulsion systems, a set of ten different configurations – some of which feature a family concept - are identified as depicted in Figure 9. To create a solid foundation for the selection of the most promising solutions, all proposed configurations are validated against operational and social boundary conditions and are evaluated based on their complete energy lifecycle and corresponding climate impact.

For each of these configurations, a multi-disciplinary analysis is conducted, in which the competences of all required competence specialists are coupled. To achieve the ambitious goal, more than sixty participants from twenty-one DLR institutes are combining their efforts and capabilities. The structured application of the simulation framework for air vehicle design formally guides and enable the exploration of the extensive design space and the successful collaboration of all the competences involved.

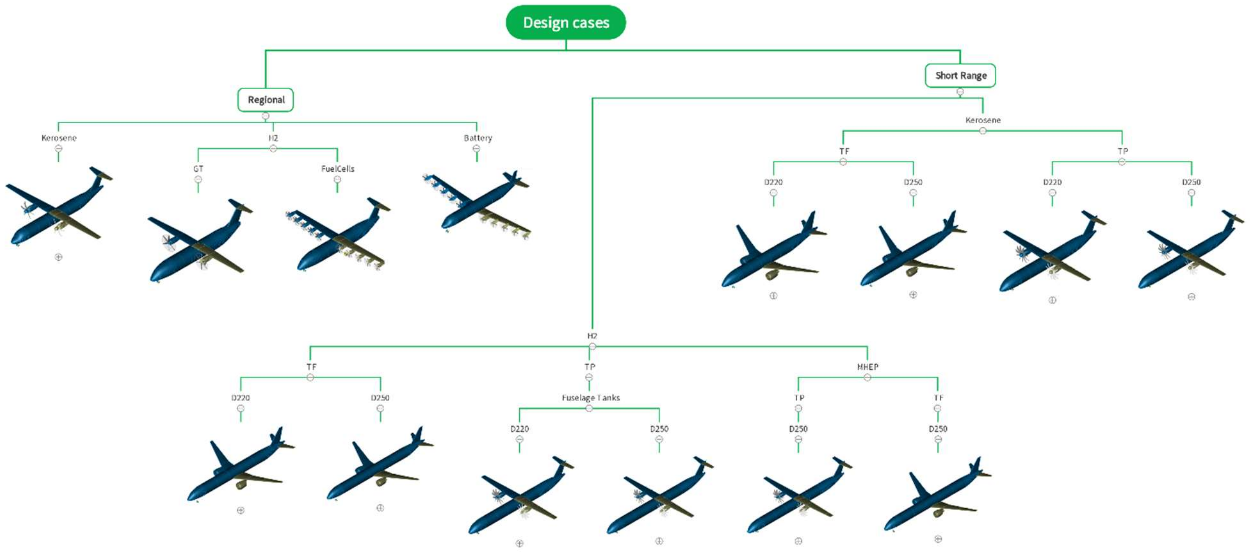


Figure 9 - The configuration landscape considered for future more sustainable air mobility solutions, categorized by design range, energy carrier, propulsion architecture and number of passengers.

To achieve the digitization of all the competences required for exploring the design space, a series of workshops is performed, in which all the project participants provide insight in the required inputs and provided outputs of their competences. This information is collected and modelled according to a simplified common data schema, to show the connections and data flow between the various competences. The software MDAx aids in displaying the resulting competence overview as extended design structure matrices (see Figure 3). This provides the basis for discussions between project participants and enhances the communication between different working groups. It is noted, that this ‘step back’ towards more analogue methods to explore the analysis capabilities of the team before refraining to the fully digitized design system is considered beneficial.

The common data schema CPACS is adopted by all participants in the project and is continuously extended to meet the modelling needs required to analyze the novel propulsion technologies and corresponding air vehicle configurations considered. To cope with the large amount of studies conducted in parallel, a version-controlled central repository is established to share the results and the workflows among all project participants. The result data is structured in such a way, that it supports in obtaining provenance information on the studies performed and it ensures the replicability of results in the future.

Another current implementation of the system is found in the application to the design of next generation military air vehicle configurations [19]. Utilizing the narrowing ‘gap’ between low- to medium fidelity and high-fidelity analysis capabilities to investigate complex aerodynamic and engine design features already in the early stages of design. E.g.: utilizing aerodynamic performance maps featuring vortex-induced flow phenomena and the effect of reduced installation losses by variable-cycle engines to investigate the boundaries of the flight envelope. To cover all requirements and cope with the multirole aspect of the configuration, specific parts of the CPACS data exchange format are generalized. In its latest version, it has the ability to cover the entire range of complex military mission descriptions, covers a larger and different sets of payload configurations and allows for the parametric description of the systems, outer shapes and structures under investigation. Figure 10 shows the DLR Future Fighter Demonstrator configuration. It features a planform stemming from high-fidelity aerodynamic considerations, specifically targeting the preservation of controllability at high angles of attack.

Figure 10 - View on the DLR Future Fighter Demonstrator configuration and its internal arrangement of major components

Three main lessons-learned:

- Coping with such a large number of different configurations, the simulation workflows, the correct input settings and the vast amount of results produced requires a thorough and structured versioning system. This ensures the replicability of results in the future as well as the possibility for colleagues to re-use knowledge and perform a well-structured comparison of configuration options.
- Experience in trying to flexibly model the details of novel system architectures, their corresponding entities and interconnections (e.g. propulsion systems and their power-breakdowns) learns that a proper balance needs to be found between the aspects and of components covered by individual engineering services and the corresponding simulation workflow overhead. The flexibility of modelling each component of the system architecture allows resolving and rearranging system architectures at will, however comes at the cost of simulation workflow and coupling complexity.
- Managing the large amount of engineering services requires mechanisms in which competence specialists can quickly adjust an engineering service, test its functionality and easily share the new version within the network of competences. It proves to be beneficial if the dedicated servers are directly connected to the version-controlled projects with which the engineering services are managed. Competence specialists can push new versions or rollback to previous versions of their engineering service to the networked server instance at any time.

3.5 Overall conclusions on implementing the simulation framework to collaborative air vehicle design

The foundations for the simulation framework for collaborative air vehicle design have been laid in 2005 and the framework has continuously evolved to its current state, in which it is effectively used to design novel aircraft having a lower impact on global warming as well as for the next generation of military configurations. To the authors knowledge, the applications of the CPACS-based simulation framework provides the largest cross-company system for collaborative air vehicle design to date. Digital simulation capabilities develop at a high pace, providing an opportunity to support in coping with the inherent complexity of designing the next generation of air vehicle concepts. Therefore, during efforts to obtain the most optimal solutions for future air mobility, research and improvement of the overall air vehicle design methodology should be continuously conducted.

Even though the rate of digitalization seems to steadily increase, teams of experts and integrators should not forget to rely on classical (analogue) ‘post-it’ methods break down a large design and analysis problem in logical parts and understand the inherent complexity of the problem. Such intermediate efforts largely increase the trust in the underlying digital design and analysis system.

The digital design process itself should be used to support setting-up and executing the overall integrated analysis capabilities and – through the generally vast amount of result data generated – provide a solid basis for decision making. Digital design methods will not replace the tasks of the competence specialists involved. On the contrary, these should be used to reduce the amount of repetitive, non-value-adding activities and support opening-up the space for finding novel solutions for air mobility. The role of most specialists will turn from knowledge executors into knowledge digitizers and results analyzers.

4. Comparison to selected similar initiatives for collaborative air vehicle design

The question arises how the simulation framework for air vehicle design compares to COTS software titles for aircraft design. These well-established software packages generally feature a clear and intuitive user-interface for air vehicle design, often feature a database representing existing air vehicle configurations and the corresponding pre-defined parameter sets can be easily manipulated by end users. Furthermore, the system of equations within the software titles are generally extensively validated. One does not need to have programming skills to be able to use the system, learning to use it takes relatively low effort and results are presented using intuitive visualizations. For these reasons, these software titles are nowadays often the primary choice for application in industrial settings. Although the aforementioned software titles provide their purpose for performing conceptual air vehicle design studies well today and in the future, these are less fit for simulating the air transport system in the multi-partner collaborative context aimed for. They do not feature a service-oriented architecture, due to which the modularity and scalability towards detailed design considerations is not trivial. Embedding new or replacing existing features requires recompiling the software and is either not straightforward for end-users or in some cases even disallowed. In conclusion, the available COTS software titles for aircraft design serve a different purpose than the CPACS-based simulation framework for air vehicle design.

In recognition of the need to combine the knowledge of multiple partners to solve the challenges the air transport domain is currently facing, the amount of initiatives on creating the technical means for collaboration have increased during the last decades. Within three large EU-funded projects VIVACE [20], CRESCENDO [21] and TOICA [22], large effort has been put in creating technologies for enabling virtual extended enterprises in the aeronautical domain. A virtual enterprise is defined as: “temporary consortium of independent member companies coming together to quickly exploit fast-changing world-wide product manufacturing opportunities” [23]. The intention of the companies involved in such consortia is to share cost, skills and competencies collectively enabling them to access markets with solutions that cannot be delivered by the individual companies alone. Although collaborative product development gains increasing interest, difficulties encountered in among others the aeronautical industry highlight effective collaborative development processes still “require a quantum jump in the way information and knowledge is shared in the extended organization” [24].

Several publications highlight the barriers enabling effective collaboration and knowledge sharing within cross-company teams of experts. These range from barriers on a technical implementation level to the very important non-technical barriers concerning the organizational and human levels that impede effective collaboration [24-26]. In [7], the authors present the results of a questionnaire identifying the most important barriers averting collaboration among a representative selection of members of the EU-funded project AGILE [6]. The ten highest ranking barriers were of a technical nature, where the lack of a secure and fluent cross-organizational workflow execution principle clearly took the highest rank. The fact that the non-technical barriers - mainly concerning lack and difficulty of human communication - ranked lower, confirms that these are often underestimated at the start of implementing collaborative engineering methodologies. Through the development and implementation of the AGILE paradigm [6], its Collaborative Architecture [7] and Knowledge Architecture [8], the majority of identified technical and non-technical barriers have been resolved.

The recent development of the cloud-based application “AirCADia Nebos” at Cranfield University features similarities to the CPACS-based framework for air vehicle design [27]. Contrary to the framework presented in section 2, where all engineering services are hosted at dedicated servers of the competence specialists, within AirCADia Tools are generally hosted as microservices using commercial cloud solutions. At the cost of having to share intellectual property, the usage of third-party off-the-shelf cloud solutions might provide a more ad-hoc scalable and in some cases more cost-effective solution for sharing knowledge. However, within AirCADia implementations of hosting tools on local workstations to secure protection of intellectual property are considered as well. Inputs and outputs are exchanged between the involved microservices through JSON (JavaScript Object Notation) files. Within the CPACS-based simulation framework, the open-source central schema for the standardized exchange of data between all engineering services involved has been developed over more than 15 years is at the heart of the parametric data exchange. CPACS bases on the eXtensible Markup Language (XML), allowing the usage and combination of namespaces. This enables competence specialists to add their own namespace to the data exchanged and thereby provide a schema for their tool specific input requirements. Similar to the working principles of the Collaborative Architecture [7], if models are required within a simulation, within AirCADia, the "chief designer" requests its addition to the workflow, the "domain designer" has to grant access. In a publication describing AirCADia [27], the following conclusions are drawn: 1) There is a lack of an integrated tool for workflow orchestration within distributed design environments. 2) Existing methods are focused on creating model connections, less attention has been given to enabling the interactions between designers. 3) The pros and cons of using COTS cloud solutions in collaborative design environments are not clear yet.

Instead of being a single tool integrating all required workflow orchestration competences, the AGILE paradigm relies on an ecosystem utilizing a collection of software titles, each serving part of the paradigm. This allows the end-users to choose the setup according to their preferences. To advance the capability development in research and academia, the usage of open-source software is often preferred. In industrial applications however, the implementation of commercial software might be preferred due to the long-term support and product updates that can be guaranteed. The combination of central data exchange and implementation of the data import/export or direct connections between the software titles using plugins enables a smooth connection between the software titles within the eco-system. Each team member either supports in setting-up, maintaining and improving the eco-system or is provided with dedicated user-interfaces serving the needs of setting-up and executing air vehicle design studies. Concerning the second conclusion drawn, the authors of this paper fully agree with the large need to provide attention on the interaction between engineers. Indeed, the usage of the simulation workflows entails more than just a push-button process, it requires the involvement of the competence specialists' knowledge [5]. As described in section 3 of this paper, actively integrating all required team members in the design process has been a major target from the early implementations onwards. Among others, the benefits of organizing design camps throughout the entire design cycle for the active integration of all team members in the process focuses on this aspect [15]. As a final note, the simulation framework for air vehicle design purposefully uses dedicated servers for hosting engineering services, such that the competence specialists retain full control over their capabilities. This is identified as a prerequisite for secure exchange of knowledge between the members of the design team. If in the future cloud solutions can be implemented in such a way that a similar level of security and authority is guaranteed, this might provide a proper alternative for sharing competences indeed.

5. Future enhancements of the simulation framework – including advanced digital design methods supporting the collaborative decision-making processes

Through the successful application of the collaborative simulation framework to combine the required knowledge within a series of projects both within DLR and within EU-wide consortia, opportunities for extending the underlying integrated design process have been identified. These focus on increasing the transparency of the process methodology, its continued enhancement through applications in future air vehicle design studies, as well as the further flexibilization and time-reduction of the design process.

The steadily increasing amount of engineering services provided by the competence specialists is at the basis of all design studies performed using the simulation framework. Next to the continued connection of existing simulation models as engineering services, the digitization of recently achieved knowledge is needed to provide answers to the challenges on the air transportation system of the future. Increased effort is put in developing methods to create novel knowledge-based engineering services, which can be flexibly adjusted according to the needs of the design team. To achieve this, a framework for semantic knowledge based engineering is being implemented - combining ontology-, inference- and rule-based modelling techniques [28]. Figure 11 provides an insight in how formalized knowledge patterns are integrated using semantic web technologies to create knowledge dependency graphs. When sets of rules are added to the knowledge patterns, a numerical analyzer allows for structuring the dependency graph as depicted in the third step of the figure. These rules can be in the form of equations, response surface models or a connection to an external engineering service. With all dependencies known, the analyzer can provide information on whether the system is solvable or – if this is not the case - under- respectively overdetermined. The latter information provides clear hints on which information is still lacking in the combined knowledge graph or which parts provide the same information based on conflicting rules. If the system is solvable, the underlying rules can be executed using the numerical solver to provide the results of the engineering service. The semantic knowledge-based engineering principle described allows for a significantly more flexible utilization of the available knowledge in the design process, since it allows effective re-using of existing knowledge patterns wherever these make sense and the combined set of knowledge fragments can be approached using different sets of requirements. An example of engineering services profiting from this flexibility is found in the conceptual design and synthesis of air vehicle configurations. Using the same set of formalized knowledge – being empirical correlations, response surface models - air vehicle configurations can be initiated for a given and complete set of top-level requirements and reverse design considerations are possible when obtaining air vehicle configurations based on pre-defined geometry (e.g.: wing planforms stemming from high-fidelity aerodynamic considerations) or for a given set of technologies. Trough connection to the central data exchange format CPACS – which in fact is an ontology for parametric air vehicle design itself – the replacement of knowledge-rules by results from higher-fidelity codes is possible.

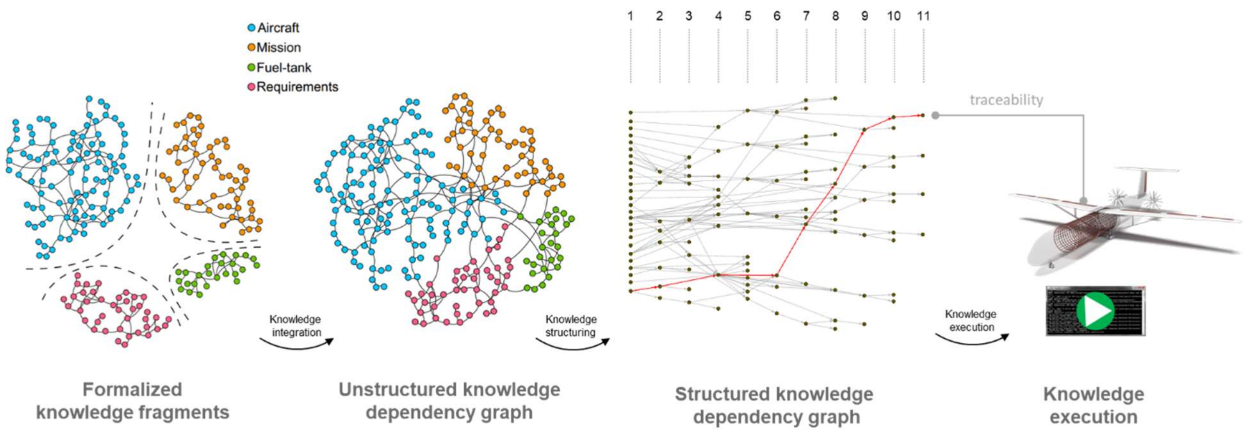


Figure 11 - Establishing and connecting formal knowledge graphs features many advantages when it comes to collaboration, integration, reusability and modularization

Although the system is working well and has been utilized in a significant amount of air vehicle design projects, an increase in transparency during and after the execution of simulations would support understanding the product development process and lower the entry barrier considerably. For this, the continued formalization of the meta-level of the process seems advantageous. The major target is to create a system, in which the provenance of the configuration development is clear and available at all times. In this, next to the lifecycle and fidelity dimension, the time-dimension of the digital continuity within the process needs to be covered: interlinking information on who made which decision, based on which information at which stage of the process and why. In this light, the design process methodology itself will largely profit from an increased utilization of model-based systems engineering (MBSE) techniques. Therefore, MBSE backbone is under development, featuring a single environment integrating multiple tools to cover the formal steps of a design cycle, linking to the simulation framework presented; from system identification, definition of stakeholders and requirements to the actual system down selection and detailed design. This largely increases the traceability between design data and decisions and allows for completely addressing all stakeholder needs and requirements. In [29], the established link between MBSE and MDO for the acceleration of the digital development process is presented in detail.

Through the intensified usage the simulation framework, covering a larger part of the product lifecycle and integrating a larger amount of engineering services of different fidelity levels, an increased amount of result data is being generated. Therefore, emphasis is laid on enhancing methods to cope with the vast amount of results on both a disciplinary analysis level as well as on an overall integrated air transport system level. An intuitive user interface for the automated processing of results is being developed, providing a solid support in the overall decision-making process. It is based on a web-based interactive dashboard, to which data can be passed through CPACS files. In this dashboard, the primary functionalities such as a pre-formatted report and basic data visualizations are directly available, but some flexibility is also accounted for, allowing the user to create a personal view on the data. This is achieved by allowing the selection of various types of visualization graphs, in combination with data filtering techniques. In this way, the user can focus on creative actions directly supporting the decision-making process rather than performing repetitive, manual visualization tasks. Moreover, thanks to the nature of web-based applications, the dashboards can easily be shared among colleagues, incrementing the active involvement of the various competence specialists in a collaborative interpretation of the results. In this, an important aspect seems again to find the right balance between digital methods for automated results processing and the active involvement of all competence specialists and further team members having a stake in the design process.

6. Conclusion and outlook

Digital simulation capabilities develop at a high pace, providing an opportunity to significantly support coping with the inherent complexity of designing the next generation of air vehicle concepts. This paper presented a simulation framework for the seamless simulation of the air transport system, including its implementations to air vehicle design and the corresponding major lessons-learned. Implementations of the framework have been shown, from its application to basic tube-and-wing aircraft design, to less-conventional configuration such as strut- and truss-braced wings. The extension of the framework across company borders largely increased the palette of engineering services available. Current applications focus on the identification and assessment of aircraft concepts and technologies for achieving more sustainable air mobility solutions and the next generation military configurations. To the authors knowledge, the CPACS-based simulation framework provides the largest cross-company system for collaborative air vehicle design to date.

At the basis of the simulation framework are the engineering services, forming the core knowledge assets of the competence specialists within the design team. The formalized setup and utilization of simulation workflows effectively integrating these engineering services provides a structure for collaborative knowledge-based design in distributed design teams. The communication between the engineering services is enabled through utilization of the central data exchange format CPACS. In setting-up and executing the workflows and especially for results interpretation and decision-making, actively involving all stakeholders throughout the entire process is of utmost importance. Based on the applications of the framework shown, the question referred to in the introduction concerning whether a common language for aircraft design be established can be answered positively.

The amount of available engineering services steadily increases, targeting to enable the analysis of complete system architectures over their entire product lifecycle at the required levels of fidelity. Novel methods to create and manage these digital assets - combining principles from semantic web and knowledge-based engineering - are close to being included in the framework, enabling a more flexible use of the digitized knowledge for air transportation simulations. Although the system is working well and has been utilized in a significant amount of air vehicle design projects, an increase in transparency during and after the execution of simulations would support attaining a deeper understanding of the product development process and might lower the entry barrier for participants new to the framework. By increasing research and experience on managing the organizational level of air vehicle design studies, the authors intend to further enhance the effectiveness of the collaboration methods applied.

With the current state of affairs in the aeronautical domain - driven by an urgent need to obtain solutions lowering the impact the air transport system has on the Earth’s climate as well as in finding the next generation military air systems – a large focus is laid on identifying new technologies for the next generation of air vehicle configurations. Assessing the impact of these technologies and integrating these effectively in the future air transport system requires the collaboration of a large amount of competence specialists. To enable an integrated and well-informed assessment over the entire lifecycle of the products, the search for the most promising technologies will go in conjunction with the advancement of digital simulation capabilities. Ultimately it is targeted to obtain an air vehicle architecture optimization framework capable of seamlessly covering the entire design lifecycle of revolutionary air transport systems.

7. Author contact details

Erwin Moerland
German Aerospace Center (DLR) – Institute of System Architectures in Aeronautics
Email: erwin.moerland@dlr.de
Telephone: +49 (0)40 2489 641 332

8. Copyright Statement

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