



Bringing Manufacturing into the MDO domain using MBSE

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Most MDO problems currently do not include manufacturing as an optimization domain. Within the H2020 project AGILE 4.0 the intent is to bring manufacturing into the MDO domain using MBSE techniques developed within the project. To demonstrate how manufacturing can be brought into the MDO domain application cases are set up that resemble MDO problems from industry. In this paper, the MDO techniques will be used for the design of a Flap for a regional jet. The manufacturing aspect is represented by including the manufacturing cost of the flap in a Design Of Experiments (DOE). In this DOE different flap kinematic mechanisms and different flap sizes and paths are explored. The DOE is set up using the MDO toolset developed within AGILE 4.0. It allows for an automatic definition of the DOE workflow. The DOE results show that the choice of flap configuration has a significant effect on the Flap manufacturing cost, the flap weight and the landing performance of the aircraft. Next steps will be to investigate more flap configurations, improved the manufacturing cost model used and to set up a true flap optimization.

Nomenclature

AC	=	Application Case
Cl	=	Lift coefficient
DOE	=	Design of Experiments
MBSE	=	Model Based Systems Engineering
MDO	=	Multi-disciplinary Design Optimization
OCE	=	Operational Collaborative Environment

I. Introduction

Most MDO problems currently do not include manufacturing as an optimization domain. Within the H2020 project AGILE 4.0 the intent is to bring manufacturing into the MDO domain using MBSE techniques developed within the project. To demonstrate how manufacturing can be brought into the MDO domain application cases are set up that resemble MDO problems from industry. This paper describes one of these application cases.

The application case discussed in this paper handles the optimization of a flap for a regional jet. In the optimization, different kinematics and structural designs will be considered as well as the manufacturing methods used for production. The intended outcome is a Pareto front mapping flap performance versus the manufacturability of the flap. Performance is quantified as the flap weight and/or the aerodynamic performance of the flap. Manufacturability will be represented by the manufacturing cost of the mono parts present in the flap and its kinematic system.

In this paper, the set-up and the initial results from the application case will be represented. Set-up means how the problem is being defined and how tools developed in the AGILE 4.0 project are used to help define the problem statement. The initial results are the results from a DOE that was run to prove the tool and workflows used provide proper results. At the moment some variables are still kept constant limiting the available DOE results. The main

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variables kept constant are the structural lay out and the manufacturing methods that are used. Because these variables are kept constant, a true Pareto front definition is not possible yet.

II. Set up of an application case scenario in AGILE 4.0

Within the AGILE 4.0 [1] there are several initiatives to apply MBSE to formulate and solve an MDO problem. In this application case these tools and methodologies were used to make the models required to define and solve the problem of finding the best flap design for a regional jet. The tool set is made available through the OCE (Operational Collaborative Environment [18]). The OCE is available through a web portal via which all tools can be accessed and used. The steps that are taken in the OCE are shown in Figure 1.

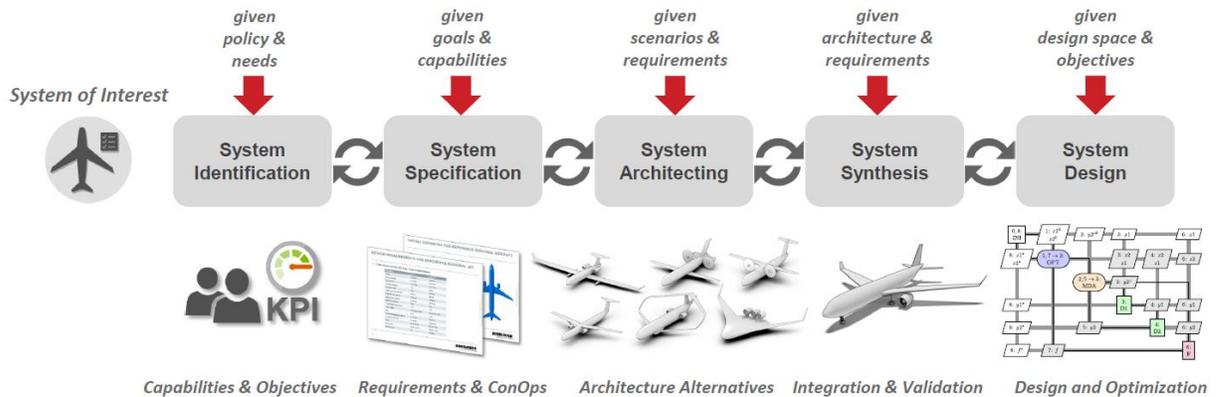


Figure 1 The AGILE 4.0 process of setting up an MDO flow

Contained within the OCE are tools and techniques that fulfill the specific development steps. The tools and techniques used are:

1. KE-Chain is used to identify the system of interest and identify the needs and stakeholders related to the systems. The models made in the KE-chain package can be visualized and adjusted in Papyrus.
2. Needs from stakeholders are formalized according to pre-defined format so they fit in a model-based environment. The needs are translated into requirements that follow a strict definition syntax. In this way, they can also be verified and tracked in a requirements framework [2].
3. Scenario modelling is done to specify the scenarios in which the system has to operate. For this Capella tools are used.
4. Architecture modelling is used to design the functional architecture of the system and relate it to the requirements [4].
5. The architecture elements are linked to requirements and requirements are linked to test cases. These test cases are composed of analysis tools. Using these relations the Requirements Verification Framework is used to understand which analysis tools must be part of the MDO analysis flow. [5]
6. Finally the MDO workflow can be defined using KADMOS[8] or MDAX[6] This MDO workflow can be exported to a neutral format, CMDOWS[7] using KADMOS. The CMDOWS file can be interpreted in in the RCE workflow manager so it can be run.

A description of how these steps are applied in this AC can be found in section IV.

III. Description of the application case

For the applications case, the design of a flap for a 90 passenger regional jet is considered. The regional jet is a generic model provided by the DLR in the CPACS format[3]. For the kinematics of the flap, two different solutions will be considered.

The first kinematic solution will be a dropped hinge solution. This is a simple kinematic solution, where the required translation and rotation of the flap are achieved by rotating the flap around a rotation point located below the wing. The position of the rotation points determines the path of the flap. By changing the rotation point the position of the extended flap can be adjusted. Actuators are required that move the flap in one direction around the rotation point. The dropped hinge solution and variations of it are used in various modern commercial aircraft such as the Airbus A350[10] and the Boeing 787.

The second kinematics solution will be a so-called “smart flap” solution [11]. In this solution, the translation and rotation of the flap are disconnected which allows for more complex kinematics potentially resulting in more optimal

aerodynamics. In the smart flap solution, the flap is translated by moving it along a track requiring an actuator. The rotation of the flap is achieved by another actuator rotating the flap around hinge points. These hinge points are part of the translated track. In this way, the translation and rotation of the flap are decoupled. The smart flap potentially offers better aerodynamic performance and more functionality; however, this comes at the cost of more complexity and therefore probably higher manufacturing cost.

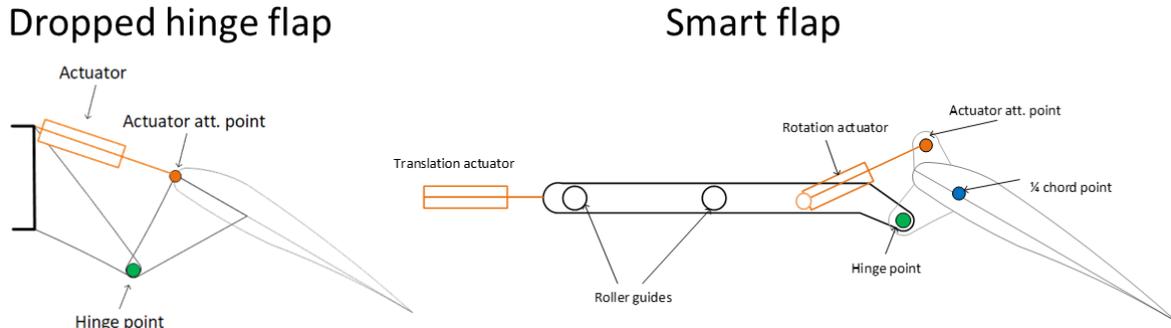


Figure 2 Flap kinematics considered in the application case

Within the application case the structural and manufacturing concepts of the flap will be investigated. However, this will not be described in this paper. This paper will focus on an initial DOE in which the influence of flap size and kinematics on the flap performance is investigated.

IV. Set up of the Application Case 1 in the OCE

The AC described in this paper considers the design of a flap. The tools encapsulated in the OCE are used to follow a process as depicted in Figure 1. The first step in this process is collecting the needs of the stakeholders in the flap design process. These needs are captured and documented in the OCE. The OCE is web based so the needs can be input directly on the web-based platform. When defining the needs other objects in the OCE framework can be linked. This means for example that a need is linked to a stakeholder object. Because the OCE is filled with objects that are linked different views on the data stored within the OCE can be generated, simplifying the filling and reviewing of the data. An example of needs captured in the OCE can be seen in Figure 3.

Need	ID	Text	Stakeholder	Linked to requirements?	Derived requirements
Design input	N-0006	Needs design inputs (loads, OML, etc.)	Flap manufacturer (FM)	Yes	OEM supplies OML, Aircraft integration
Weight and CG limits	N-0008	Needs to be in the weight limit and min/max CG	Flap manufacturer (FM)	Yes	Flap weight
KC's measurability	N-0009	Needs to be able to measure (KC's)	Flap manufacturer (FM)	Yes	Flap KC's, Flap KC's FM
Product delivery time	N-0010	Product needs to be delivered on time	Flap manufacturer (FM)	Yes	Flap delivery, Flap delivery dates
Flap shape	N-0011	Flap needs to be of a certain shape	OEM	Yes	Flap planform, Flap OML deviation
Flap delivery time	N-0012	Flap needs to be delivered on time	OEM	Yes	Flap delivery, Flap delivery dates
Flap costs	N-0013	Flap needs to be within budget	OEM	Yes	Flap manufacturing costs
		Flap needs to be as light as possible			Flap weight, Material

Figure 3 Example of needs from OEM and Flap manufacturer

The needs that are defined are used to define the requirements for the system of interest. In this AC case the system of interest is the flap and the flap manufacturing system. The requirements are more specific and follow a given syntax. To know what requirement syntax must be used the requirement type must also be defined. In the OCE the user is helped in defining the requirement in the correct format. Furthermore each requirement is also linked to other objects like means of compliance and test cases. These elements are used later in the process when requirements are used to find the analysis and modeling tools that need to the part of the analysis workflow. An overview of some requirements in the OCE can be seen in Figure 4

Requirement	ID	Text	Priority	Type	Parent/source requirement	User need
Flap replacement process	R-0027	with performance Replacement process time of Maximal 8 hours while maintenance	Medium	Suitability		Flap req
Flap manufacturing costs	R-0028	The flap shall be manufacturable for less than \$80k at shipset 100	Medium	Design constraint		Profit F
Flap weight	R-0029	The flap shall weight less than 40kg	Medium	Design constraint		Flap we limits
Documenting flap manufacturing process	R-0030	The flap shall have a document based manufacturing process	Medium	Functional		Produc
Flap parts replacement	R-0031	The flap shall operate for at least 15 years in salty environments without replacement of class 1 parts	Medium	Environment		Operati

Figure 4 Example of requirements stemming from the needs

To understand the context of the needs and requirements the scenario in which the system of interest operates or is designed needs to be modelled. This is done in an application that is linked to the OCE. In this application case, the focus has been on modelling the scenario of the design process because this gives a better understanding on how different flap design options materialize. This scenario is partly shown in Figure 5. The operational scenario has not been defined.

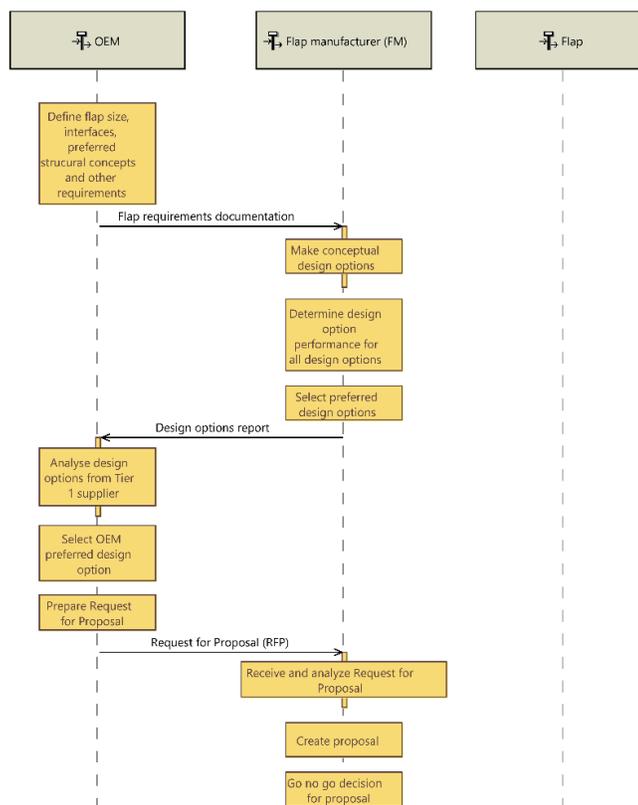


Figure 5 Scenario for interaction between OEM and supplier for a flap proposal

Once the scenarios are known the architectural options can be modeled. This again done in an external application which is made available through the OCE. For this application case the focus has been on modeling the architectures for the flap itself, the architecture of the manufacturing system and on the links between these architectural views. A small out take of the architectural model can be seen in Figure 6.

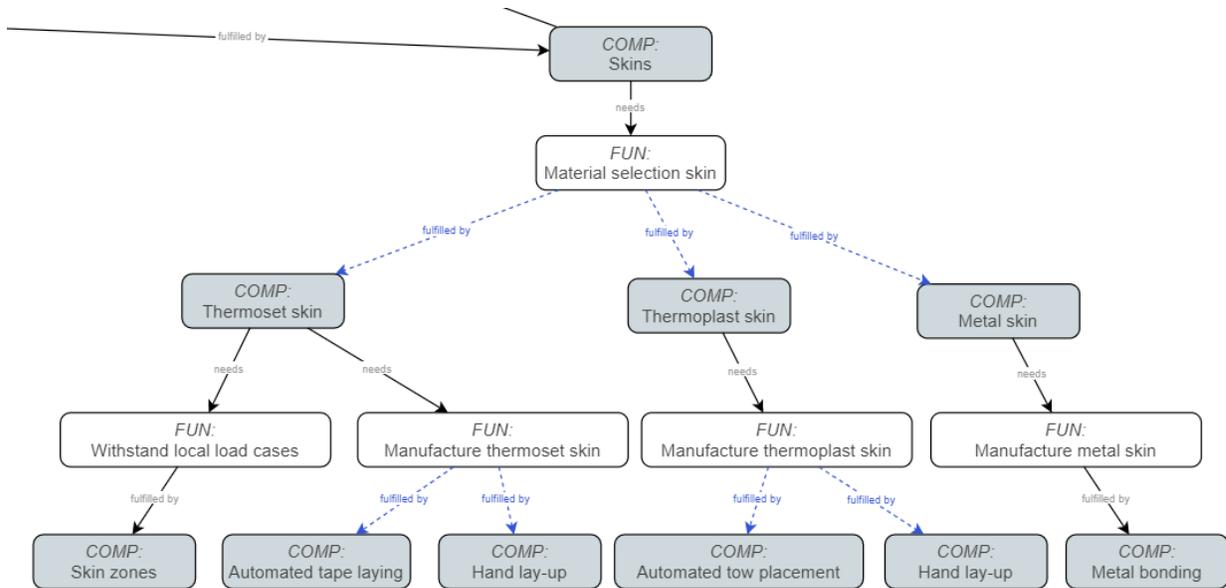


Figure 6 Example of architecture models used in AC1 to demine the possible manufacturing architecture for a flap skin

Once it is known, what the flap architecture will look like, the next step is to prepare the workflow for analysing what we want to know. For this AC, an optimization is envisaged however to understand the behaviour of the variables first a DOE will be built. Both a DOE and optimization workflow can be built by assigning the right requirements and variables to the workflow that is built in the OCE.

For generating the workflow in the OCE two different tools can be used: KADMOS and MDAX. In this application case KADMOS is used. Before this workflow can be prepared, first the tools that can be used in the workflow must be added to the OCE. The tools are added to the OCE using a specific format in which the inputs and outputs are linked to a specific data schema. In this case the CPACS format is used. An overview of some of the available tools in the OCE can be seen in Figure 7. Within the OCE the tools are called design competences.

Design competence	Function description	Model version	Input description	Output description	Input data	Output data
Flap Generator	Moveable generator for flaps	1.0	Flap outer geometry, hinge line & positions	IGES files with geometry, XML with detailed part descriptions	Flap_Generator-input_FnW-JjgF.xml	Flap_Gen-output_FnW-JjgF.xml
AMload	Generate the loads for the flap	1.0	Loadcase, overall aircraft design incl. flap geometry	Pressure and forces	AMload-input_gfHMeeO.xml	AMload-output_gfHMeeO.xml
CAD2FEM	Calculate the internal stresses and strains	1.0	IGES geometry files, XML files from structure modeller, forces and pressures	Internal stresses and strains	CAD2FEM-input_aDDTKoL.xml	CAD2FEM-output_aDDTKoL.xml
PROTEUS	Determines the required thicknesses of the internal structure	1.0	Internal stresses and strains, material database	Thickness of the internal structure	PROTEUS-input_i1DAu2A.xml	PROTEUS-output_i1DAu2A.xml
Mass Properties Model	Calculates the weight of the flap	1.0	Geometry, XML with materials from stress generator, material database	Total flap weight and weight per part	Mass_Properties_Model-input_MNSfsIx.xml	Mass_Properties_Model-output_MNSfsIx.xml
CATMAC	Calculates costs of the flap	1.0	Manufacturing and assembly details, rate	Costs	CATMAC-input_10gsTH5.xml	CATMAC-output_10gsTH5.xml

Figure 7 Descriptions of design competences or tools in the OCE

To create the workflow it needs to be known what design competences must be used. This is done through the parameters, requirements and test cases. To enable the creation of the workflow, requirements must be assigned roles. These can for example be objectives, quantities of interest, constraints or design variables (shown in Figure 8). The parameters are linked to requirements. Each requirement has a means of compliance. This means of compliance describes what test case is used to determine if a requirement is met or not. A test case view of a requirement in the OCE is shown in Figure 9. In this test case, the design competences used to determine the value of a parameter are defined. The OCE view on a test case is shown in Figure 10.

Design variables

Design variables will be used in strategies that implement optimizer or design of experiments. For each design variable please specify the nominal value, upper and lower bounds and the type of variable. In case a DOE architecture is selected, it's possible to provide a comma separated list of samples.

Design variable	Nominal value	Lower bound	Upper bound	Type	DOE samples (csv)	Parameter
Flap chord	0.5	0	1	REAL	0.15,0.35	FlapChord
Flap type	0	-1	1	INT	0,1	MechanismType
Flap deployed position	0	-1	1	REAL	0.3,0.7	FlapTranslation

Constraint variables

Constraint variables will be used in solution strategies that implement optimizers, such as MDF and IDF. For each constraint please specify the type of constraint and the reference value.

Constraint variable	Constraint type	Reference value	Parameter	Parameter (manual input)	Requirement	Linked
Constraint: Minimal reserve factor	>=	1		/cpacs/toolspecific/PROTEUS/Min_reserve_factor_c	Reserve factors	Yes

State variables

State variables are parameters that will be monitored throughout the execution of the final workflow without being of any of the three categories given above. This means that these variables will be written as final output of the final workflows. State variables are **mandatory** for MDA or DOE workflows architectures.

State variable	Parameter	Parameter (manual input)	Requirement	Linked to requirement
QoI: Landing distance		/cpacs/toolspecific/LandingPerformance/Landing_distance	Aircraft landing distance	Yes
QoI: Flap total cost		/cpacs/toolspecific/OpenSourceCost/Assembly/Assembly_Totals/Total_cost	Flap manufacturing costs	Yes
QoI: Flap mass		/cpacs/toolspecific/MDM/mass_properties/total_mass_o	Flap weight	Yes

Figure 8 Variable roles and description for the application case DOE

Requirement	ID	Text	Test case	Performance parameter	Problem role
Reserve factors	R-0003	The flap structural elements shall have reserve factors higher than 1	Structural test case	Minimal reserve factor	Constraint

Figure 9 Requirement description linking the requirement to a test case

Structural test case

View the properties of Test case "Structural test case"

Name	Structural test case
ID	No value ⊘
Means of compliance	Structural analysis using Nastran
Diagram	No value ⊘
Design competences	AMload , Multi-Disciplinary Modeler - MDM , Proteus +0

CLOSE

Figure 10 Test case definition

By collecting all the design competences required, an overview of the design competences that must be part of the workflow is made. Because the in- and outputs of the design competences are stored within the OCE and because all in and outputs follow the same data schema the system can automatically connect all the design competences in a workflow. The final ingredient required to build the complete workflow is the type of workflow that should be built. This can for example be a DOE or an optimization. For this paper, a DOE is built, which is discussed in the next sections.

V. The application DOE workflow

As explained in the previous section the OCE can be used to define a DOE or an Optimization. For this application case the first analysis run will be a DOE of the main variables to see if all required tools can be coupled and to understand the response of the system to these variable changes. What is investigated first is the response in flap weight, cost and landing distance to a change in flap size and kinematics. The variables considered can also be seen in Figure 8. The upper and lower bounds from the DOE are adjusted to keep them in a viable range. The DOE that will be run is a full factorial so combinations will be made with the extremes of the variables. In addition a “middle” point is added for the “Flap chord” variable, because it is expected this variable has a large influence on cost and weight.

Table 1 DOE variables overview

Variable	Role	Range	Description
Flap chord	Design variable	0.15-0.35 chord	The flap chord length is specified as a percentage of the local wing chord. This variable determines the size of the flap.
Flap translation in landing configuration	Design variable	0.3-0.7 chord	The flap translation is measured in percentage of the wing chord, a higher number means more translation and more lift increase
Mechanism type	Design variable	Dropped or Smart	As described above the mechanism type determines the total flap weight and cost
Flap system total weight	Quantity of interest		The flap system total weight is the weight of the flap plus the kinematic system, meaning the hinges, beams bearings etc.
Flap system total cost	Quantity of interest		The flap system total cost is the cost of the flap plus the kinematic system, meaning the hinges, beams bearings etc. Only mono-part cost is considered
Landing distance	Quantity of interest		The landing distance at Maximum Landing Weight with flaps extended in landing condition.
Minimal reserve factor of the skin	Constraint	Higher than 1	The structure of the flap is not allowed to fail therefore reserve factors must be higher than 1. Because of the availability of analysis tools, the constraint is limited to the skins.

After the applicable requirements have been selected in the OCE and the correct DOE architecture is chosen, the DOE is set up automatically by the OCE. The result is represented in the XDSM in Figure 11. In the DOE different tools are included to enable the analysis of the variables. For the communication between the tools, CPACS XML files are used plus other files to communicate binary data such as Finite Element Models. As can be seen in Figure 11 there are many connections between the tools.

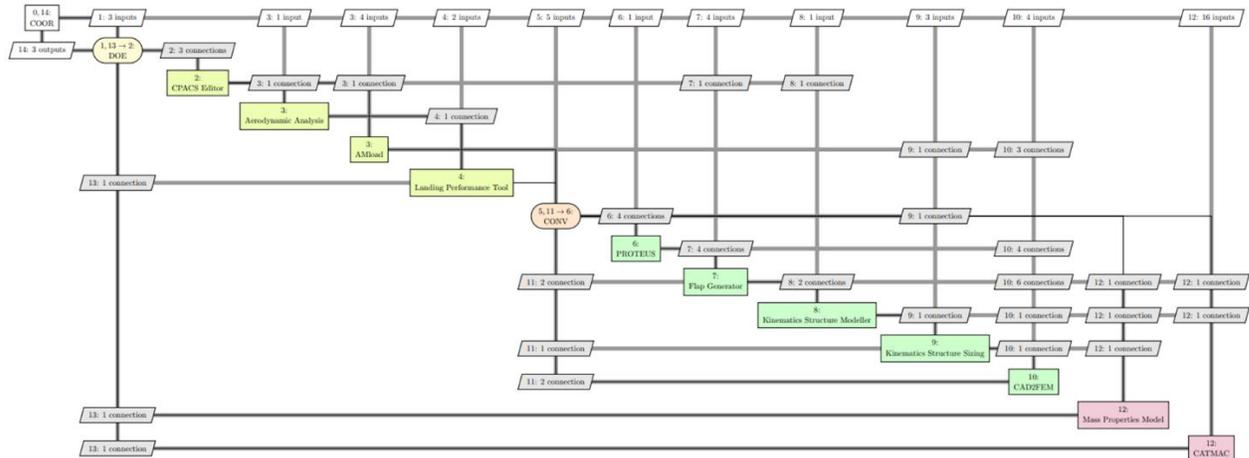


Figure 11 XDSM of the DOE workflow

For the workflow several tools are used each with a specific functionality and playing specific role in the workflow. These are:

1. **RCE**, the workflow manager used, it couples the different tools together in a workflow that can be run [9].

2. **Aerodynamic analysis tool**, calculates the wing 3D Cl_{max} in landing configuration based on the wing geometry, flap geometry and flight conditions. This tool uses ESDUpac A9931 software [12].
3. **Landing performance tool**, calculates the landing distance based on Cl_{max} and aircraft characteristics using Howe's[13] empirical estimation method for commercial transport jets taking into account FAR regulations.
4. **AMload, a loads analysis tool**, determines the loads exerted on the flap in certain flight conditions[14].
5. **Open Source Cost Tool**, a tools that calculates the recurring cost of manufacturing the mono parts in the flap [15].
6. **MDM including CAD2FEM**, MDM is a tool that generates a model of the flap that can be used by other tools. It is couples to CAD2FEM, which transforms the model from MDM into a FEM model, which stored in the form of a BDF file. MDM can also estimate the weight of the flap [16].
7. **PROTEUS**, a sizing tool, based on a FEM model it determines the required thickness of the flap skin [17].

Using the combination of tools described above the DOE is run. It has to be noted that the tools that are run are located in different companies and on different computers. To enable a seamless workflow to be run it uses a software tool called Brics [18]. This tool ensures that data files are downloaded from and uploaded to a server and it ensures the tools are started at the right time with the right data. This is done in combination with RCE. Each tool is encapsulated by an RCE workflow to ensure Brics is used properly. In case of the DOE the start of a tool only has to be authorized once by the tool owner. After authorization, RCE and Brics ensure all DOE tasks are executed. The DOE itself is another RCE workflow that is calling all the individual tool workflows.

VI. Design of experiment results discussion

This section discusses the result of the DOE that was executed based on the definition described in the previous sections. In Table 2 the DOE results are represented. As can be seen there are 3 values for the flap chord. In this case bigger number mean a bigger chord. The middle value has been set at 0.26 because one of the tools used was producing errors with the actual middle value of 0.25.

Table 2 DOE results, the design variables are represented in the blue columns, the quantities of interest in the yellow columns

ID	Chord	Translation	Mechanism type	Flap movable weight [kg]	Flap kinematics weight [kg]	Flap total weight [kg]	Cost [\$]	Landing dist. [m]
1	0.15	0.3	dr hinge	25.5	2.2	27.7	7978	2058
2	0.26	0.3	dr hinge	61.8	5.5	67.3	12273	1972
3	0.35	0.3	dr hinge	56.3	9.3	65.6	12821	1913
4	0.15	0.7	dr hinge	25.8	4.8	30.6	8404	2044
5	0.26	0.7	dr hinge	45.2	13.0	58.2	11742	1942
6	0.35	0.7	dr hinge	46.8	23.1	69.9	13952	1880
7	0.15	0.3	smart flap	23.2	5.93	29.1	8393	2058
8	0.26	0.3	smart flap	61.8	11.7	73.5	12563	1972
9	0.35	0.3	smart flap	56.3	18.67	75.0	12952	1913
10	0.15	0.7	smart flap	25.8	7.33	33.1	8656	2044
11	0.26	0.7	smart flap	45.2	15.76	61.0	11407	1942
12	0.35	0.7	smart flap	46.8	27.06	73.9	12809	1880

The results produced by the DOE are acceptable. Meaning that the results for the quantities of interest lie within the expected range. The cost figure is on the low side because the cost tool does not take into account all elements of the manufacturing cost and because the estimation methods used probably use out dated data as is also reported in [15].

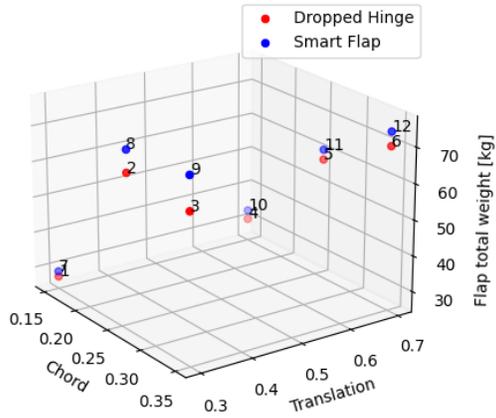


Figure 12 DOE results Flap total weight

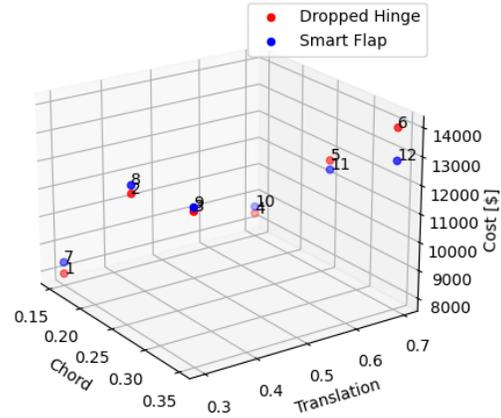


Figure 13 DOE results Cost

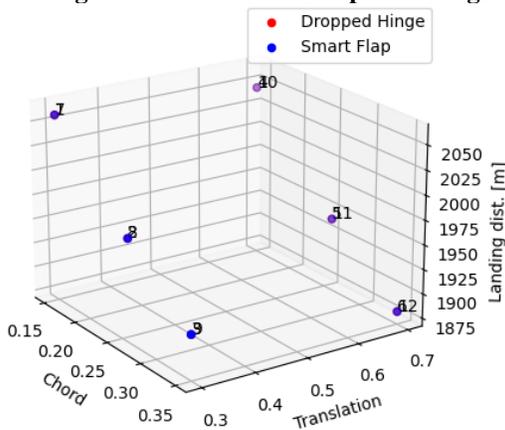


Figure 14 DOE results Landing distance

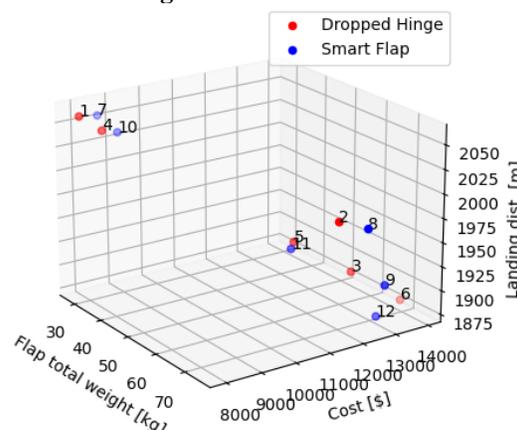


Figure 15 DOE results Flap total weight Quantities of Interest

The biggest question mark that arises from the results is the flap movable weight for the 0.26 chord length flaps. For comparable translation and mechanism types, these are almost as heavy as or even heavier than the 0.35 chord length version. Digging a bit deeper into the results the weight increase is the result of significantly thicker flap skins resulting from the PROTEUS tool. To understand if this is a tool anomaly or if this is the real behaviour, further investigations will have to be conducted.

In Figure 16 to Figure 21 the hinge concepts are represented in the MDM tool are shown. These pictures show Experiments 6 and 12, which have the biggest flap chord and the biggest translation resulting in the biggest flaps. As can be seen the kinematic parts for the two concepts are quite different. As can be seen the fairing required for the dropped hinge is a lot bigger than for the smart flap concept. Unfortunately, the weight and cost tools do not take into account the flap fairing resulting in distortion of the results.

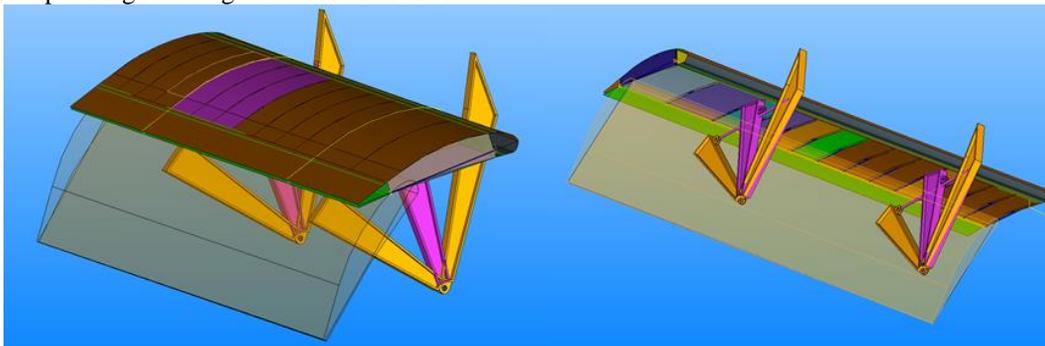


Figure 16 Dropped hinge experiment 6. Orange represents extended mechanism

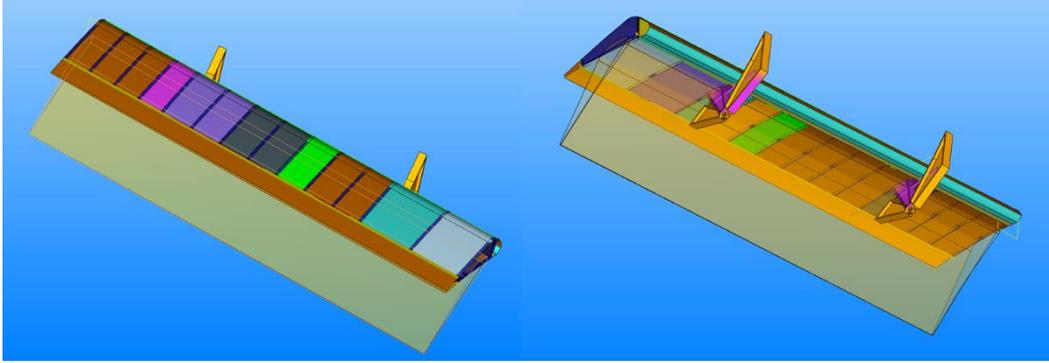


Figure 17 Dropped hinge experiment 3. Orange represents extended mechanism. Translation of 0.3 resulting in less extension of the hinges below the wing

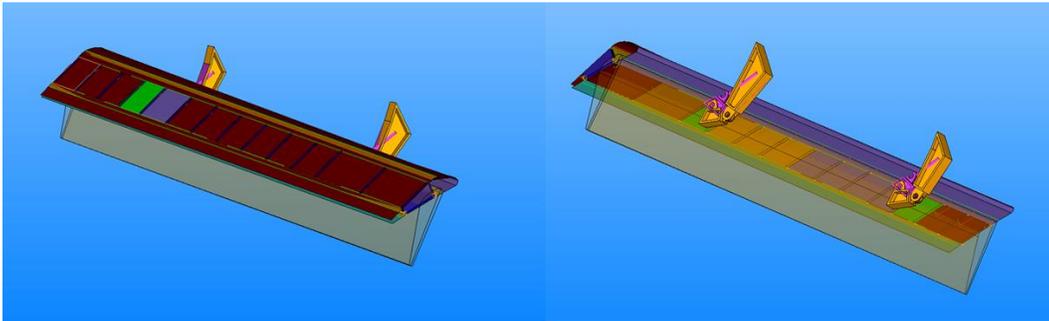


Figure 18 Dropped hinge experiment 1. Orange represents extended mechanism. Small chord and translation.

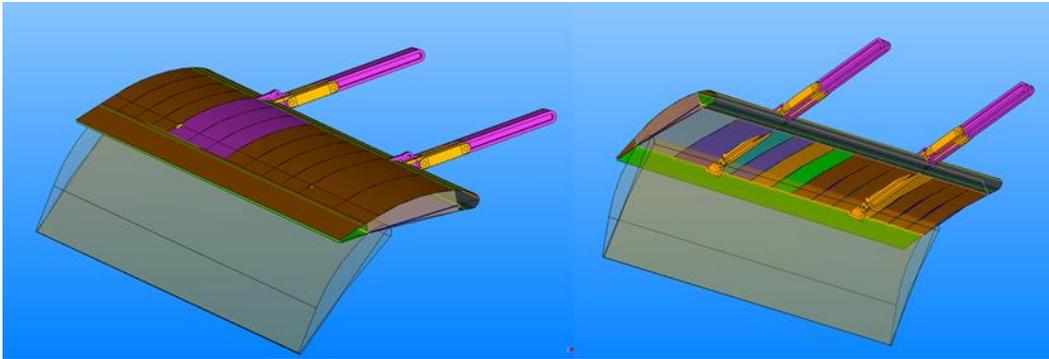


Figure 19 Smart flap experiment 12. Orange represents extended mechanism

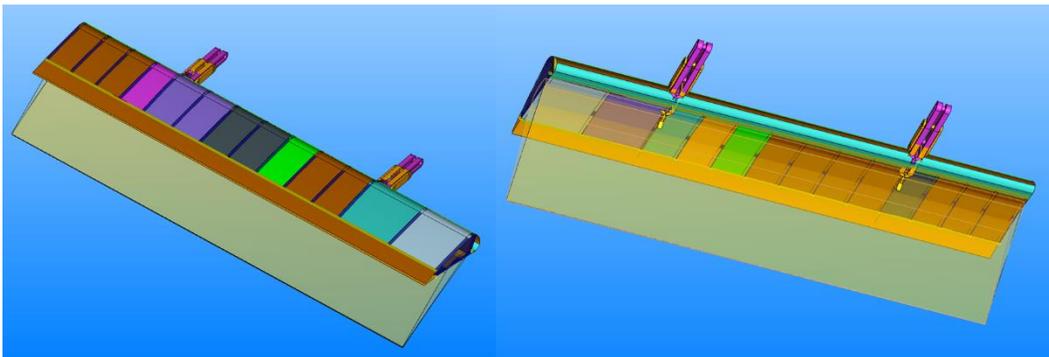


Figure 20 Smart flap experiment 9. Orange represents extended mechanism. Translation of 0.3 resulting shorter flap tracks

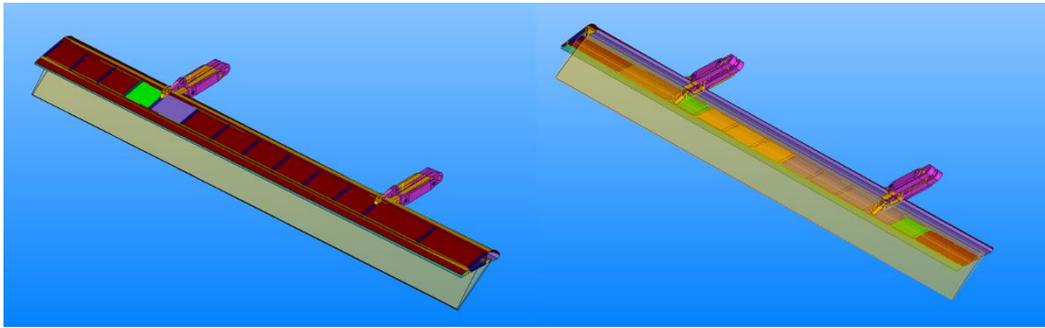


Figure 21 Smart flap experiment 7. Orange represents extended mechanism. Small chord and translation.

In Figure 22 and Figure 23 the correlations between the different variables are shown. Basing the correlations on such a small sample group can be very sketchy but some interesting items can be seen from the plot, which require further investigation. Firstly, it seems the flap chord has more influence on the landing distance than the flap translation. To validate that this is the case better Aerodynamic tools are probably required to validate the CI estimations. What can also be seen is that translation has no influence on flap cost. Looking at the data this is surprising. It seems the increase in cost from the dropped hinge is cancelled out by the decrease in cost from the smart flap mechanism. Furthermore, in the data it can be seen that the translation results in a weight increase in the flap kinematics mechanism and a decrease in the flap movable weight. The decrease of the flap movable weight was not expected and has to be investigated at the tool level. The cost of the flap kinematics and the flaps movable probably show the same behaviour as the weight figures. Therefore to get a better insight in the distribution of cost these cost items should be separated in future DOE's.

Pearson (Spearman)	Chord	Translation	Mechanism_type	Flap_movable_weight	Flap_kinematics_weight	Flap_total_weight	Cost	Landing_distance
Chord	1.000 (1.000)	0.000 (0.000)	0.000 (0.000)	0.794 (0.716)	0.789 (0.798)	0.922 (0.857)	0.954 (0.946)	-0.976 (-0.956)
Translation	0.000 (0.000)	1.000 (1.000)	0.000 (0.000)	-0.291 (-0.292)	0.422 (0.386)	-0.052 (-0.048)	-0.000 (0.000)	-0.197 (-0.293)
Mechanism_type	0.000 (0.000)	0.000 (0.000)	1.000 (1.000)	-0.014 (-0.024)	0.319 (0.386)	0.118 (0.290)	-0.016 (0.000)	0.000 (0.000)
Flap_movable_weight	0.794 (0.716)	-0.291 (-0.292)	-0.014 (-0.024)	1.000 (1.000)	0.421 (0.399)	0.931 (0.843)	0.890 (0.787)	-0.733 (-0.599)
Flap_kinematics_weight	0.789 (0.798)	0.422 (0.386)	0.319 (0.386)	0.421 (0.399)	1.000 (1.000)	0.723 (0.762)	0.736 (0.755)	-0.861 (-0.876)
Flap_total_weight	0.922 (0.857)	-0.052 (-0.048)	0.118 (0.290)	0.931 (0.843)	0.723 (0.762)	1.000 (1.000)	0.974 (0.895)	-0.905 (-0.806)
Cost	0.954 (0.946)	-0.000 (0.000)	-0.016 (0.000)	0.890 (0.787)	0.736 (0.755)	0.974 (0.895)	1.000 (1.000)	-0.943 (-0.905)
Landing_distance	-0.976 (-0.956)	-0.197 (-0.293)	0.000 (0.000)	-0.733 (-0.599)	-0.861 (-0.876)	-0.905 (-0.806)	-0.943 (-0.905)	1.000 (1.000)

Figure 22 Correlation matrix of the variables used in the DOE

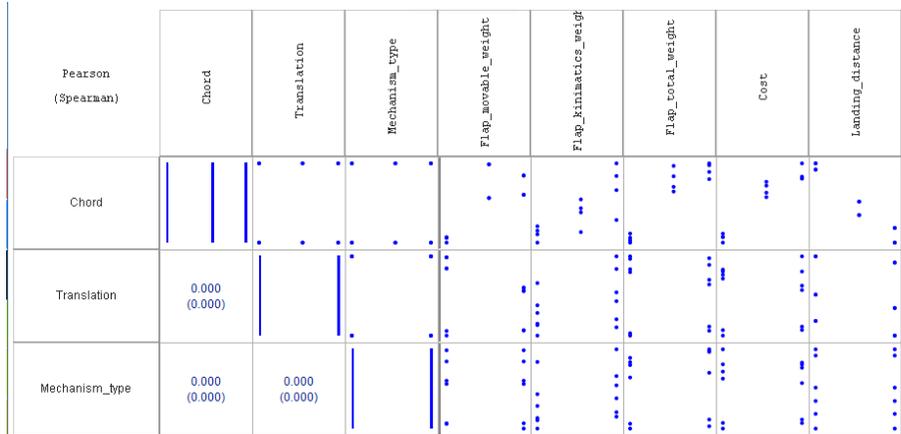


Figure 23 Correlation plot

VII. Conclusions and future work

In this paper, an application case in the AGILE 4.0 EU project is presented. It showcases the use of tools and methods developed in AGILE 4.0 to perform optimizations and design of experiments for different flap designs considering both weight and manufacturing cost. It shows how these tools and methods can be used and how the use results in a DOE workflow. The results of this DOE show how flap weight, manufacturing cost and aircraft landing performance relate to different flap configurations. By calculating the manufacturing cost in the DOE, manufacturing can be considered together with flap weight and aircraft landing performance. In this way manufacturing is brought into the MDO domain.

The next steps in the project will be to expand the number of experiments in the DOE to better understand the behaviour of the flap. Furthermore higher fidelity tools will be employed for determining the aerodynamic performance of the flap. Once the behaviour is better understood the number of design variables will be increased. This will allow for the incorporation of more structural and manufacturing concepts. Goal of adding these design variables is to decouple the flap weight and cost to enable the definition of a Pareto front for these variables. Finally, once the more complex DOE's are running stable optimizations will be run to find the optima in the design space for lowest cost, weight5 and landing performance.

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References

- [1] P. D. Ciampa, L. Boggero, J. Vankan, T. Lefebvre, B. Beijer, A.M.R.M. Bruggeman, T. van der Laan, M. Fioriti, P. della Vecchia and J. Vos, "MBSE-MDAO agility in Aircraft Development: Achievements and Open Challenges from the AGILE4.0 Project," in AIAA Aviation Forum, Chicago (US-IL), 2022
- [2] L. Boggero, P. D. Ciampa and B. Nagel, "An MBSE Architectural Framework for the Agile Definition of System Stakeholders, Needs and Requirements," in AIAA AVIATION 2021 FORUM, 2021.
- [3] M. Alder, E. Moerland, J. Jepsen and B. Nagel, "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," in Aerospace Europe Conference, 2020.
- [4] J.H. Bussemaker, L. Boggero, and P.D. Ciampa, "From System Architecting to System Design and Optimization: A Link Between MBSE and MDAO" in INCOSE International Symposium, June 2022.
- [5] A.M.R.M. Bruggeman, B. van Manen, T. van der Laan, T. van den Berg and G. La Rocca, "An MBSE-Based Requirement Verification Framework to Support the MDAO Process", AIAA Aviation Forum, 2022."
- [6] A. P. Risueño, J. Bussemaker, P. D. Ciampa and B. Nagel, "MDAx: Agile Generation of Collaborative MDAO Workflows for Complex Systems," in AIAA AVIATION 2020 FORUM, 2020.

- [7] I. van Gent, G. La Rocca and M. F. M. Hoogreef, "CMDOWS: A proposed new standard to store and exchange MDO systems," CEAS Aeronautical Journal, vol. 9, no. 4, pp. 607-627, 2018.
- [8] I. van Gent and G. La Rocca, "Formulation and integration of MDAO systems for collaborative design: A graph-based methodological approach," Aerospace Science and Technology, Vol. 90, 2019, pp. 410-433."
- [9] <https://rcenvironment.de/>
- [10] Struber, H., "THE AERODYNAMIC DESIGN OF THE A350 XWB-900 HIGH LIFT SYSTEM", 29th Congress of the International Council of the Aeronautical Sciences, St. Petersburg, Russia, 2014
- [11] Bastiaansen, A.M.F.(To Fokker Aerostructures B.V.), "An Airplane wing, and airplane and a flap system", World Intellectual Property Organization WO 2014/073954 A1
- [12] ESDU 99031, "Computer program for the estimation of lift curve to maximum lift for wing-fuselage combinations with high-lift devices at low speeds"-
- [13] Howe, D, Aircraft Conceptual Design Synthesis (2000)
- [14] H. Timmermans and B. Prananta; 2016; "Aeroelastic Challenges in the Aircraft Design Process"; READ & SCAD conference; Warsaw; September 2016
- [15] Laan, A.H. van der, Johnman, A., Puffelen, T. van, Nolet, S., Maanen B. van, Daugulis, E., Berg, T. van den, "An open source part cost estimation tool for MDO purposes" in AIAA AVIATION 2021 FORUM, VIRTUAL EVENT, 2021.
- [16] Berg, T. van, Laan, A.H. van der, "A multidisciplinary modeling system for structural design applied to aircraft moveables", in AIAA AVIATION 2021 FORUM, VIRTUAL EVENT, 2021.
- [17] N. P. M. Werter and R. D. Breuker, "A novel dynamic aeroelastic framework for aeroelastic tailoring and structural optimisation," vol. 158, p. 369–386, December 2016.
- [18] Baalbergen, E.H., Vankan, J., Boggero, L., Bussemaker J.H., Lefebvre, T., Beijer, B., Bruggeman, A.M.R.M., Mandorino M., "Advancing Cross-Organizational Collaboration in Aircraft Development", AIAA 2022 Aviation Forum.