COLLABORATIVE CONCEPTUAL DESIGN OF A MID-RANGE AIRCRAFT UNDER CONSIDERATION OF ADVANCED METHODS FOR TECHNOLOGY ASSESSMENT

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A conceptual design and related trade studies of a new mid-range aircraft is presented in this paper. The focus in this paper is on two aspects, the preliminary results of the trade studies on the one hand and the collaborative design process of the DLR internal project ATLAs on the other hand. The key element in ATLAs is an automated workflow of several components or engineering services that are provided and hosted at different DLR sites entirely spread over Germany. In this workflow the disciplinary modules are developed by respective specialists and integrated by overall aircraft designers and workflow architects.

Nomenclature

ARB	=	AVACON Research Baseline
AVACON	=	Advanced Aircraft Concepts
BF	=	Block Fuel
CFRP	=	Carbon Fiber Reinforced Polymer
CPACS	=	Common Parametric Aircraft Configuration Schema
CRM	=	Common Research Model
DLR	=	German Aerospace Center / Deutsches Zentrum für Luft- und Raumfahrt
EIS	=	Entry into Service
GTF	=	Geared Turbo Fan
HLFC	=	Hybrid Laminar Flow Control
HTP	=	Horizontal Tail Plane
ICA	=	Initial Cruise Altitude
ICAO	=	International Civil Aviation Organization
ISA	=	International Standard Atmosphere
L/D	=	Lift over Drag
LuFoV	=	Federal Aeronautical Research Programme / Luftfahrtforschungsprogramm V (2018-2022)
MTOW	=	Maximum Take-Off Weight
MWE	=	Maximum Weight Empty
NMA	=	New Midsize Airplane
OWE	=	Operational Weight Empty
SFC	=	Specific Fuel Consumption
SL	=	Sea level
TLAR	=	Top Level Aircraft Requirements
TOFL	=	Take Off Field Length
UHBR	=	Ultra-High Bypass Ratio Engine
VTP	=	Vertical Tail Plane
v_{APP}	=	Approach Speed

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I. Introduction

Modern aircraft and aircraft technologies are increasingly developed and analyzed using multidisciplinary and integrative methods. System integration plays an important role as potential enabler for new technologies and innovations. Technologies such as hybrid laminar flow control in the area of aerodynamics, or on-board autonomous kitchens in the cabin are only two examples in the myriad of possible technology driven improvements for aircraft performance and operations. In the past mainly performance indicators such as block fuel or DOC where applied as an objective function for aircraft design. To further improve aircraft as part of the entire air transportation eco-system potential benefit of each technology must be assessed in a holistic manner. This involves including more disciplines within the design procedure as well as the adoption of advanced methods for technology assessment.

The project "Advanced Technology Long-range Aircraft Concepts" (ATLAs) is the fifth in a row of DLR projects on collaborative aircraft design, in which a multitude of disciplines and competence centers are involved (Figure 1) (the interested reader is referred to [1], [2], [3] for publications on previous project results). In the course of the project, advanced assessment procedures will be integrated into the overall aircraft design process to create the capability to evaluate future configurations in a more holistic way. A central use case of ATLAs is the design of an advanced mid-range aircraft. This category of aircraft is currently under discussion in the aircraft community, due to Boeing's announcement of such a concept at the Paris Airshow 2017.

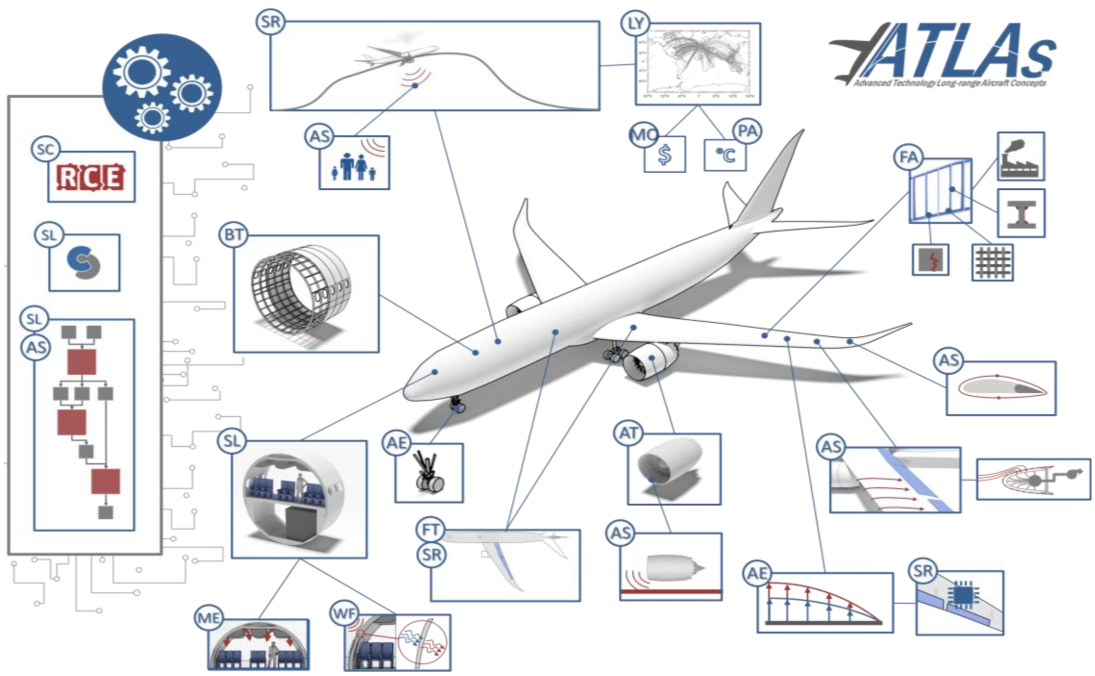

Figure 1. Functional breakdown of DLR institutes contributions

II. Current Related European Research Project Landscape

PERFECT

The project ATLAs is closely coupled with another DLR internal high fidelity preliminary design and evaluation of future engine concepts project PERFECT. It targets the conceptual and preliminary design of engine concepts comprising the thermodynamic cycle definition as well as the dimensioning of the appropriate engine components. One central use case is the advanced mid-range aircraft defined within ATLAs. The link between both projects ensures a mature understanding of the airframe engine integration from conceptual design throughout the higher fidelity level of the respective disciplinary analysis models of both projects. Similar to the overall aircraft design process in ATLAs an improvement in the collaboration among disciplines and engine components is targeted in PERFECT.

AVACON

The research project AVACON with nine different partners from industry, research entities and universities also aims at collaborative design and technology assessment. The project is funded by the national aeronautic research program LuFo V-3. The baseline aircraft as a starting point for technology and configuration assessment is common between AVACON and ATLAs. The AVACON research baseline ARB2028 is a conventional tube and wing configuration with a high aspect ratio CFRP wing and UHBR engines under the wing. Both technologies are assumed to be state of the art for an entry into service in year 2028. The underlying concept of operations (CONOPS) of the aircraft is a mid-range capability combined with enhanced economics on shorter missions. Some more information and top level aircraft requirements are presented in paragraph IV. Target aircraft configurations and selected technologies differ in both projects. An AVACON core study is on the effect of an over wing nacelle engine integration as sketched in figure 2.

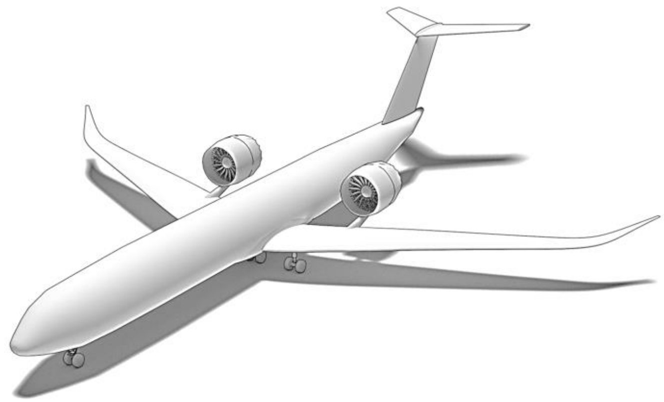

Figure 2. Over wing nacelle configuration in AVACON

VICTORIA

While the perimeter in ATLAs is conceptual aircraft design of a mid and long range aircraft, the scope of another DLR internal project VICTORIA (Virtual Aircraft Technology Integration Platform) is hi-fidelity preliminary design and analysis in an MDO environment. The goal of VICTORIA is set up the foundations for the comprehensive digital description and development of aircraft and helicopters, taking advantage of modern materials, improved physical modeling, multidisciplinary simulation and optimization on high performance computers while taking into account relevant physical effects. In addition to highly parallel, highly accurate solvers for fluid/structure coupled simulations more rapid methods applied in ATLAs for designing and optimizing engines and the overall vehicle will be used.

Figure 3. Hi fidelity MDO mode used in VICTORIA

The intention is to link both projects after their respective mid-term reviews and to analyze the mid-range aircraft designs from ATLAs within VICTORIA.

III. Collaborative design / Model Based System Engineering within the ATLAs project

Over the last years collaborative design methods were successfully developed and applied within the DLR [4], [5]. As shown in [4] four main components characterize the collaborative design process: engineering routines, common data language, process integration framework and methods for collaboration. Within ATLAs the established knowledge and methods has been applied.

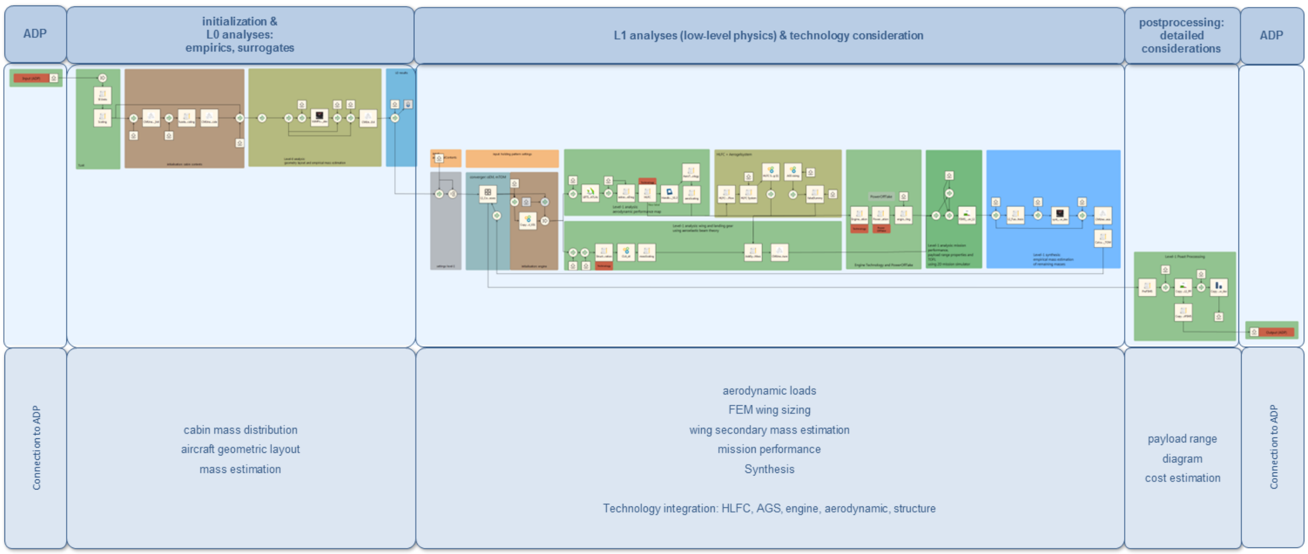

Figure 4. Simulation workflow within ATLAs

The workflow is depicted in Figure 4. It can be divided in three main parts. The first part, the initiator part, calculates within *VAMPzero* a first mass estimation and aircraft geometry based on the input parameters. After the initiation part, engine weight and performance data are loaded from a database called *TWdat*. That tool is hosted and maintained by the engine department of DLR in Cologne. In two parallel branches, thereafter the aerodynamic performance and the wing structure are estimated. For the aerodynamic performance the modules *LIFTING_LINE* and *HandbookAero* from the aerodynamic department in Brunswick are remotely connected and used. The estimation of the structure takes place within *CLA*, the conceptual load analysis tool is provided by the aeroelastics department in Göttingen. Knowing the engine, mass and aerodynamic properties the design mission is flown using the mission simulator *FSMS*. All calculated data are fed back into *VAMPzero* for synthesis. The second part of the workflow is iteratively performed, until MTOW and OWE converge. All calculations within this part are performed under consideration of the new technologies. At least, in the post-processing part, DOC and further mission analysis are performed for the converged aircraft configuration. All listed tools are developed by different DLR institutes involved in the project. The data exchange between the different tools take place with the central data exchange format CPACS [3], [7]. As framework the Remote Component Environment *RCE* [6] is used. The execution of the workflow is performed through the Aircraft Design Platform *ADP*. *ADP* is a user interface, developed at DLR, which allow user to run workflows developed in *RCE* more easily. Input parameter can be defined in the GUI and also the results of the workflow are directly visualized in this interface.

IV. Research Baseline Aircraft

For configuration and technology assessment, a baseline aircraft needs to be clearly defined and described. The top level aircraft requirements (TLARs) applied in the research project ATLAs have been derived in some market analysis and scenarios of future air passenger demand for EIS 2028. Some details of the pre studies can be found in [10]. The associated TLARs are summarized and compared to the DLR model of the B767-300 below in table 1.

TLARs	*Unit*	*Boeing 767-300*	*ARB2028*
Design Range	nm	4000	4600
Std. PAX number (2-class layout)	-	261	257
Pax mass	kg	99.23	100
Std. passenger payload	kg	25900	25700
Max payload	kg	40900	30000
Cruise Mach number	-	0.80	0.83
Take-off field length (SL, ISA)	m	2600	< 2000
Approach speed	kt	≤ 141 (Cat. C)	≤ 141 (Cat. C)
Wing span limit	m	≤ 52 (4D)	≤ 52 (4D)

Table 1: TLAR definition

The baseline aircraft for an EIS in 2028 includes two technologies that are assumed to be state of the art for that EIS timeframe. It makes use of an UHBR engine technology and a high aspect ratio CFRP wing with a 5% weight improvement against today's CFRP wing technology. The general arrangement and the key characteristics of the baseline aircraft are common between both research projects ATLAs and AVACON. They are shown in figure 5 and in table 2 respectively.

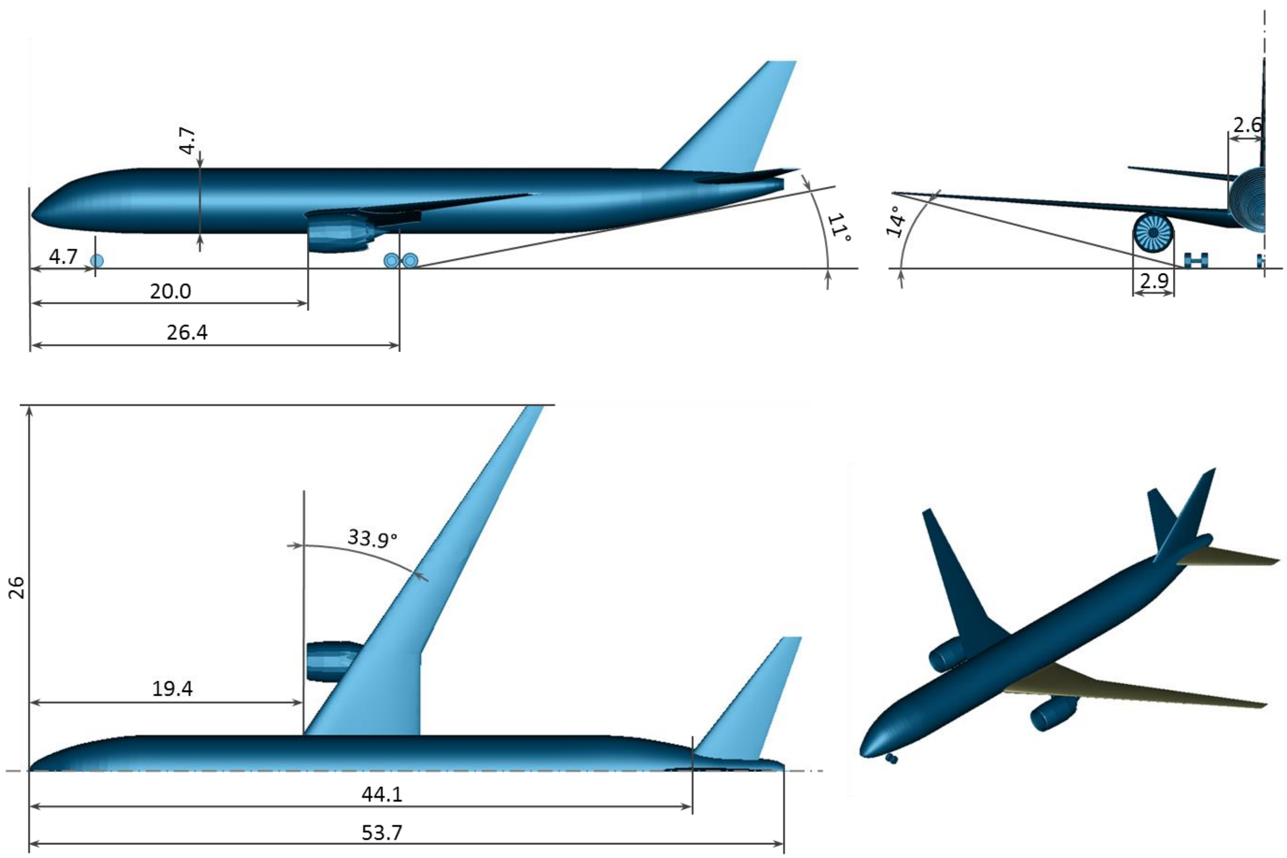

Figure 5: General arrangement of the baseline aircraft 2028

Range	nm	4600
Pax (2 class)	-	257
Max. Payload	t	30
Max. Take-off Weight	t	140.0
Max. Landing Weight	t	115.4
Max. Zero Fuel Weight	t	111.2
OWE	t	81.2
Wing Span	m	52
Wing Area	m²	220
Thrust Level, SLS	kN	230.8
Fan Diameter	m	2.4
Bypass Ratio	-	15.6
SFCcruise bucket pt. with Offtakes	Lb/h/lbf	0.475
BF 4600nm	t	29
BF 2000nm	t	12.6
Cruise Speed	-	0.83
ICA	ft	35000
Time-to-climb (FL330, ISA)	min	26.2
$c_{L,max\ TO}$	-	2.3
$c_{L,max\ LDG}$	-	2.7
c_L cruise	-	0.53
L/D cruise	-	20.6
TOFL (SL, ISA)	m	2000
v_{APP}	kts	134

Table 2: Key aircraft characteristics ARB 2028

A more detailed description of the conceptual overall aircraft design of the research baseline aircraft can be found in [9].

V. Technology Identification and Assessment

Identifying, selecting and managing suitable and beneficial technologies, to be implemented in the aircraft, is a mandatory as well as complex step within the overall design process – especially in its preliminary stage. It is complex due to the multi- and inter-disciplinary character of technologies. It is complex due to uncertain parameters such as it maturity level and assumed entry into service time. It is complex because of the tremendous number of options and further reasons. Thus, one additional goal in the project is the development of a professionalized procedure for technology decisions as an integrated part of the aircraft design workflow. The provided solution is a network-based platform for a multi-user-oriented participation in projects, in particular in the structuring and execution of evaluation questions. Here it will be applied for the technology selection, management and assessment. At the current development status, the platform offers computer-aided support in

1. project structuring and management,
2. managing of valuation objects (e.g. technologies),
3. managing of evaluation indicators,
4. performing of weighting processes,
5. decision-making,
6. discussions and moderation,
7. performing elections,
8. performing surveys,
9. creating of product, compatibility and cross-impact matrices.

Technical speaking, the platform has been being developed as a web-application. This makes possible an easy access from different locations and computer systems. It uses the common programming languages as PHP, HTML5 and Java for the dynamic creation of the user-interfaces. The data are recorded in a MySQL database. The platform is named *Systemparlament* (System Parliament, figure 6) because it works similar to a parliament with its different fractions, perspectives or topics, and the primary target is to find a compromise between all aspects.

The technology selection process follows a five-step-procedure as it is sketched in figure 7: In the first step all project participants (users) have to select individually their preferred key performance indicators from the database. If an indicator is not recorded as expected, the user may extend or modify the indicator list; the new items will be provided for all users. After the indicator selection, the users have to priories their chosen indicators by pair-wise comparison. The result is a user specific vector of the indicator's weights. This procedure is repeated equally for the technologies (step 2). In step 3 the user's weighting vectors are merged to an overall vector across all participating users. In step 4 the selected and weighted technologies and indicator are arranged to a product matrix (Harris) for a first impact assessment, done by each user personally. In step 5, the outcomes are automatically merged to a user across result – finally a **ranking of the selected technologies**. Besides the product matrix, cross-impact and compatibility matrices are generated. They enhance the understanding about the expected technology implications. In the optional step 6, the gained information can be stored in the technology database, making the information also available for other or up-coming projects.

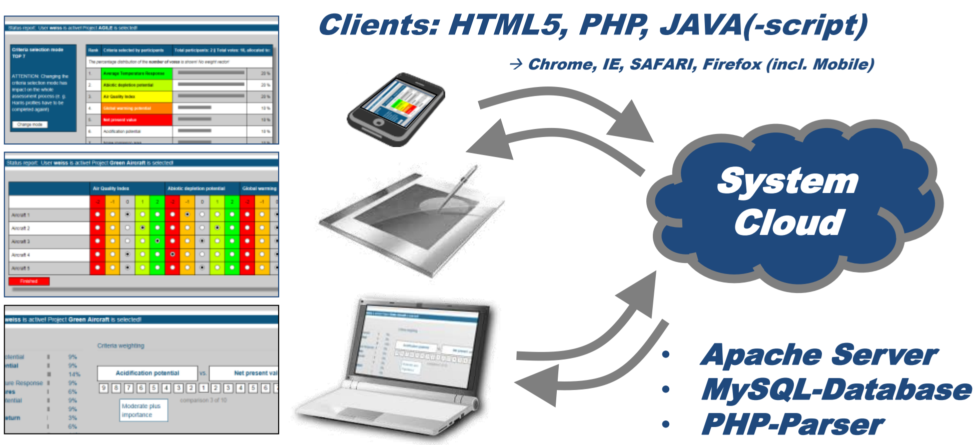

Figure 6: Computer-aided multi-client system analysis, based on a web-server solution

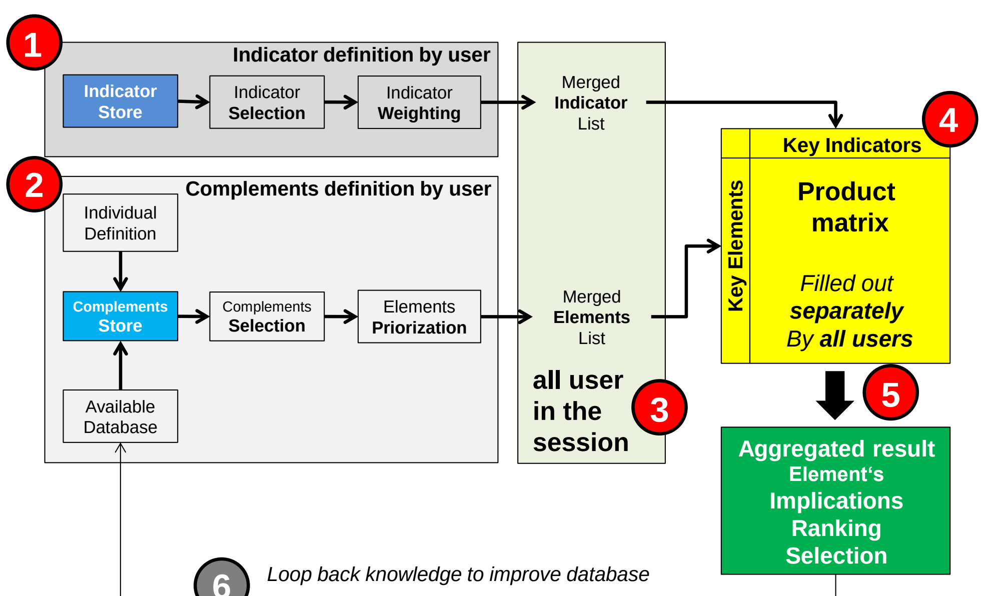

Figure 7: Computer-aided multi-client system analysis, based on a web-server solution

Applying the aforementioned procedure, in the project ATLAs an indicator and a technology vector have been derived. Reduced to the TOP 10, they are depicted in figure 8. Although all listed technologies and indicators are considered in the project, the time-line of their implementation will deviate from the prioritization due to technical reasons (e.g. tool availability). For example, the integration of the HLFC system, the CFRP technology or the UHBR turbofan engine into the DLR aircraft design work flow is highly advanced. Thus, the project team has been decided to prefer them in the project time-line. They are followed by a new technology for improving the cabin air environment, later described as “CO2 management” and designated in the technology list (figure 8) as “Aerogel” and “Sauerstoff++”. In chapter VI their integration in the aircraft design chain is introduced and first study results are presented. In advance, for each technology a plan for its integration into the aircraft design work-flow has been developed. First, a qualitative process flow was sketched by involving all technology representatives of the project again. As shown in figure 9 and as an example, the first-order interdependencies for the HLFC application are shown. The processed results (chapter VI) are fed back to the System Parliament’s database for conserving and multiplying the gain of knowledge about the technology under investigation.

Indicator		Weighting
1	Net present value	16.3 %
2	Average Temperature Response	14 %
3	External Noise Impact (Annoyance)	11.3 %
4	User comfort index	9 %
5	Abiotic depletion potential	7.5 %
6	Risk of failure	6.7 %
7	Global warming potential	5.4 %
8	Strategic relevance	4.2 %
9	Air Quality Index	3.5 %
10	Shareholder Value	2.6 %

Complement		Priority
1	Aerogel	9.8 %
2	CFRP Wing	7.6 %
3	Windowless Fuselage	7.5 %
4	Full Electric Moveables	7 %
5	UHBR Turbofan	7 %
6	CFRP Fuselage	6.8 %
7	Multifunctional control surfaces	6 %
8	HLFC Wing	5.9 %
9	Reduced Crew Cockpit	5.6 %
10	Sauerstoff++	5.4 %

Figure 8: TOP 10 indicator vector (left) and technology vector (right)

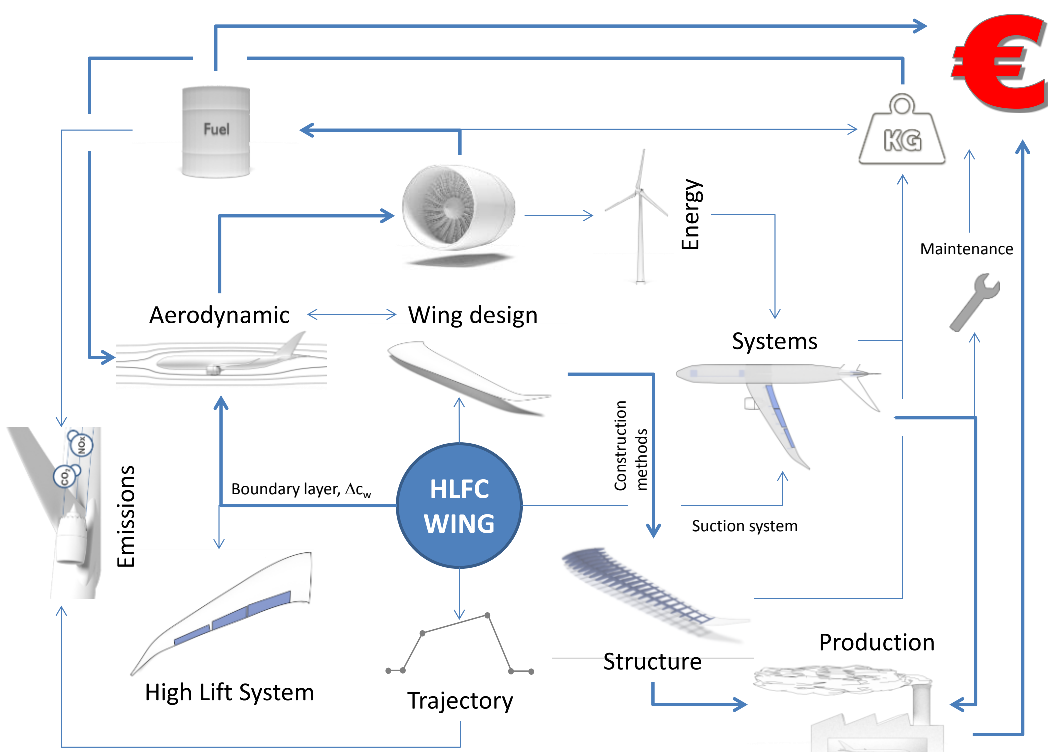

Figure 9: Reduced process flow between the disciplines, applying HLFC

VI. Trade Studies and Preliminary Results

HLFC

Increasing the laminar portion of the flow around wings and tails of an aircraft is subject of several research projects for decades now. It aims at reducing the total friction drag and hence the aerodynamic performance of the aircraft. Hybrid laminar flow control (HLFC) is one concept that sucks the boundary layer in the region from the leading edge to the front spar of the wing or tail plane. It is called hybrid since it also relies on the laminar characteristic of the airfoil shape behind the suction area. In this trade study the behavior of a HLFC concept and its application on the midrange research baselines wing are assessed on overall aircraft performance, taking the required power of the suction system and its mass impact into account. In simple terms, the HLFC technology is a tradeoff between the reduced viscous drag and the increased system weight and complexity as well as the increased specific fuel consumption due to the higher shaft power offtakes. Beside this tradeoff the operability is of major importance. To avoid insect contamination of the leading edge during takeoff a Krueger flap is applied. According to [8] and internal discussion with experts the system and structural weight as well as the high lift potential of the Krueger flap is in the same range as a conventional slat. However, the complexity and the costs are increasing.

The applied relation between the laminar flow fraction of the local wing chord of the upper side and the suction mass flow is shown in the following figure 10. It is conspicuous that below the suction mass flow of 1.0 kg/s the laminar flow fraction is almost zero. Between a mass flow of 1.0 kg/s and 2.5 kg/s the laminar flow fraction is rising substantial and is gradually approaching 50% for mass flows greater than 2.5 kg/s. The whole trade study is conducted keeping constant the wing loading and the thrust to weight ratio.

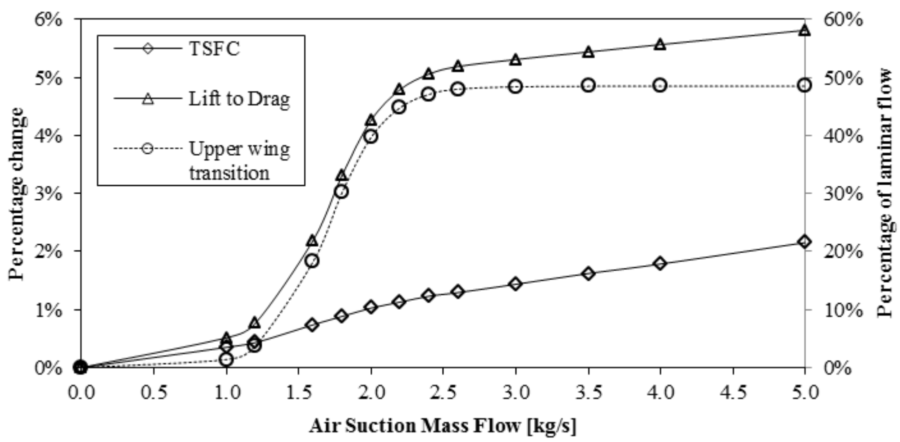

Figure 10: Benefit and cost characteristics of HLFC

A comparison between the aerodynamic advantages and the propulsive disadvantages in terms of lift to drag ratio and thrust specific fuel consumption (TSFC) both in mid cruise condition is shown in figure 10**.** The behavior of the lift to drag ratio resembles the laminar flow fraction graph. The further increase in lift to drag ration for mass flows greater than 2.5 kg/s occurs as a result of the increased wing area and the relating Reynolds effects. The TSFC is increasing almost linear with increasing suction mass flow and the relating power which is required by the compressors. The laminar flow fraction is shown again in the following figure11 in order to make the correlation between the other figures more obvious. The total system mass shown in figure 11 is increasing with increasing suction mass flow due to the bigger ducts, compressors, electrical power transfer and generators. The increasing system mass is also the main reason why the decline of the operating empty mass (OEM) at a suction mass flow of 1.5 kg/s is not that steep as for the maximum takeoff mass (MTOM).

The progression of the MTOM first increases because the system mass, the structural wing mass and also the TSFC increases without having big aerodynamic advantages of the HLFC system. At suction mass flow of around 1.0 kg/s the laminar flow fraction increases resulting in a decreasing design block fuel mass and therefore in an declining MTOM. The design mission block fuel reduction has its maximum of about 3% at a suction mass flow of 2.4 kg/s. At this point the laminar flow fraction almost reaches the 50% for the first time. For bigger suction mass flows the transition position slope in figure 11 is very small although the system mass and the required power of the HLFC system continuously increase. The consequence is the increasing block fuel. Worth mentioning is the relation between MTOM, OEM and Block fuel. The local minimum of MTOM occurs at a suction mass flow of 2.2 kg/s whereas the OEM has its local lower point at around 1.8 kg/s and the design mission block fuel mass at 2.4 kg/s. This illustrates perfectly the correlation between these three parameters. The difference between the block fuel of the design mission and the 800nm mission is a consequence of the different cruise section fraction of both missions.

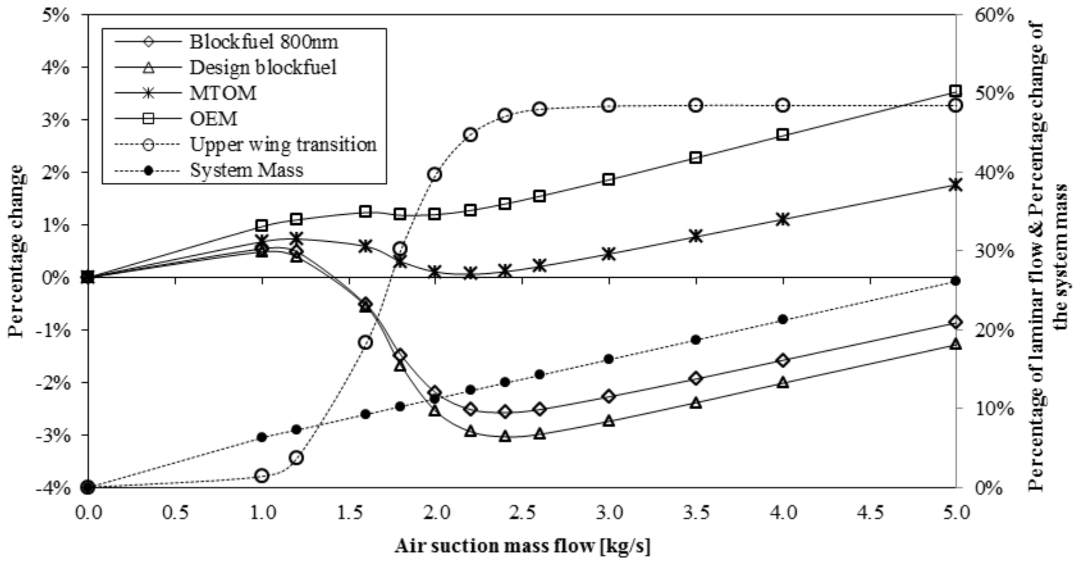

Figure 11: Overall aircraft trades under consideration of HLFC technology

In order to compare these values with other investigations and to have an idea about the actual net data quantities, table 2 shows some important parameters of the Baseline, the HLFC-1.2 and the HLFC-2.4. The 1.2 and the 2.4 stands for the air suction mass flow of the HLFC system.

Parameter	Unit	Baseline	HLFC-1.2	HLFC-2.4
MTOM	kg	140000	141023	140153
OEM	kg	81200	82115	82363
Block fuel	kg	28793	28905	27919
L/D mid cruise	-	20.62	20.78	21.66
TSFC mid crusie	kg/N/h	0.0487	0.0489	0.0493
System mass	kg	8400	9002	9503
Wing structure mass	kg	16400	16567	16447
Additional offtake power (total)	kW	0	79.1	158.2

Table 2: Comparison of key parameter of different HLFC designs

To conclude the HLFC trade study the payload-range diagram of the baseline, the HLFC-1.2 and 2.4 is illustrated in figure 12. The HLFC-2.4 version which has approximately the lowest Block fuel mass has a longer maximum range than the Baseline. This is due to the slightly higher maximum fuel capacity and the higher overall efficiency of the HLFC-2.4. Even though the maximum fuel capacity of the HLFC-1.2 is even greater, the reduced overall efficiency reduces the maximum range. Another interesting aspect is the slope of the MTOM segment. The slope of the HLFC-2.4 is less than the one of the Baseline which is an indicator of the overall efficiency. Due to the fact that the design Mission is the same for the whole trade study, the slope of this segment turns around the design point. Consequently the point of the maximum payload and the maximum range moves towards reduced ranges.

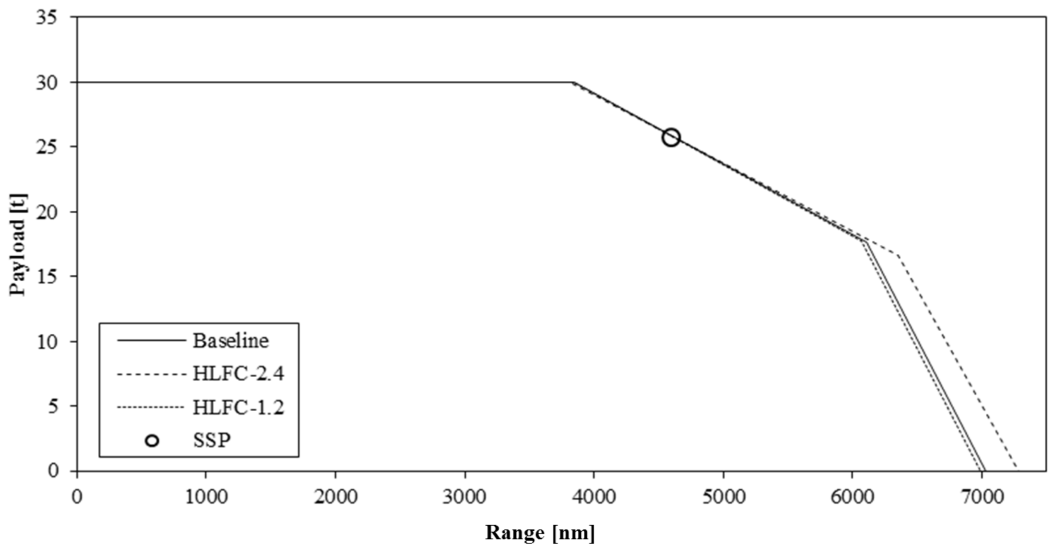

Figure 12: Comparison of payload vs. range characteristics

CO_2 Managed Cabin

Another technology which has been and will be investigated in the ongoing DLR project ATLAs is the CO_2 managed cabin. The major expected benefit in terms of aircraft efficiency is the reduced fuselage structural mass. The higher share of oxygen in the cabin air makes it possible to reduce the pressurization leading to a smaller possible fuselage wall thickness. Because this effect has not been examined yet thoroughly this trade shows just the potential of different fuselage mass reductions as seen in figure 13. Due to the fact that the CO_2 management system is dependent on the cabin size and passenger number its additional system mass and power requirement stays unchanged at 226 kg and 4.5 kW in this trade study.

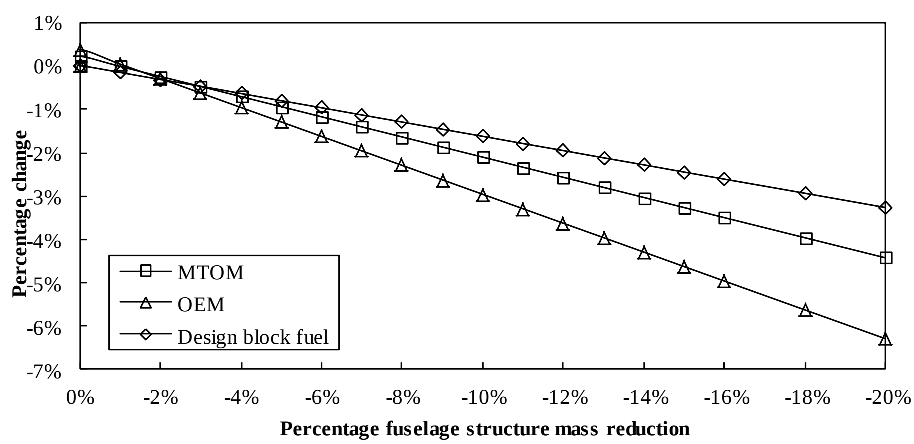

Figure 13: Trades on potential fuselage reduction due to CO2 managed cabin

The MTOM, OEM and design block fuel mass are illustrated in figure 13. It can be derived that these three parameters are increasing by applying the CO_2 management system without assuming any fuselage weight reduction. After the very first growth all three parameters are decreasing again by increasing the fuselage mass reduction. The highest slope occurs at the OEM graph because it is directly dependent of the fuselage mass whereas the block fuel is indirectly dependent resulting in the lowest slope. The MTOM is a combination of the two other parameters which is indicated in figure 13.

Combination of the HLFC and the CO_2 Managed Cabin

To demonstrate the potential of the efficient collaborative design environment the previously investigated technologies are combined. Some relevant results are illustrated in figure 14. For the CO_2 Cabin technology a 10% fuselage structural mass reduction is assumed.

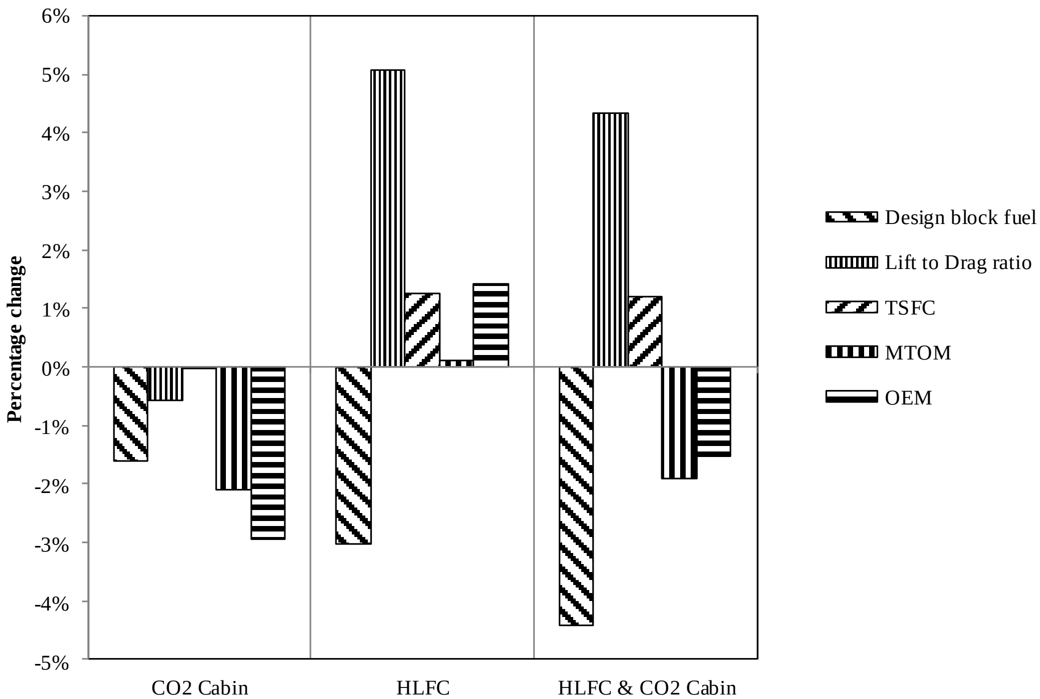

Figure 14: Overall aircraft trades under consideration of HLFC and CO2 managed cabin

VII. Conclusion

The DLR internal research project ATLAs is one of a series of projects that are very closely interconnected. One central use case is an advanced future midrange aircraft with a common baseline among several projects. The key element in ATLAs is an automated workflow of several components or engineering services that are provided and hosted at different DLR sites entirely spread over Germany. In this workflow the disciplinary modules are developed by respective specialists and integrated by overall aircraft designers and workflow architects. First results of initial trade studies on advanced midrange aircraft technologies were derived in a model based system engineering approach within DLR and were discussed in this paper. Two examples of the technologies that were ranked within the project are HLFC and CO2 managed cabin. The overall aircraft performance improving by applying HLFC on the upper side of the wing leads to a block fuel reduction potential of around 3% for the advanced midrange aircraft. Further technologies and its combination will be investigated in the course of the project.

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