Development of a Methodology for Assessing and Exploiting Innovative Aircraft Concepts and Technologies

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ABSTRACT

Aiming to reduce the CO2 and NOx emissions or even to achieve emission-free air transport, aeronautic researchers and engineers have made effort to pursue green and efficient on-board energy storage and conversion systems with advanced aircraft technologies. In the framework of Energy Transition in Aviation Project (EWL), the perspectives concerning aircraft design are studied. The challenges and requirements of aircraft design for integrating new airframe and energy system technologies are discussed at first. Then, the modelling approaches including parameterization and disciplinary simulation methods are illustrated in detail. After that, some preliminary results regarding the overall aircraft level impacts (takeoff weight, operating weight empty and fuel burn) of technology progress are presented and discussed.

KEYWORDS: **Aircraft conceptual design, modeling and simulation, alternative fuel, sustainable aviation**

NOMENCLATURE

AR	=	aspect ratio	*EWL*	=	Energiewende in der Luftfahrt
b	=	wing span	*LFC*	=	laminar flow control
BLI	=	boundary layer ingestion	*Ma*	=	Mach number
BWB	=	blended wing body	*MTOW*	=	maximal takeoff weight
CL	=	lift coefficient	*OWE*	=	operating weight empty
CD	=	drag coefficient	*R*	=	flight range
CDi	=	induced drag coefficient	*Re*	=	Reynolds number
CDvis	=	viscous drag coefficient	*TAW*	=	tube and wing
CDw	=	wave drag coefficient	*T/W*	=	thrust to weight ratio
CPACS	=	Common Parametric Aircraft Configuration Schema	*W/S*	=	wing loading
e	=	Oswald coefficient	λ	=	taper ratio

1 INTRODUCTION

Despite the dramatic progress in the past decades, aviation industry is still facing significant pressure in reducing fuel consumptions, emissions and costs, especially when it comes to the ambitious goals set by aviation authorities such as Flightpath 2050. To realize the challenging goals, researchers and engineers endeavor to develop new concepts and technologies. In 2013, IATA technology roadmap [1] has identified 24 potential airframe and propulsion technologies which might be available for sustainable aviation in 2050 timeframe according to technology readiness level. Within the US NASA N+ programs, a bunch of innovative airframe technologies have also been identified to reduce emissions [2, 3]. However, both studies have concluded that the technology development alone cannot reach the desired emission reduction goals. Within this context, a joint research project "Energy System Transformation in Aviation, EWL[1]" has been initiated in Germany to identify and further study possible transformative energy systems that can be used for civil transport aircraft in combination with target aircraft configurations and airframe technologies. In this manuscript, challenges and requirements are firstly discussed from an aircraft design perspective. As the principal part of this paper, methodologies and preliminary results are then shown and discussed in detail. At the end, future development directions and features will be presented.

2 BACKGROUND

In this section a general description is given about the background including the challenges and requirements on aircraft design for energy transition in aviation.

2.1 Related research on vehicle concepts with airframe technologies

In recent decades, a vast body of work on developing new aircraft configurations and advanced airframe technologies has been carried out for greener aviation. In the following the most representative studies and their major findings are listed.

I. Boeing study has shown a blended wing body (BWB) concept could lead to a fuel saving of 27% as compared to a conventional A380-like tube-and-wing (TAW) configuration [4].
II. Xu and Kroo have investigated the benefits of load alleviation and natural laminar flow and have concluded that the combination of these two technologies to a Boeing 737-800 aircraft could bring a fuel saving of 18% [5].
III. NASA-MIT D8 "Double-Bubble" Concept with boundary layer ingestion (BLI) and active load alleviation has conducted a fuel burn reduction of 70.87% as compared to a B737-800 baseline concept [6, 7].
IV. NASA Hybrid Wing Body (HWB) Concept (with N+3 airframe technology packages such as BLI and Distributed propulsion system) has conducted a fuel burn reduction of 54% as compared to a 777-200LR baseline [6, 7].
V. The "Advanced Truss-Braced Wing" concept proposed by NASA and MIT with hybrid electric propulsion has a 70% fuel burn reduction at very low range condition [8].
VI. Saeed et al. from Cambridge University has designed a flying wing concept with laminar flow control [9]. With an 84% of the total wetted area being laminarised, they have achieved a 70% fuel savings when neglecting the system penalties.

2.2 Advanced aviation energy system

In addition to the progressive research and development work for more advanced aircraft concepts and airframe technologies, the transformative new energy storages and on-board conversion systems are seen to be game-changing factors in emission-less or emission free aviation. A short summary of research work concerning the advanced aviation energy systems is listed as follows.

I. Between 2002 and 2004 Airbus Germany has conducted a system analysis study on Liquid Hydrogen Fueled Aircraft – Cryoplane. The major conclusion was liquefied hydrogen (LH2) was able to bring up to 14.8% reduction of MTOW as a result of the high specific energy density. Though, the OWE has increased by 23% due to the additional structure weight of LH2 tanks, which together with the drag increase caused by the additional wetted area of isolated LH2 vessels lead to a higher total energy consumption by 9-14% [10].
II. In 2004 NASA has studied the fuel cell and LH2 application to BWB aircraft concept and has indicated revolutionary technology advancement requirements for the real implementations [11].

[1] EWL is abbreviated from German words *Energiewende in der Luftfahrt*, which is an interdisciplinary project in Germany conducted by Technische Universität Braunschweig, Leibniz Universität Hannover, HBK-Braunschweig, DLR, PTB and Fraunhofer-Gesellschaft.

III. Between 2011 and 2014 the EU FP7 AHEAD (Advanced Hybrid Engines for Aircraft Development) project has studied the LH2 and liquefied natural gas (LNG) as on-board energy storages for BWB concept and has concluded that the new concept could reduce the CO2 emissions by around 50% comparing with Boeing 777-200ER baseline [12].

IV. In 2013 researchers at Bauhaus Luftfahrt have shown a hybrid electric aircraft could lead to a block fuel reduction of 16% as compared to a jet fuel powered conventional aircraft with the same MTOW condition [13].

V. From 2010 to now the NASA SUGAR project [14–16] has considered different new energy storages (cryogenic fuels including methane & hydrogen) and conversion systems (advanced batteries, electric motors, fuel cells, advanced gas turbine) and possible hybridizations for future subsonic transport aircraft, which indicated promising results in terms of fuel burn, greenhouse gases and NOx emissions [17].

To summarize, a lot of airframe, propulsion and energy system technologies are promising in realizing the challenging aviation emission reduction goals. The Aeronautics Research Centre Niedersachsen (NFL) initiates the joint project "Energy System Transformation in Aviation, EWL" by taking its advantage in collaborative research capabilities in a vast of disciplines not only in conventional aviation branches but also in fundamental energy storages and conversion branches. From the current technology readiness level as well as the prognoses in the scenario projected in 2050, all the aforementioned new energy storages have problems in aviation applications, e.g. the low specific energy density of batteries and low volume energy density of hydrogen make the realization of "energy transition" for large and long range transport aircraft quite difficult. One strategy is to reduce the energy requirement by incorporating game-changing airframe technologies. With the coupling effect, the possibility might be largely increased in achieving ambitious emission reduction goals. As part of the EWL project, the primary objective of aircraft design (technology integration & assessment) is to combine, trade and further package different airframe and energy system technologies as well as operation strategies into overall aircraft level in target timeframe and scenarios.

2.3 Requirements and challenges for aircraft design

As explained in the previous section, the goal of aircraft design is to explore the potential benefits of introducing innovative airframe and propulsion technology packages for better airplane energy efficiency, it is necessary to consider the multidisciplinary impact within the overall aircraft context, i.e. conventional and unconventional aircraft configurations as references and as novel technology integrators need to be studied.

On the one hand, the vehicle design research needs to focus on developing an effective platform to capture the individual disciplinary technology enablers impact and to evaluate the aircraft level benefits and tradeoffs. With the input of disciplinary studies, dominant and promising technologies in each discipline will be identified in terms of maximal aircraft energy consumption and / or emission reduction potentials with compatibility and development costs and risks constraints. The identified technologies need to be combined and integrated into overall aircraft level, such that the interdisciplinary effects can be incorporated. As such, different vehicle configurations (tube + wing, hybrid wing body, etc.) representing short, medium and long range missions need to be modelled and studied together with different energy systems.

In addition to identifying possible technology combinations at the overall aircraft level and further giving indication to research and development directions of individual disciplinary technologies, it is also necessary to develop a novel aircraft mission analysis tool capable of studying the performance of aircraft utilizing alternative energy, such that the assessment and optimization of the disciplinary technology benefits can be integrated to capture the snowball effect.

As the work focuses on the preliminary study at the beginning of the project and functions as a technology integrator through the project, the fidelity level will be confined to an "as simple as possible and as complex as necessary" level. To be specific, the modelling should have a wide design space to capture at least the most representative possibilities of airframe technologies and energy systems. At the same time, pure statistic data from historical aircraft need to be extended to reflect the future scenarios. Therefore, approaches such as surrogates derived from high-fidelity physic-based simulations or experiments need to be developed for the estimation. To summarize, the accuracy level needs to be compromised for the wide design features.

3 METHODS

Considering the flexibility, extensibility and fidelity, most current aircraft design software, such as FLOPS, PASS, EDS, RDS, CEASIOM, VAMP, might not be suitable for aviation energy transition studies, especially when it comes to fundamentally new propulsion and energy systems which cannot be easily modelled using simple approximations and corrections. In addition, "high fidelity" conventional aircraft design tools, such as PrADO [18] or MICADO [19], are not easily applicable in dealing with transformational energy systems and flight missions due to the wide design space features. As such, new aircraft conceptual design and technology assessment platform (relaxed complexity as compared to PrADO or MICADO and comparable accuracy by physics-based surrogates) is being developed within EWL project to exploit new aircraft concepts and technology factors as well as constraints. Similar to the recent work endeavored at Stanford University [20] and MIT [7], the flexible physics-based aircraft design and technology integration tool has the advantage of handling wide design space problems, which is extremely important for early stage aircraft configuration and technology identifications. Besides, the design tool is built to be able to incorporate multidisciplinary results, which can give reasonably accurate predictions at the overall aircraft level. In addition to a typical aircraft conceptual/preliminary design logic [18–20, 7], some features and modelling strategies are illustrated as follows.

3.1 Aircraft parameterization

Parameterization or a common description of aircraft parameters is important for aircraft level technology and performance assessment and multidisciplinary optimization. Besides, parameterization is also a necessity when we consider the further air transport level estimation of emissions, noise, direct operating costs or life cycle costs, which are dependent on aircraft parameters and operation parameters. In the current modelling, a parameterization method based on DLR CPACS [21, 22] format is used. Further extensions are proposed for radical energy systems.

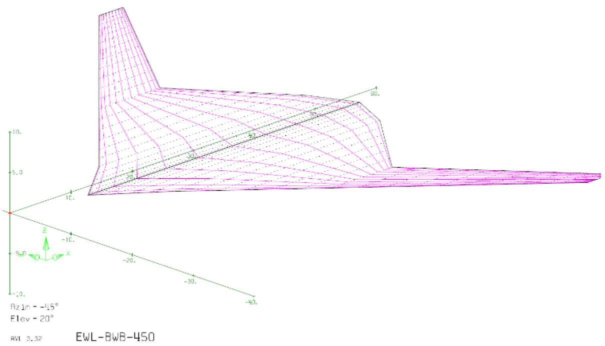
3.2 Aerodynamic modelling

As the desired lift coefficient is decided by aircraft mass, flight altitude and flight speed, the task of aircraft design level aerodynamic modelling is to estimate the lift to drag ratio at a given lift coefficient (C_L) condition together with a given Mach number (Ma) and Reynolds number (Re).

To be specific, a component-based approach proposed by Gur et al. [23] is adapted to estimate the component drag coefficient for a given C_L, Ma, Re combination. The total drag coefficient $C_{D,total}$ is categorized into three groups, i.e. the induced drag C_{Di}, the viscous drag $C_{D,vis}$ and the wave drag.

I. The induced drag is calculated using an advanced vortex lattice method AVL developed at the MIT by Drela and Youngren [24]. As an example, the EWL BWB geometry is visualized by AVL tool in Fig. 1 and the aerodynamic performance at $C_L = 0.25$ is also shown in Fig. 2.
II. The viscous drag is modelled as a function of equivalent skin-friction coefficient, form factor and the wetted area and reference area ratio. The equivalent skin-friction coefficient can reflect the laminar / turbulent impact. The form factor is modelled to include the impact of geometry features such as thickness ratio, the quarter-chord sweep angle and flight Mach number Ma. The wetted area to reference ratio is an important indicator to reflect vehicle concepts. For example, a typical tube-and-wing civil transport aircraft has a S_{wet}/S_{ref} around 6.0 and a BWB has a S_{wet}/S_{ref} of 2.4, which alone could result in a maximal L/D improvement from 16 to 23 according to a very simple calculation method [25, 26].
III. The wave drag is calculated based on the Lock's estimation method [27][28][29].

It has to be noted that the accuracy of aerodynamic modelling will be enhanced through high fidelity computational fluid dynamics (CFD) calculations, especially for the laminar flow control impact.



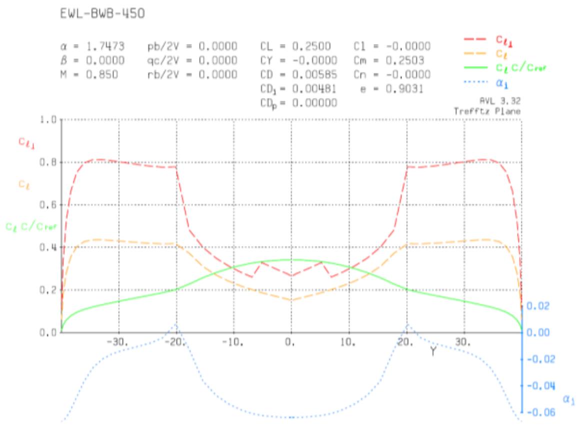


Figure 1 A blended wing body aircraft geometry in AVL

Figure 2 Example calculation results from AVL

3.3 Component weight modelling

Generally, within conceptual aircraft design stage, the component weight is determined by statistical data or physics-based estimations, i.e. correlations based on historical aircraft or simplified beam models. It has to be noted that the most correlations are only valid for a certain range of parameters. For unconventional aircraft, such as BWB, necessary modifications are being made.

For blended wing body (BWB) configurations, one significant difference as compared to the conventional tube-and wing configuration is the pressurized cabin modelling. In addition, the weight estimation of BWB cabin (center body) and aft center body cannot be directly derived from statistic regression due to the insufficiency of extant data. As such, a surrogate approach (cf. Eq. 1 and Eq. 2, in which K_s is a scaling factor, *MTOW* is maximum take-off weight, S_{cabin} is cabin area, W_{aft} is weight after body, N_{eng} is number of engines, S_{aft} is after body area, λ_{aft} is taper ratio) developed by Bradley [30] based on Finite Element Analysis (FEA) is at the first stage used in the modelling. Within the project, more detailed structure analysis with FEA will be carried out for composites and advanced structure architecture and new surrogates will be built up for aircraft design to improve the accuracy and reliability of simulations.

$$W_{cabin} = 0.316422 K_s (MTOW)^{0.166552} (S_{cabin})^{1.061158} \quad (1)$$

$$W_{aft} = \left(1 + 0.05 N_{eng}\right) 0.53 S_{aft} (MTOW)^{0.2} \left(\lambda_{aft} + 0.5\right) \quad (2)$$

3.4 Modelling of transformative energy systems

The electric powered flight is modelled similar to the methods in literature [31–33, 13], with the battery mass energy density, chain efficiency (stored energy on aircraft to mechanical energy) and the electric motors power density and efficiency (mechanical energy to thrust) being regarded as input parameters which can be modified to reflect different scenarios. More detailed modelling such as battery efficiency based on state of charge is important to give more reliable predictions.

The electric motors are currently sized based on the maximal required flight power. A more comprehensive modelling by incorporating flight mission considerations is currently under development and will be significantly extended based on input from detailed disciplinary technical studies.

For hydrogen or liquefied natural gas plus fuel cell powered systems, additional modelling for tank systems and fuel cells are currently modelled based on literature data [34–37]. For example, a gravimetric storage density η_{grav} defined by the mass of fuel in the tank (W_f) and the total tank mass (W_t) is used (cf. Eq. 3) to reflect the mass increase impact of additional cryo-tank systems.

$$\eta_{grav} = \frac{W_f}{W_f + W_t} \quad (3)$$

Further extensions are being made by integrating the detailed energy system modelling approaches delivered by other team members in the project.

3.5 Overall process

The overall procedure of the aircraft design framework for EWL project is plotted in Fig. 3. After an initial sizing process based on design requirements, the first guess of the dominant aircraft parameters can be estimated and saved to CPACS file as center aircraft data. Through aerodynamic, structure and weight, propulsion and energy systems analysis, the required data for a full mission analysis are prepared. The technology progress effect such as laminar flow control, boundary layer ingestion is captured by building up surrogates based on simulation results from other team members. Through mission segments, the convergent aircraft design results will be used for global system studies.

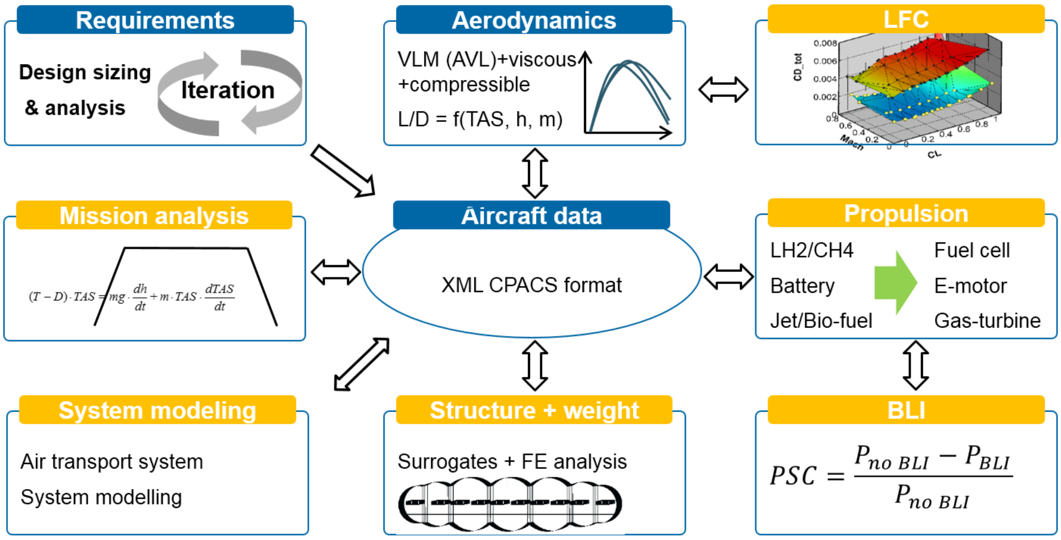


Figure 3: The overall procedure of EWL aircraft design

4 RESULTS

4.1 Reference aircraft and technology factors

In the beginning, a reference aircraft designed by the methods aforementioned is shown, with a maximal takeoff weight of 37651 kg and an operating weight empty of 21325 kg (cf. Table 1). The reference aircraft represents the typical regional jet class aircraft such as CRJ 900/1000[2].

Table 1: The major parameters of reference aircraft

Parameter	Value	Unit
MTOW	37651	kg
OWE	21325	kg
Design payload	9180	kg
Cruise Mach number	0.78	-

[2]See the following website links by Bombardier Commercial Aircraft (accessed on the 15th of May 2017)
http://commercialaircraft.bombardier.com/content/dam/Websites/bca/literature/crj/CRJ%20Series_CRJ%20900_Factsheet_201607_EN.pdf
http://commercialaircraft.bombardier.com/content/dam/Websites/bca/literature/crj/CRJ%20Series_CRJ%201000_Factsheet_201607_EN.pdf

Design range	2500	km
Wing area	77	m^2

Table 2 presents the EWL-identified technology items with corresponding improvement factors and explanations. For example, the "laminar flow control factor" is derived from equivalent skin-friction coefficient that is further decided by the level of laminarization, which can be either determined by low fidelity estimations or high fidelity CFD calculations, or even corrections from wind-tunnel experiments within the project.

Table 2 Technology improvement factors

Technology improvement factor	Range	Baseline value (current technology)	Explanation
Laminar flow control factor	0 – 0.8	0	The factor is modified through equivalent skin-friction coefficient which is further decided by the percentage of laminarization
Advanced structure factor	0 – 0.25	0	The factor works with the estimation of aircraft structure weight
1-g wing factor	2.5 – 1.0	2.5	The factor scales the structure mass of aircraft wing
Boundary layer ingestion factor	0 – 0.05	0	The factor scales the propulsion efficiency

4.2 Sensitivity study and results

In this section, the sensitivity studies on different technology progresses are firstly given to show the trend and also to verify the calculation methods. Then, the impact of the four major technology progress at the overall aircraft level is studied.

Fig. 4 presents the relative reductions of MTOW, OWE and fuel burn depending on different laminar flow control levels as compared to our reference aircraft and baseline technologies. As shown in the figure, the reduction results indicate satisfying trend with the increase of equivalent percentage of laminarization from 0 to 0.8. Taking a further look at the figure, it can be found that more than 13% MTOW reduction and 8% OWE reduction can be expected from LFC, which finally leads to a fuel saving up to 46%.

Similarly, another sensitivity study on the impact of different structure development factors is plotted in Fig. 5. The MTOW, OWE and fuel burn savings also show reasonably good trend with the increase of advanced structure development level. As can be read from the figure, the OWE decrease can be up to 16% which results in a MTOW reduction of 11% and fuel burn saving of more than 8%. It has to be noted that the aircraft and the operation conditions are not optimized accordingly in the current study just to neglect the coupled impacts. As such, further reductions of fuel burn can be expected when the aircraft is optimized and flies at optimal flight conditions.

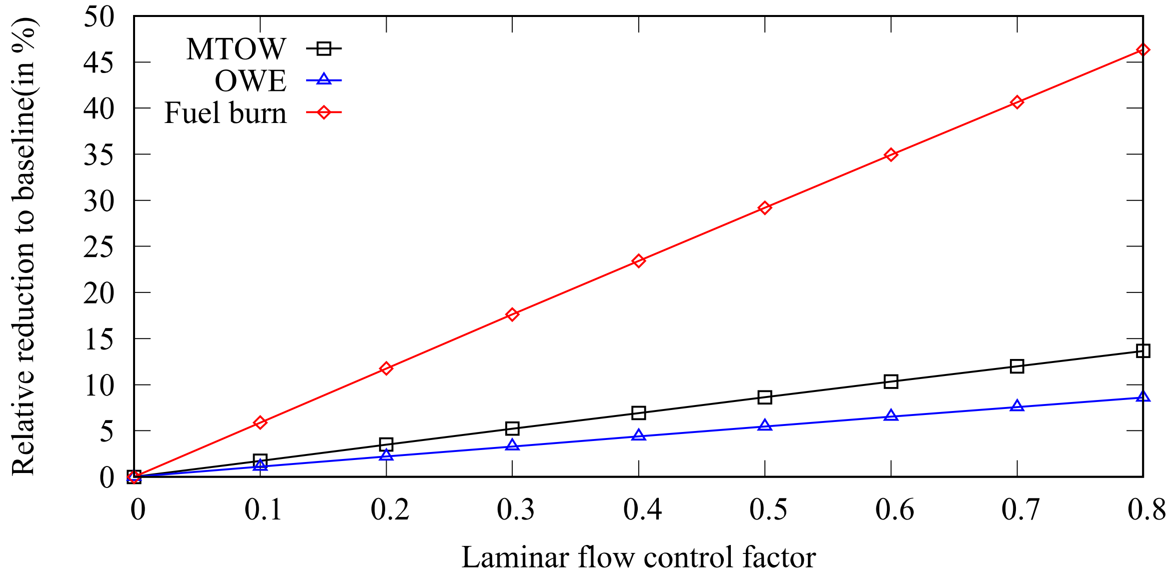


Figure 4: Sensitivity study of laminar flow control on MTOW, OWE and fuel burn

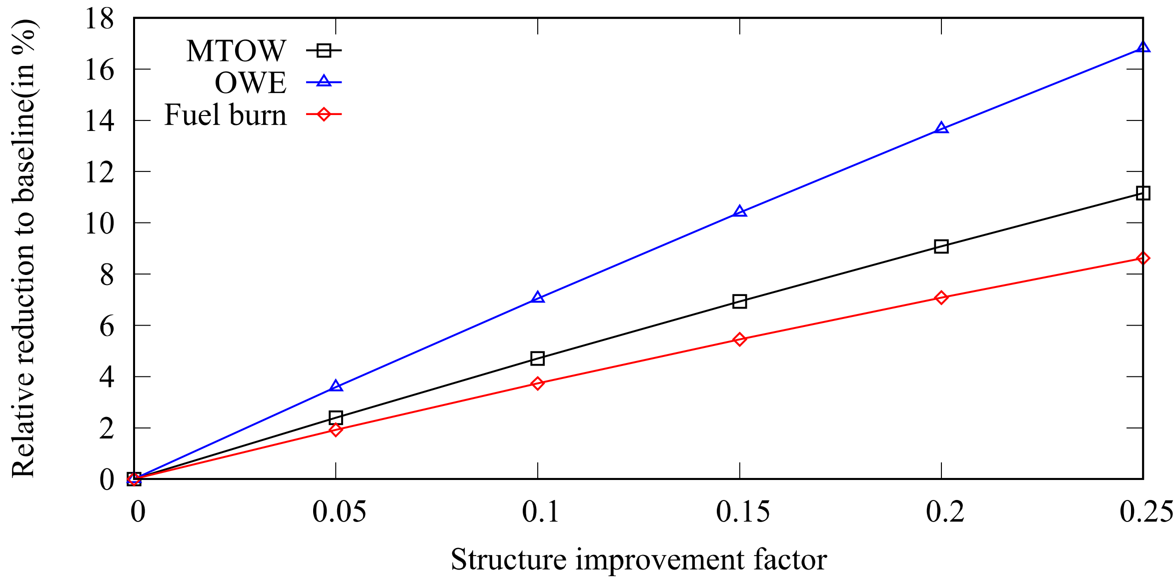


Figure 5: Sensitivity study of structure advancement on MTOW, OWE and fuel burn

Table 3 Overall aircraft impact of technology progress

Parameter	Absolute value (kg)	Relative reduction (%)
MTOW	27493	27.0
OWE	15264	28.4
Fuel burn	2442	57.3

Table 3 shows the overall aircraft impact of the four major EWL-identified game-changing technologies. The technology progress level is set to be maximally achievable in the timeframe of 2050, i.e. the right bound of "Technology improvement factor" range in Table 2. For the optimistic technology development scenario, the fuel burn can be reduced by 57% with the MTOW reduction of 27% and the OWE reduction around 28%. The results are comparable to the predictions of NASA ERA project and NASA-Boeing SUGAR project. These preliminary results indicate promising opportunities for further application radical new energy systems, such as advanced batteries, fuel cells, LH2, etc. The radical reductions of takeoff weight and total energy consumption can largely relax the utilization of green energy storages such batteries – either with an acceptable MTOW increase with given specific energy of battery and power density of electric motors or much more relaxed requirements on specific energy of battery and power density of electric motors for a given MTOW constraint [38]

5 CONCLUSION AND OUTLOOK

Within this paper, methods and modelling strategies for wide design space problems are introduced and illustrated. The main findings are summarized as follows.

I. In the context of energy transition for aviation research project, a generalized framework is developed to investigate the airframe technologies and new energy systems.
II. For a regional jet aircraft reference, study on the technology progress level impacts showed good sensitivity.
III. With a combination of four major EWL-identified technologies, the total fuel burn at the design range is reduced by 57% with the MTOW reduction of 27% and the OWE reduction around 28% in the optimistic scenario.

As the presenting manuscript only covers the methods and results at the first stage of our project, further development directions and features are listed in the following.

I. A detailed validation of the methods with high fidelity simulations or experiment data need to be carried out.
II. The coupled effect of radical airframe technologies and game-changing energy systems have to be investigated.
III. More comprehensive interactions with other EWL team members are required, such as integration with the fundamental modelling of transformative energy systems or the global system level analysis.
IV. Full aircraft design level optimization has to be carried out for further exploiting the benefits of aviation energy transition.

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