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Modelling, simulation and optimization methodologies for low-emission aircraft concepts

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The further reduction of greenhouse gas emissions is essential for climate neutral aviation to accommodate the expected increase in air travel and at the same time to pursue its service to society and environment. This calls for rapid introduction of advanced and disruptive technological solutions for airframe, propulsion and energy carriers, well beyond the continuous improvements of the past decades that have led to the state-of-the-art aircraft technologies. Many technology investigations have therefore recently been made in various directions, including innovative airframe concepts, advanced propulsion concepts and carbon-free energy carrier concepts.

Description of work

For design, analysis and evaluation of such novel concepts, fast, flexible and efficient modelling tools are required. Moreover, multi-disciplinary modelling and optimization are required to incorporate the most appropriate and innovative technologies and identify most promising design solutions. NLR is active in this area

in various state-of-the-art research and development projects in which these tools for multi-disciplinary modelling and optimization are developed, as well as deployed in innovative aircraft design use-cases. For example, in the Clean Sky 2 project NOVAIR the design of aircraft configurations for hybrid-electric-propulsion (HEP) has been investigated. Collaborative multi-disciplinary modelling and optimization methodologies and tools are pursued in the ongoing Horizon2020 (H2020) project AGILE4.0. In the ongoing H2020 project IMOTHEP, HEP system design for conservative and radical aircraft configuration concepts are under investigation.

Results and conclusions

This paper presents a brief overview of the recent developments in the mentioned areas. Among others, the efficient modelling and quick evaluation of the overall aircraft emissions are essential for the assessment of the greenhouse gas effects of novel aircraft and propulsion concepts. This requires adequate representation of the aircraft level behavior including engine and propulsion aspects and considering flight mission and exhaust emissions details. The main methodologies and tools that are used in these analyses are presented and some typical results are shown.

Applicability

This paper presents an overview of methods and tools for conceptual level aircraft design that are currently in use and under development at NLR. Flexibility, versatility and simplicity are key aspects of these tools for the concept design phase. The presented methods and tools allow for quick and versatile modelling for the development of future low-emission aircraft. Some example applications of the methodologies are presented. For low-emission aircraft there seems to be different potential for the various HEP configurations that were considered.
The most promising aircraft concepts can be further evaluated in more detail. Enhancements of aircraft configurations and propulsion architectures can be investigated in cooperation with European research partners and airframers such as Airbus. Besides quick analyses of the aircraft design, also design optimizations can be explored. Evaluations of new propulsion technologies can give valuable insights in emerging requirements and component developments to achieve the envisaged benefits.

GENERAL NOTE

This report is based on a presentation given at the ECCOMAS-CM3 conference, on 23 November 2021, in Barcelona, Spain. This presentation is part of the ECCOMAS-2021 Mini-Symposium (MS) on the following topic: "MS 3B - Methods and Tools for Innovative Design Solutions of Aircraft/ Aero-Engines Configurations".

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Summary

The further reduction of greenhouse gas emissions is essential for climate neutral aviation to accommodate the expected increase in air travel and at the same time to pursue its service to society and environment. This calls for rapid introduction of advanced and disruptive technological solutions for airframe, propulsion and energy carriers, well beyond the continuous improvements of the past decades that have led to the state-of-the-art aircraft technologies. Many technology investigations have therefore recently been made in various directions, including innovative airframe concepts (e.g. as presented in [1]), advanced propulsion concepts (e.g. as presented in [2]) and carbon-free energy carrier concepts (e.g. as presented in [3]).

For design, analysis and evaluation of such novel concepts, fast, flexible and efficient modelling tools are required. Moreover, multi-disciplinary modelling and optimization are required to incorporate the most appropriate technologies and to identify the most promising design solutions. NLR is active in this area in various state-of-the-art research and development projects in which these tools for multi-disciplinary modelling and optimization are developed, as well as deployed in advanced aircraft design use-cases. For example, in the Clean Sky 2 (CS2) project NOVAIR [4] the design of aircraft configurations for hybrid-electric-propulsion (HEP) has been investigated. Collaborative multi-disciplinary modelling and optimization methodologies and tools are pursued in the ongoing Horizon2020 (H2020) project AGILE4.0 [5]. In the ongoing H2020 project IMOTHEP [6], HEP system design for conservative and radical aircraft configuration concepts are under investigation.

This paper presents a brief overview of the recent developments in the mentioned areas. Among others, the efficient modelling and quick evaluation of the overall aircraft emissions are essential for the assessment of the greenhouse gas effects of novel aircraft and propulsion concepts. This requires adequate representation of the aircraft-level behaviour including engine and propulsion aspects and considering flight mission and exhaust emissions details.
The main methodologies and tools that are used in these analyses will be addressed and some typical results will be shown.

Contents

1 Introduction

The further reduction of Greenhouse Gas (GHG) emissions is essential for climate neutral aviation to accommodate the expected increase in air travel and at the same time to pursue its service to society and environment. This calls for rapid introduction of advanced and disruptive technological solutions for airframe, propulsion and energy carrier, well beyond the continuous improvements of the past decades that have led to the current state-of-the-art aircraft technologies. The high ambitions for the development of low-emission aircraft are currently a key driver for many investigations on aircraft concept design and the corresponding modelling, simulation and optimization methodologies.

These drivers include for example initiatives like the European Commission's Green Deal. The Green Deal intends to achieve climate neutrality by 2050 through, among others, the reduction of transport emissions by 90% (compared to 1990-levels) [7]. More specifically for aviation, but on a more global level, the ICAO Resolution "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)" (adopted also by the EU) aims to stabilize aviation CO2 emissions at 2020 levels. This resolution requires airlines to monitor their emissions on all international routes, and offset their emissions by purchasing eligible emission units generated by projects that reduce emissions in other sectors (e.g. renewable energy) [8].

As a consequence of such initiatives, costs of aircraft GHG emissions will increase. Also, sustainable Aviation Energy Carriers (AECs) are likely to become economically viable and will emerge in operations. Furthermore, it is likely that the relative cost components for energy in aircraft operations will increase.

These shifting factors of emissions, energy supply and operating costs will lead to enhanced requirements for aircraft developments. Near future aircraft shall further drastically reduce their GHG emissions by all means, including improved energy carriers, improved aircraft design and improved operations. Future aircraft will require drastic re-design for integration of sustainable AECs, in particular non-drop-in fuels such as hydrogen (H2) and batteries, for integration of energy conversion, and for integration of alternative propulsion concepts such as distributed electric fans or propellers. Future aircraft will also be required to improve their energetic efficiency through innovative systems and radical aircraft configurations such as blended-wing-body (BWB) aircraft.

For the design, analysis and evaluation of such novel future aircraft concepts, fast, flexible and efficient modelling tools are required. Moreover, multi-disciplinary optimization is needed to incorporate the most appropriate technologies and to identify most promising design solutions. NLR is active in this area in various state-of-the-art research and development projects in which tools for multi-disciplinary modelling and optimization are developed as well as deployed in innovative aircraft design use-cases. For example, the design of aircraft configurations for hybrid-electric-propulsion (HEP) and the system design for conservative and radical aircraft configuration concepts are under investigation. In support of this, also multi-disciplinary modelling and optimization methodologies and tools are under development.

Among others, the efficient modelling and quick evaluation of the overall aircraft emissions are essential for the assessment of the GHG effects of novel aircraft and propulsion concepts. This requires adequate representation of the aircraft level behaviour including engine and propulsion aspects in combination with flight mission and exhaust emissions details. This paper presents a brief overview of the recent developments in the main methodologies and tools that are used in these analyses and some typical applications and results will be shown. These developments are part of the R&D activities and methodologies under development in the Aerospace Vehicles (AV) division of NLR. A lot of the work in NLR's AV division is dedicated to numerical and experimental investigations. The focus of this paper is on some of the modelling and simulation capabilities that are used in the investigations. More specifically, the technical background of this paper originates from developments in some recent R&D projects, in particular:

1. The Clean Sky 2 project NOVAIR [4],running in 2017-2022, where concept design and assessment of novel aircraft configurations for HEP is considered;
2. The Horizon 2020 project AGILE4.0 [5], running in 2019-2022, where collaborative MDO methods for aircraft level design are developed;
3. The Horizon 2020 project IMOTHEP [6], running in 2020-2023, on Investigation and maturation of technologies for hybrid electric propulsion.

The main activities and aircraft applications of these projects and their respective logos are illustrated in Figure 1. The support of these projects in the underlying work of this paper is gratefully acknowledged.

Figure 1: The 3 projects CS2-NOVAIR, H2020AGILE-4.0, H2020-IMOTHEP, of the underlying research presented in this paper, with compact illustration of the main activities of these projects and their logos.

2 Low-emission aircraft options

Many options exist to progress to the further reduction of emissions in aircraft operations. This section describes some examples of these options for low-emission aircraft operations that have impact on aircraft design, thus resulting in novel low-emissions aircraft designs.

The reduction of fuel consumption and associated GHG emissions can be addressed by optimizing operations. This optimization can be achieved for example by operating improved turboprop aircraft on short and medium range routes, instead of the larger turbofan aircraft, which are less efficient for short range. This can be applicable for example for ranges of 1000-2000 km that could be operated at cruise altitudes of 6-8 km and Mach 0.5-0.6, which is lower and slower than the typical cruise altitude and speed of about 11 km and Mach 0.78 for single aisle turbofan aircraft. For example, Embraer is currently investigating such advanced turboprop concepts for potential entry into service (EIS) later this decade [9] (Figure 2).

Figure 2: Embraer is currently investigating such advanced turboprop concepts for potential EIS later this decade [9]. Picture adopted from an Embraer source.

The rapidly emerging role of sustainable Aviation Energy Carriers (AECs) also can be considered [23]. Obviously, the use of the sustainable AEC hydrogen, instead of kerosene, would completely avoid any in-flight emission of CO_2. For example, a concept was proposed by Bauhaus Luftfahrt for long-haul flight [3], using Liquid Hydrogen (LH_2) stored in cylindrical fuselage tanks and used for combustion in H_2 turbofan engines (Figure 3). However, the integration of the cryogenic LH_2 tanks and the H_2 fuel system and H_2 engines brings many design challenges that require technical innovations related to lightweight design, safety and certification.

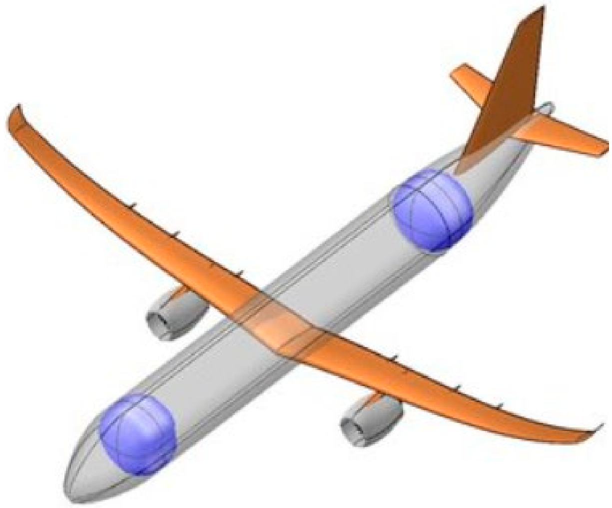

Figure 3: Long-haul aircraft concept proposed by Bauhaus Luftfahrt using LH2 stored in cylindrical fuselage tanks and used for combustion in H2 turbofan engines [3]. Picture adopted from a Bauhaus Luftfahrt source.

The increasing costs of energy in aircraft operations also can be considered. Fuel cost makes up about 20% of the total operating cost for typical airliners. Other costs, such as crew and maintenance costs, are also between 15-25%; cost of ownership is about 30-40%. With the higher costs due to carbon offsetting schemes and introduction of alternative, but more expensive, AECs, the cost component for energy will increase. To address this energy cost component, the energy required for aircraft operations needs to be reduced. This can be achieved by improving the energetic efficiency of aircraft through introduction of efficient aircraft configurations and innovative systems. For example, Airbus is investigating the design of BWB aircraft configuration for medium range of 3700 km and 200 PAX [10] (Figure 4). This airframe provides high aerodynamic efficiency in cruise as well as high internal volume, which has advantages for storage of high volumetric energy carriers such as H2. Moreover, hybrid-electric propulsion (HEP) may be considered in this configuration, where the propulsive powertrain is partly fed by combustion of H2 and partly fed by electric power from batteries.

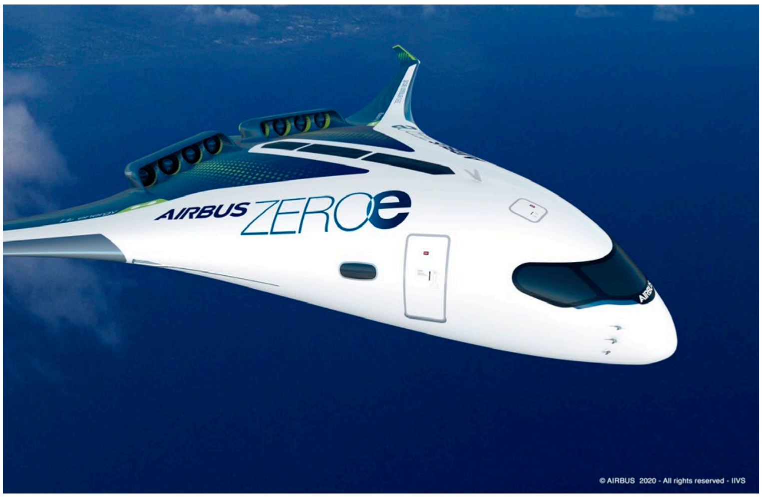

Figure 4: Airbus is investigating the design of BWB aircraft configuration for medium range of 3700km and 200PAX [10]. "Picture adopted from an Airbus source.

3 Low-emission aircraft: basics

The basic principles behind low-emission aircraft are directly related to the fundamental physics of flight. Energetically efficient transport through air of a payload requires a lift force to carry the weight. This lift is generated by motion of air along a lifting surface. This relative motion of air and the lift it creates, inevitably induce drag forces that counteract the relative motion. This dissipative system of motion and counteracting drag forces requires external power supply to maintain its equilibrium. In powered flight, this power supply is achieved through a controlled thrust force that counteracts the total drag force (Figure 5).

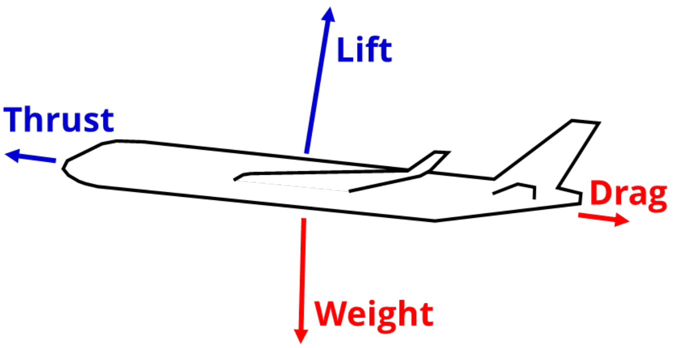

Figure 5: Illustration of the basic force equilibrium in powered flight, where the aircraft depicted is flying at a small climb angle.

The basic purpose of air transport is to carry a payload over a certain distance. This transfer of payload is achieved by a flight mission, essentially including climb to a certain altitude and descend to the target destination (Figure 6), and usually including cruise flight to travel distance. The equations of motion on aircraft level lead to the force equilibrium that must be maintained during the whole mission, and therefore the thrust force must be fed by an onboard energy supply. Obviously, the required amount of onboard energy for the mission depends on the value of the thrust force, the air speed of the aircraft and the distance travelled. This onboard energy is contained in an energy carrier such as kerosene, hydrogen or electricity, and adds to the total weight of the aircraft. For large aircraft and long-haul flight this may even add up to 50% of the total take-off weight of the aircraft.

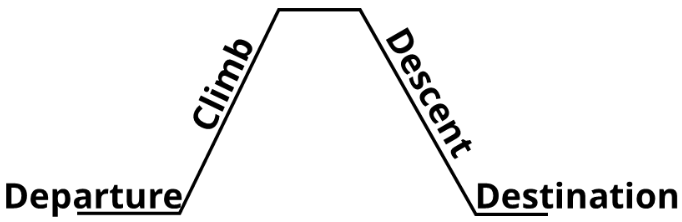

Figure 6: Illustration of a basic flight mission, which essentially includes departure and climb to a certain altitude, and descent to the target destination. Of course, usually a mission also includes cruise flight between climb and descent to travel the intended distance.

The main basic weight components that shall be carried by an aircraft are payload, airframe and engines, and onboard energy. As explained, the onboard energy mass can be very substantial and depends on the mission. But additional mass due to extra onboard energy or due to extra payload, also requires additional lift and thrust forces, and therefore larger and heavier wings and engines. These heavier wings and engines add to the airframe mass, and therefore again require extra onboard energy, and so forth. This iterative mass increase is typical for aircraft design and is also known as the snowball effect (Figure 7). The good thing of this effect is that it also works in opposite direction for mass decrease.

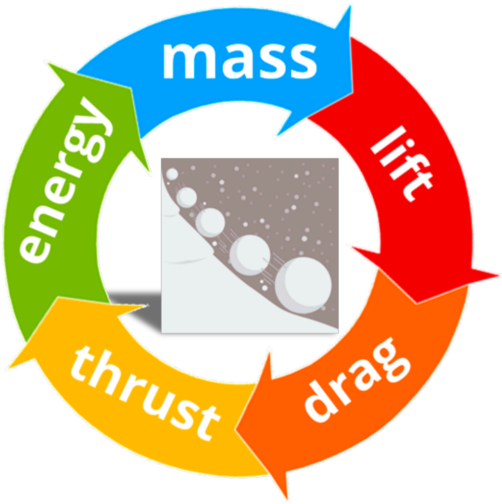

Figure 7: The snowball effect for aircraft design: Additional mass leads to iterative increases in lift, drag, thrust, energy, and the required mass for airframe and engine systems and structures to account for those increases.

4 Low-emission aircraft: aircraft modelling tools

For the conceptual design of low-emission aircraft, we need versatile modelling and simulation tools to do the required analyses. If we look at the basic force balance of the aircraft, we need tools to predict the key components for that balance.

For example, for weight, we need aircraft weight estimation tools. NLR has tools for conceptual sizing and preliminary weight estimation. For example, the MUCH tool [11] can be used for initial estimates of airframe, engines and systems weights based on global sizing and heuristics.

For example, for lift the estimations are determined from the aerodynamic characterization of the airframe, typically the lift-drag polar, and the airframe basic geometry, typically the reference area, which is based on the lifting surface of the aircraft. This aerodynamic characterization can be done in different ways, ranging from low fidelity (lo-fi) estimates e.g. based on panel methods, to high fidelity analyses e.g. based on Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) computations. For lo-fi conceptual modelling the MUCH tool can be applied, which makes use of the open source tools openVSP [16] and VSPaero [17].

For drag estimation, also the aerodynamic characterization for conceptual modelling with the MUCH tool can be applied. Although in this case the accuracy of the estimates is more sensitive and lo-fi methods are mostly not good enough. For example, in relation to drag contributions coming from shock waves in transonic speeds, and from interference between connected airframe components such as wing and pylon, high modelling accuracy is required. Therefore, more accurate drag prediction methods are available at NLR e.g. the MATRICSV tool, based on potential flow combined with boundary layer modelling, and ENFLOW CFD software providing Euler or RANS based flow modelling.

When having the three basic forces of weight, lift and drag determined for an aircraft concept, the required thrust force can be derived from the aircraft's equations of motion, as illustrated in Figure 8. This brings us to the next basic aspect of air transport: the mission and energy analysis.

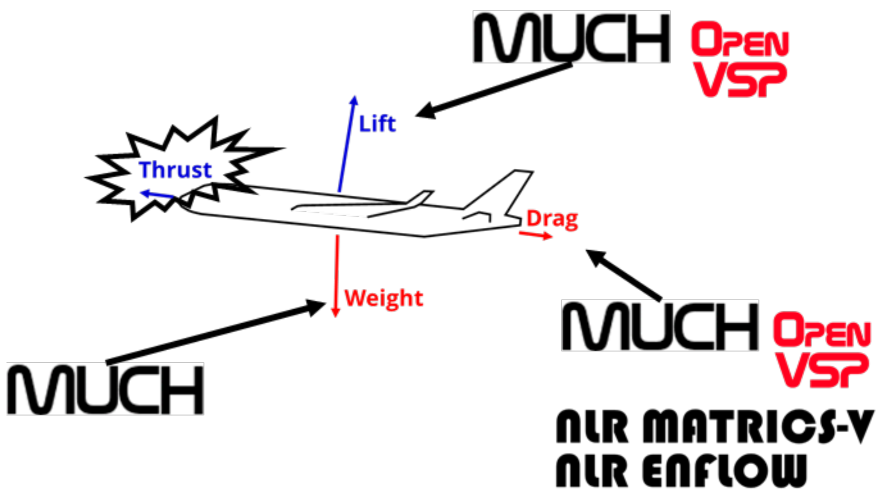

Figure 8: Illustration of various tools in use at NLR in different modelling fidelities for conceptual sizing, preliminary weight estimation and aerodynamic characterization.

5 Low-emission aircraft: mission simulation tools

If we want to properly model the mission, we need an unambiguous representation of the intended flight. We consider here only forward flight, without roll or yaw, because the prime interest here is the energetic evaluation of the mission. That allows to simplify the mission to its flightpath in terms of altitude and ground distance, i.e. by the aircraft motion in x and z direction and rotation about the y axis. Here the coordinate system is assumed to be right-handed and fixed to ground with the x axis horizontally in forward flight direction and z axis upward perpendicular to ground surface. Rotations of the aircraft other than pitch, like in roll or yaw motions and flight manoeuvres, are analysed for example for dynamic stability and handling qualities evaluation, but are out of the scope of this study.

Besides altitude, the mission definition shall include also the (indicated) air speed as function of horizontal position. The mission is defined from "block-off" at departure gate to "block-on" at arrival gate, so including taxi, take-off and landing. Also, the activation state of devices such as landing gear (LG), high-lift, non-propulsive systems, like the environmental control system (ECS), and potentially other systems shall be included in the mission definition. Also, it should be noted that the mission may include definitions for missed approach and go-around or diversion flight, if for example the aircraft performance and energy consumption in failure cases shall be evaluated. At the same time, a basic and easy to use tabular mission model is desired, for example implemented in MS Excel (Figure 9).

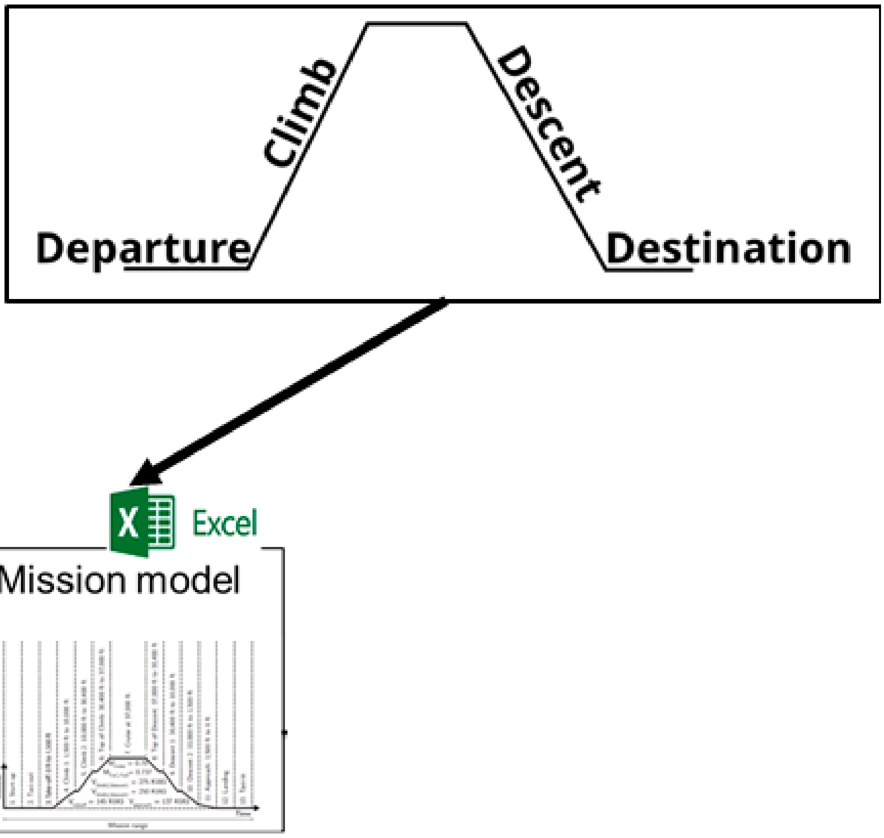

Figure 9: Illustration of the mission representation of the intended flight, which shall define speed and altitude as function of horizontal position for the whole flight including taxi, take-off (TO) landing etc. Activation of devices such as LG, high-lift, ECS, etc. shall also be included. A basic tabular Mission Model is used for this, for example implemented in MS Excel.

From the mission definition the state of the aircraft can be derived as function of time, in terms of horizontal location, altitude, flightpath angle, attitude and speed along the flightpath. From this state of the aircraft and the equations of motion, the force equilibrium can be determined in each point of the mission, yielding as a result the required thrust force, as explained previously. The power required for the thrust force along the flightpath, at the prescribed air speed, yields the required momentary power supply. Time integration of this power supply, together with the non-propulsive power requirements, yields the energy that is needed for the mission. Obviously, the required power that shall be supplied by the energy carrier (e.g. kerosene, hydrogen) also depends on the efficiency of the propulsive device. For example, for a turbofan engine, the thermal efficiency of the gas turbine and the propulsive efficiency of the fan also determine the power that has to be supplied by the fuel flow to the engine. The propulsive device can be of any type, for example turboprop, turbofan or electrically driven fan. The power supply that is needed by this device can subsequently be calculated by appropriate modelling. For example, for a turbofan engine, the required fuel mass flow for a certain thrust requirement, at a given speed and altitude, can be calculated with NLR's GSP engine modelling tool [12], as illustrated in Figure 10.

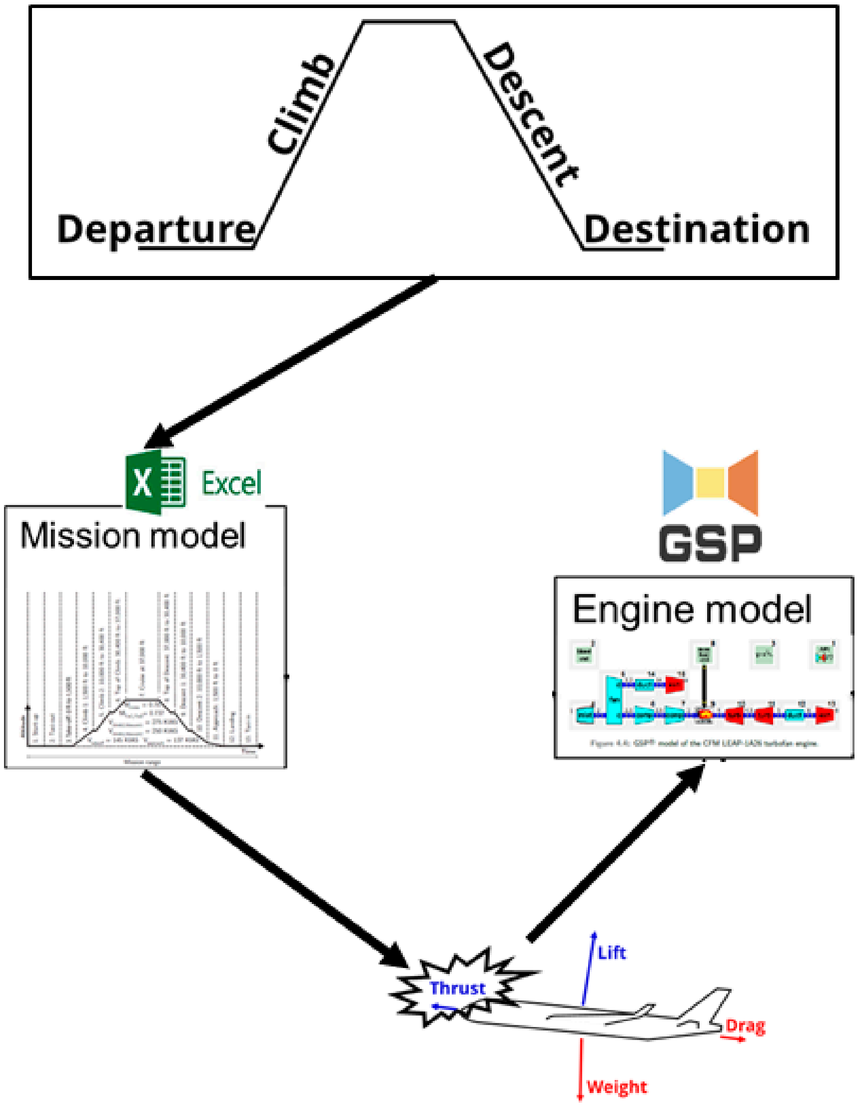

Figure 10: Illustration of the integration of the power required for the thrust force along the flightpath, at the prescribed air speed, which yields the required power supply and energy that is needed for the mission. The required fuel mass flow for a certain thrust requirement, at a given speed and altitude, can be calculated for example with NLR's GSP engine modelling tool.

The integration of the fuel mass flow during the mission yields the fuel consumed at any point of the mission. The resulting total mission fuel mass is calculated by the accumulation of fuel flow along the whole mission (Figure 11).

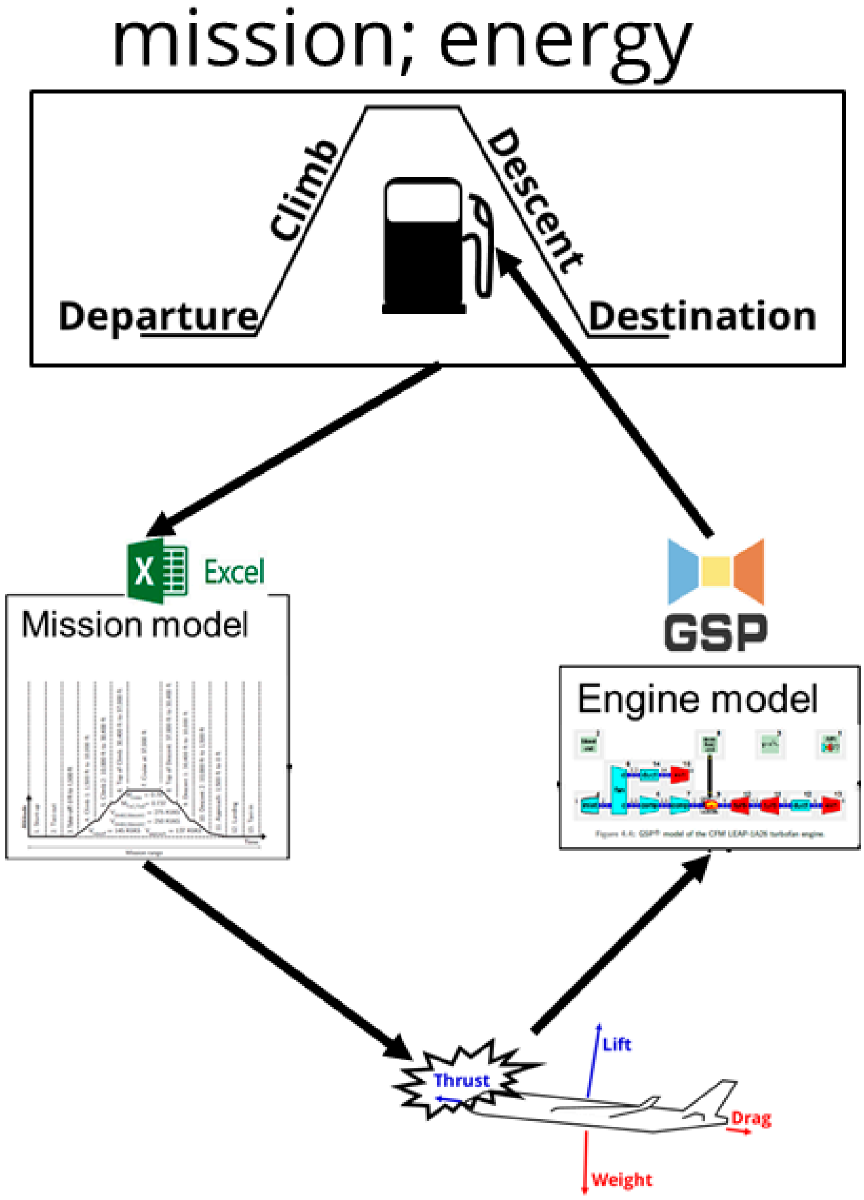

Figure 11: Illustration of the mission fuel consumption, which can be calculated by the accumulation of fuel flow, as predicted here by the GSP engine model, along the whole mission.

6 Low-emission aircraft: integration and evaluation

In addition to the basic aircraft models and the mission simulation, the interactions between these two must be taken into account. For example, as explained before, the mass of fuel required for the mission can be a substantial proportion of the take-off weight (TOW) of the aircraft. Also, it must be noted that the calculation of this fuel mass needed for the mission requires the solution of an inverse problem: the mission fuel mass depends globally on the mission (range, speed, altitude, etc), on aerodynamic and engine efficiencies, on the payload mass, on the masses of airframe, engines and systems, and on the mission fuel mass itself. Also, the fuel mass may depend on specific mission procedures such as loiter or diversion. Obviously, the fuel mass gradually decreases during the mission, leading for example for large long-haul aircraft to a total landing weight that may be less than half the TOW. Furthermore, in hybrid electric aircraft, the fuel mass depends also on the energy capacity of the batteries in parallel HEP architectures, and on the details of how the energies are converted to propulsive power. Besides the energy requirements, which determine the mass of fuel and of batteries on HEP aircraft, also the power requirements determine the sizing and mass of engines, electric motors, power electronics and distribution and batteries. In particular for HEP aircraft, this interaction between mission, systems sizing, fuel and system masses, and the consecutive airframe sizing, leads to a delicate interplay among mission requirements, airframe design, propulsion and powertrain sizing and overall aircraft optimization. This interplay is directly related to the snowball effect: increased mass requires more lift, which induces more drag, demanding more thrust, more energy, more mass, etc, as illustrated in Figure 12.

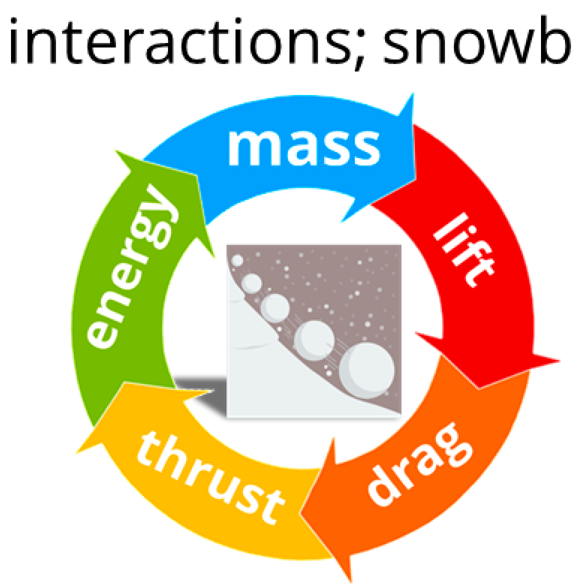

Figure 12: Illustration of the snowball effect in aircraft design: increased mass requires more lift, which induces more drag, demanding more thrust, more energy and more mass, etc.

To model this interplay among all these factors, and to analyse the interactions among the mission and the aircraft and the propulsion systems, NLR has developed the MASS tool [14] (Figure 13). The MASS tool is primarily an integration framework, in which the main required component models can be incorporated from various sources.

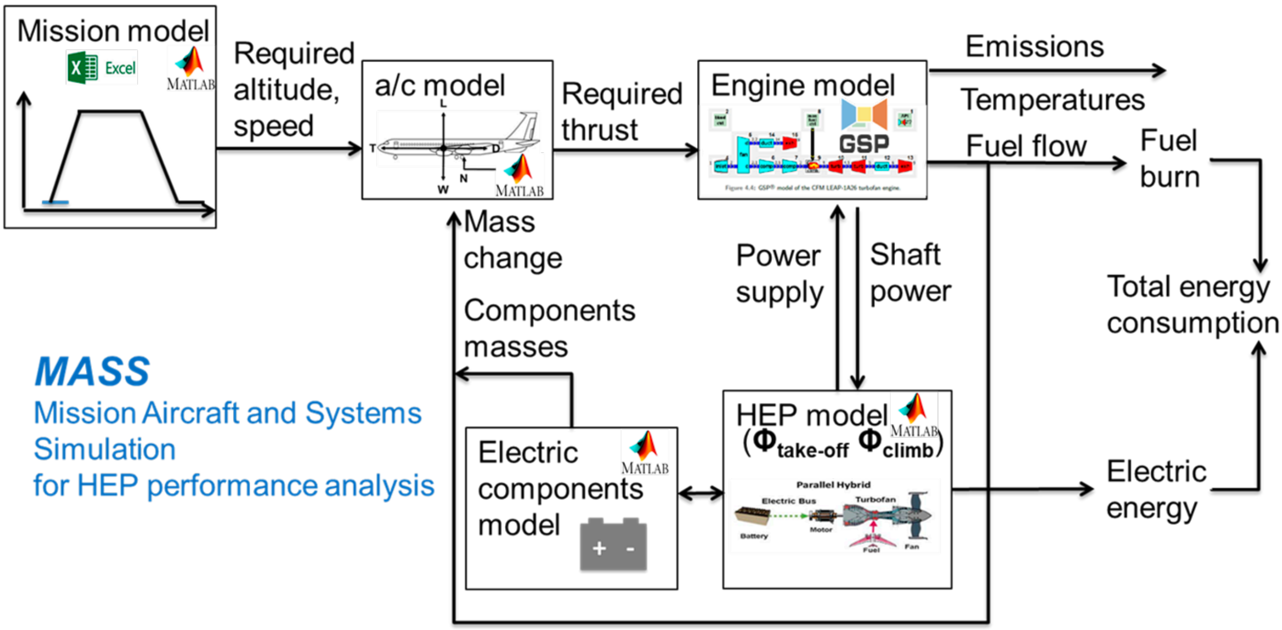

Figure 13: Illustration of the NLR MASS tool [13], which is primarily an integration framework, in which the main required component models can be incorporated from various sources. Note that non-propulsive power demand is not explicitly included in this illustration but of course can be incorporated in MASS analyses.

As an example of these component models, we can use the tabular Mission Model, as previously explained. This Mission Model can be implemented as a basic MS-Excel table, or may be imported from other mission definitions as, for example, provided in CPACS format [15].

Another key component model is the aircraft model, which may be implemented in Matlab or may be imported from other sources. The aircraft model essentially contains the aircraft mass and the aircraft aerodynamic behaviour, and possibly other aspects of the aircraft characteristics. The aircraft mass is broken down into the key items such as operating empty weight (OEW), fuel mass, payload, maximum take-off weight (MTOW), and is potentially further detailed into system and subsystem weights. The aerodynamic behaviour requires an adequate aircraft level lift and drag characterization, typically by drag polars for the relevant operational conditions in terms of speed and altitude. The aircraft model can be adopted from the lo-fi tools such as MUCH, or from the higher fidelity tools such as MATRICS-V or ENFLOW, that were previously explained in section 4. The aircraft model essentially shall predict the requires thrust in any point of the mission.

Another key component model is the engine model, or actually more in general: the propulsion model, or even more general: the powerplant model. This essentially translates the required thrust, and possibly non-propulsive power demands, into the required energy flow to the powerplant. For large aircraft, this powerplant model would be typically based on a gas turbine, which can be adequately modelled with the NLR GSP tool. Also other powerplant models can be used, for instance for instance hybrid-electric drive trains with propellers or ducted fans. In that case the propulsive and non-propulsive power architecture will be different, for which the MASS structure can be easily adapted.

Another key component model is the HEP system model, which can be included for HEP aircraft evaluations. This HEP system model contains all the required components for the considered HEP system architecture. For example, in case of parallel HEP, batteries, power electronics and electric motors could be considered. The modelling of these components depends on the interaction with the gas turbine propulsion unit and on the scheduling of deployment of the electric components that is applied during the mission. These component models may be relatively simple, like basic relations of specific power and specific energy values, or more detailed like power-, voltage- and time dependent battery models.

For any considered HEP architecture MASS allows to evaluate the system sizing for a given mission and to optimize the overall aircraft model according to various objectives and constraints. Instead of the parallel HEP architecture, also other architectures such as series HEP or turbo-electric propulsion can be considered, for which the MASS structure can also be easily adapted.

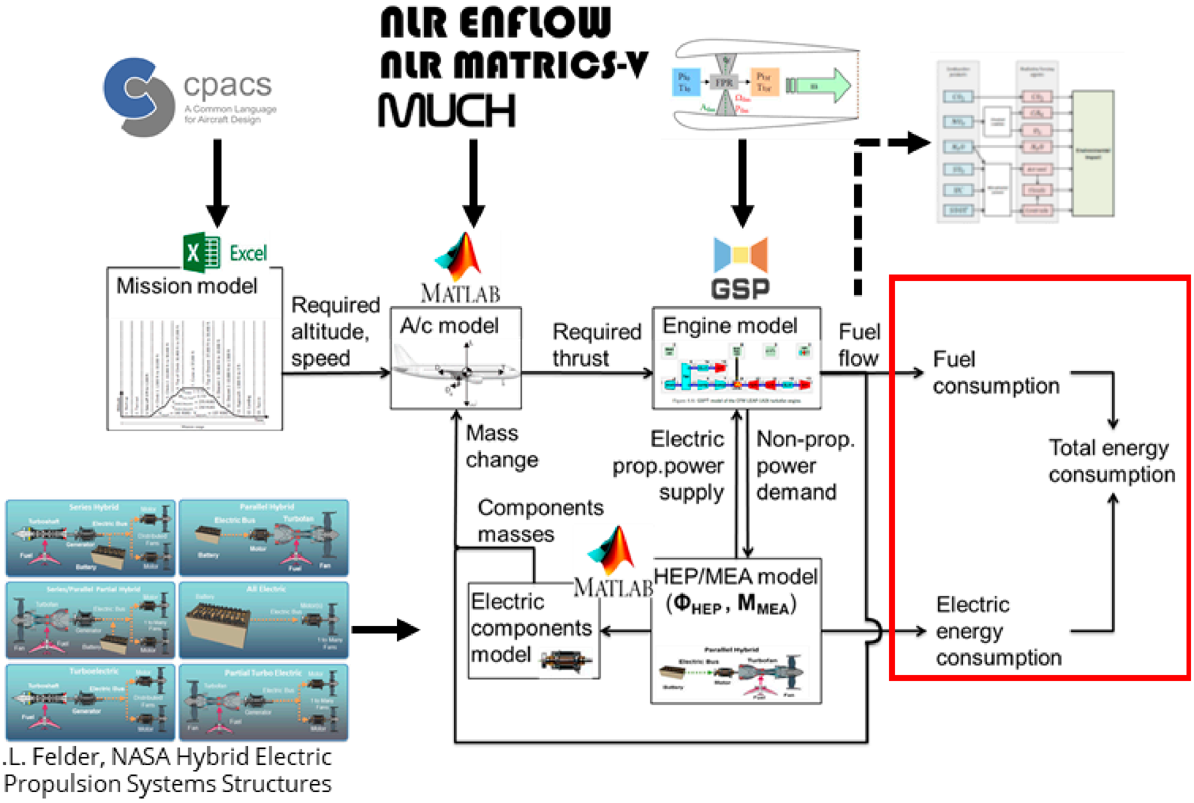

Figure 14: Illustration of the NLR MASS tool in which the main required component models are included for the mission, for the aircraft behaviour, for the engine, for the HEP electric components and HEP powertrain architecture (for example, as defined by NASA [21]) and potentially for emissions characterization. The MASS tool predicts the aircraft total energy consumption, which may comprise both fuel (kerosene or other) consumption and battery electric energy consumption.

The MASS tool, in combination with the other modelling tools and methodologies described above, has been applied in several aircraft concept design studies. Some example applications of these tools and methodologies are presented briefly in the subsequent sections. Three different concept level aircraft design studies are considered. First from the CS2 project NOVAIR, a parallel HEP powertrain retrofit study for an A320neo with EIS in 2035 is presented. Next, a single-aisle airframe design study for parallel HEP is presented, which is related to the H2020 project AGILE4.0. Finally, a turbo-electric BWB concept design case is presented, as considered in the H2020 project IMOTHEP.

7 Case study 1: A320@2035EIS parallel HEP

The first case study deals with a parallel HEP retrofit on an Airbus A320 category aircraft for EIS in 2035 (Figure 15). The aim is to identify the fuel and energy reduction potential of parallel HEP for such aircraft. Therefore, first an estimation is made of the performance of this category aircraft for EIS in 2035 but with conventional powertrain architecture. This estimation is made by accounting for some relevant expected technology developments up to 2035 and projecting those on the A320neo aircraft with EIS in 2014. These technology developments are implemented as assumptions, which include improved engine propulsion efficiency by 20% SFC reduction, improved aerodynamic drag reductions of about 10% and improved airframe and system weights of about 5% in total on aircraft level. With these estimated technology developments, the overall fuel burn on short range missions of the improved 2035 EIS aircraft reduces by about 30% compared to the original 2014 EIS A320neo aircraft. The improved 2035 EIS aircraft is considered in this case study as the reference aircraft.

In this case study we consider a short-range mission of 1500 km with 150 PAX and total payload of 14.3 t. We assume a fixed reserve fuel mass of 1.8 t. For non-propulsive power off-takes we assume fixed settings in cruise of 80kW from the electric generators and 6% bleed air. For the considered mission, the EIS-in-2035 reference aircraft was found to have a take-off mass (MTO) of 67t. The maximum take-off mass (MTOM) is assumed to be 73.5t, equal to the original A320neo MTOM, yielding a “mass budget” for HEP components of about 6.5t.

Then, for the parallel HEP system retrofit, we first assume a 15% downscaling of the turbofan engine in terms of power. Downscaling the engine is essential for achieving energetic benefits with parallel HEP: assisting the engine in peak power phases (i.e. take-off and climb) by additional power from electric motors allows the engine to be downscaled which results in a lower engine weight and better performance during the cruise phase. The 15% downscaling was a result of previous studies (e.g. [14]) which indicated that about 5% reduction in energy consumption can be achieved with downscaled engines between 82% and 90%. Then the parallel HEP system retrofit actually exists in the sizing of the main electric components, in this case only the battery packs, electric motors and inverters are considered. The assumed main specifications of the HEP components for EIS in 2035 are given in the upper right of Figure 15. The parallel HEP architecture is typically suitable for electric support of high-power flight phases, i.e. mainly take-off and climb, and not in other flight phases. Therefore, the HEP variables considered are the electrification ratios in take-off and climb: phi-TO, phi-climb, which are defined as electric power that is provided divided by the total propulsive power.

Figure 15: Illustration of the parallel HEP system retrofit on an A320 category aircraft [22] for EIS in 2035. The 2 turbofan engines are replaced by 15% downscaled turbofans equipped with electric motors on the low-pressure turbine (LPT) shaft and batteries for electric power supply. The assumed main specifications of the HEP components for EIS in 2035 are given in the upper right of the figure. The electric support of the HEP system is applied in the high-power flight phases, i.e. take-off and climb, as indicated in the lower right of the figure. As such the design variables in this case study are phi-TO, phi-climb, representing the power supply of the HEP system in these flight phases.

Next, for these HEP variables the potential for fuel- and energy-reduction for the considered mission is evaluated by the MASS tool. MASS is used for the mission evaluation, the HEP system sizing, and the fuel- and energy optimization. The fuel- and energy consumption (bFuel and bEnergy in Figure 16) are evaluated for the considered mission relative to the reference aircraft. The constraints that are taken into account in this optimization are the aircraft MTOM (i.e.: take-off mass (MTO) must be lower than maximum take-off mass (MTOM): MTO < 73.5 t), and the engine allowable operation, expressed here by the high-pressure turbine (HPT) inlet temperature (TT4) (i.e.: TT4 < 1900 K). The results are shown in Figure 16.

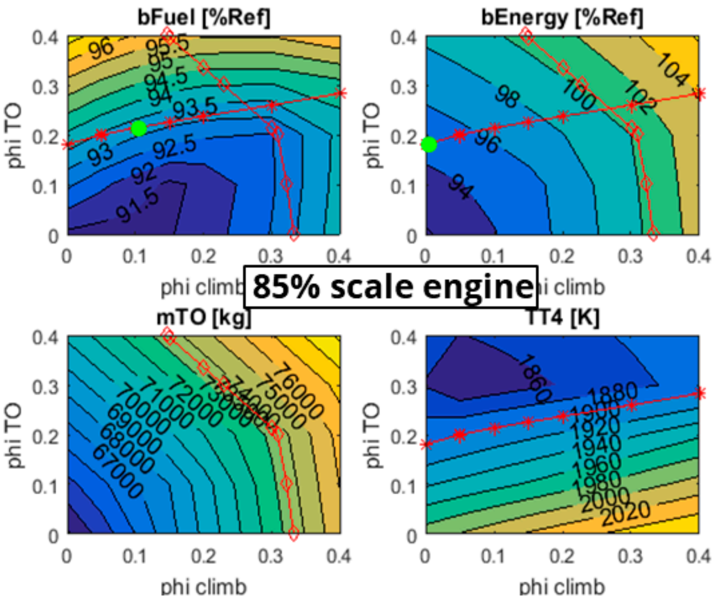

Figure 16: Overview of the results from the evaluation and optimization with the MASS tool of the HEP variables phi-TO, phi-climb, and their potential for fuel- and energy-reduction for the considered mission (1500 km with 150pax). The results found in this case study indicate that the parallel HEP retrofit on a 2035 EIS A320neo aircraft has: Fuel reduction potential up to 7% (bFuel in upper left graph, green dot) and Energy reduction potential up to 5% (bEnergy in upper right graph, green dot).

Further details of this study have been published in [14].

8 Case study 2: single aisle configuration optimization

The second case study also deals with a parallel HEP retrofit on an A320 category aircraft, similar as the previous. In this case the HEP design variables are phi-take-off, phi-climb and the engine size scaling factor (φ_{TO}, φ_{Cl} , S_{en} , resp.). The same 2035 Technology assumptions for the HEP components as in the previous case are used: battery specific energy of 500 Wh/kg; electric motor and inverter specific power of 7.5 kW/kg. But now the study is extended with also wing planform design variables: the root chord, inner span, inner sweep, outer span and tip chord (c_r, b_i, Λ_i, b_o, c_t, resp.) are also considered here (Figure 17).

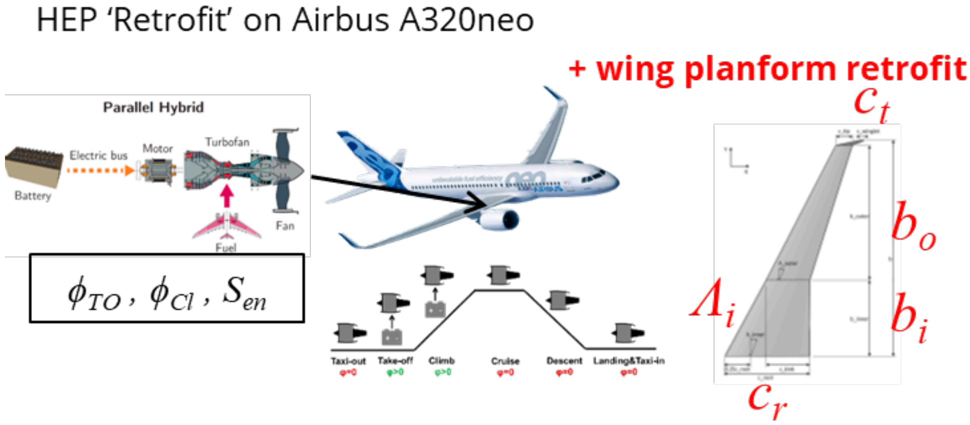

Figure 17: Illustration of case study 2: a parallel HEP system retrofit on an A320 category aircraft [22] for EIS in 2035. The design variables in this case study are phi-TO, phi-climb, engine size scaling factor (φ_{TO}, φ_{Cl} , S_{en} , resp.) and the wing planform variables root chord, inner span, inner sweep, outer span and tip chord (c_r, b_i, Λ_i, b_o, c_t , resp.). The electric support of the HEP system is applied in the high-power flight phases, i.e. take-off and climb, as indicated in the lower centre of the figure.

The considered mission is similar as in the previous case study: 1500 km range; 150pax comprising about 15t payload; cruise altitude and speed of 11km and 0.78mach, resp. The mission also includes the taxi and landing phases, and the HEP system is only deployed in take-off and climb.

The aim in this case study is to identify the fuel reduction potential for an A320 category aircraft by applying parallel HEP in combination with wing planform variations. Only concept level models and analyses are considered, using simplified but fast analysis models. Just like in the previous case study, the MASS tool is used for the mission evaluations. In fact, a design study is defined for the 8 design variables, using a Latin hypercube sampling (LHS) data set of about 200 design points. For each of these design points the mission evaluation is executed with the MASS tool and the mission fuel burn is evaluated. This data set is then used to create a feed-forward artificial neural network (ANN), which then represents an estimation of the mission fuel burn as a function of all 8 design variables (phi-take-off, phi-climb and engine size scaling factor, root chord, inner span, inner sweep, outer span, tip chord). Then the ANN is used in a gradient based optimization with the Matlab fmincon algorithm [18].

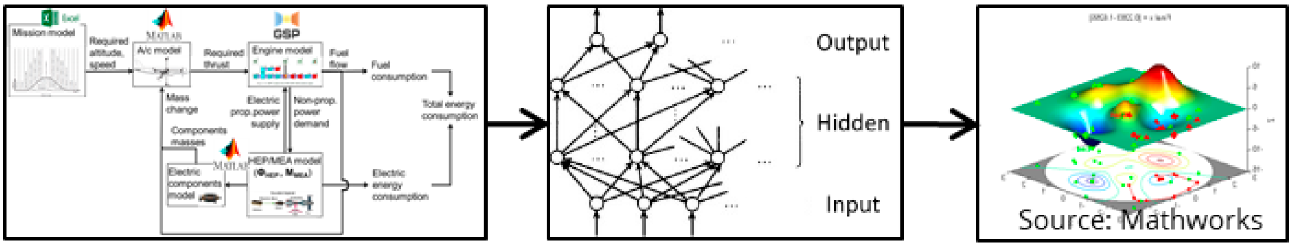

Figure 18: Illustration of optimization process: an LHS data set of about 200 design points is defined for the 8 design variables. For each of these design points the mission evaluation is executed with the MASS tool (left panel in the figure) and the mission fuel burn is evaluated. This data set is then used to create a feed-forward ANN (illustrated in the middle panel in the figure), which then represents an estimation of the mission fuel burn as a function of the 8 design variables. Then the ANN is used in a gradient based optimization with the Matlab fmincon algorithm (illustrated in the right panel in the figure).

The optimum design point found in this way yields a reduction in fuel burn of about 17% in comparison to the A320neo @2014EIS ref aircraft, i.e. without any HEP and with the original A320neo wing planform. See Table 1.

Table 1: Values of the 8 design variables and of the results for the mission fuel burn predictions for the Reference aircraft (the original A320neo) and for the Optimum aircraft (the optimized aircraft with retrofitted HEP system and re-designed wing planform). A fuel burn reduction of about 17% is found for the Optimum aircraft.

	ϕ_{TO} [-]	ϕ_{Cl} [-]	s_{en} [%]	c_r [m]	b_i [m]	Λ_i [deg]	b_o [m]	c_t [m]	$m_{f,burn}$ [kg]
Reference	0	0	100	7.1	6.35	22.24	11.25	1.375	4836
Optimum	0.21	0.3	88	4.0	7.46	35	15.6	0.75	4018

Further details of this study have been published in [19].

It should be noted that this case study, in comparison to the previous case study, was simplified in the sense of constraints that were taken into account in the optimization. E.g. the engine limitations for TT4 and the aircraft level MTOM were not considered here.

9 Case study 3: BWB turbo-electric concept optimization

The third case study deals with the concept design of a turbo-electric BWB aircraft for EIS in 2035. The aim in this design study is to determine the optimized propulsion powertrain for a given short- and medium range (SMR) aircraft mission with the following specifications:

- Design Range; Maximum Range: 1500km; 5100km
- Design Payload; Maximum Payload: 16t; 20t
- Cruise Altitude and Mach: 12km; 0.78.

The mission evaluations and the mission fuel burn optimization are performed with the MASS tool, which includes in this case the following component models (also see Figure 19).

The BWB airframe model is needed to predict the required thrust during the whole mission. In that sense it provides a thrust-power demand to the propulsive devices, in this case the ducted fans. The BWB airframe model incorporates the aerodynamic behaviour and the airframe weights.

The ducted fan (DF) model is needed to predict the required shaft power of the DFs. The DF model is based on quasi-isentropic pressure-duct equations. It was developed for quick and simplified prediction of the fan pressure ratio (FPR), shaft power and propulsive efficiency as a function of thrust demand, true air speed, altitude and fan area. Of course, this model is strongly simplified and has limited validity, but in this study, it is suitable for quick estimation of the DF propulsive efficiency.

The electric component models are used to predict the required generator shaft power. Simplified models are used for the weight and performance of the electric motor (EM), power electronics (PE), cooling system (CS) and electric generator (EG). These models are based on fixed specific power and efficiency estimations for 2035 technology levels. The following estimates for these values were used: EM specific power: 11 [kW/kg]; EM power factor: 0.95; EM efficiency: 0.96; PE specific power: 20 [kVA/kg]; PE efficiency: 0.99; CS specific power: 0.68 [kW/kg]; EG specific power: 20 [kW/kg]; EG efficiency: 0.98.

The turboshaft model is used to predict fuel flow. The turboshaft (TS) model is derived from a CFM-LEAP core model, which is part of a CFM-LEAP-1A turbofan model developed in GSP. The TS model predicts the fuel flow and HPT inlet temperature (TT4) as a function of shaft power demand, altitude, Mach and offtakes for bleed air and LPT shaft generator power. This model has been adapted to 2035 EIS technology assumptions.

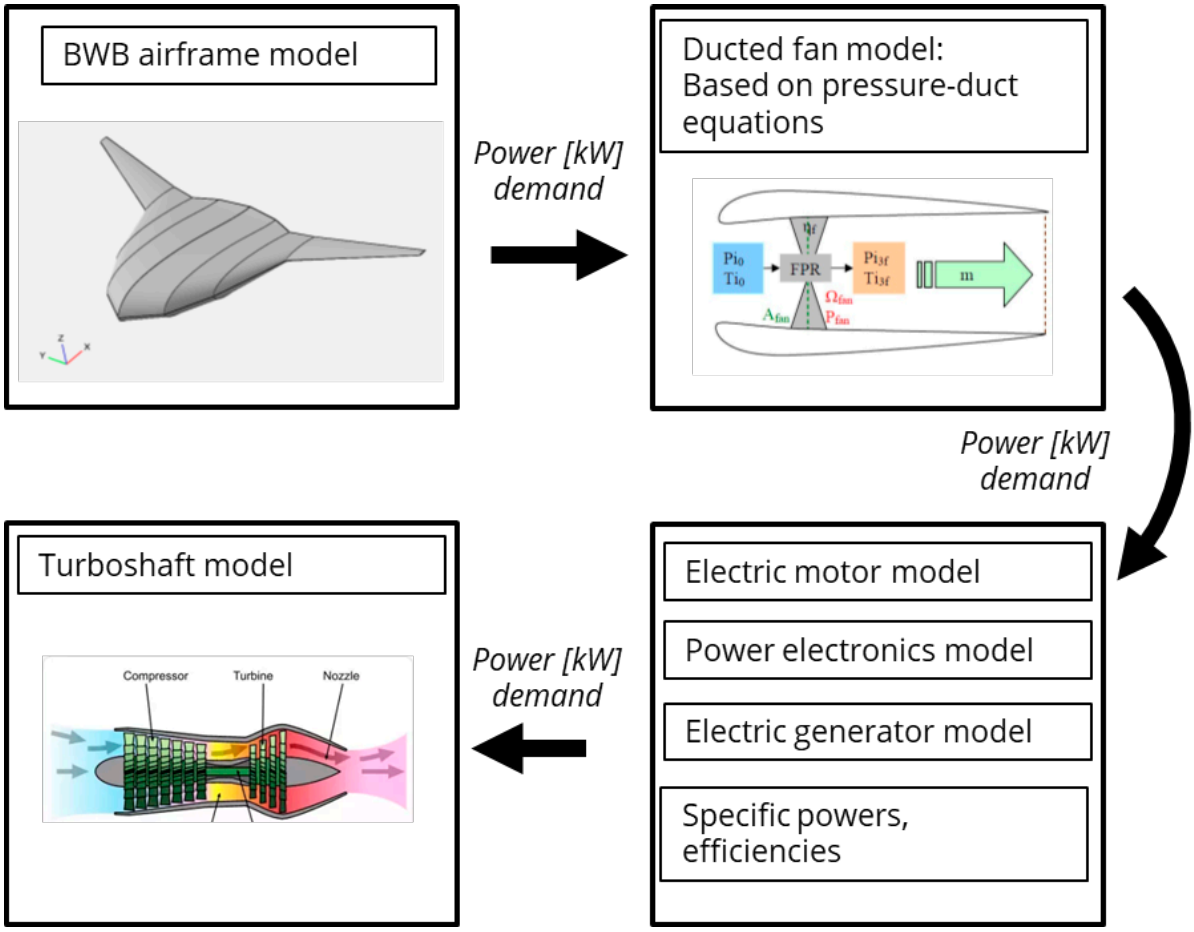

Figure 19: Illustration of the component models used in case study 3: The BWB airframe model predicts the required thrust during the whole mission and provides the thrust-power demand to the propulsive devices, in this case the ducted fans. The DF model is based on quasi-isentropic pressure-duct equations and predicts the required shaft power that must be provided by the electric motor. The electric component models predict the required generator shaft power that must be provided by the turboshaft. The turboshaft model is derived from a CFM-LEAP core model and predicts the fuel flow and HPT inlet temperature (TT4) as a function of shaft power demand, altitude, Mach and offtakes for bleed air and LPT shaft generator power.

One of the reasons for considering a turbo-electric propulsion architecture here, is that this allows for optimizing the propulsive efficiency by maximizing the total fan area. This is achieved in this case study by considering a variable number of DFs, each with an equal and fixed fan area of 1m^2. As such the total fan area depends directly on the number of DFs, which are assumed to be installed on the aft body of the BWB aircraft. The initial design comprises 6 DFs with total fan area of 6m^2, which is approximately equal to the total fan area of the CFM-LEAP-1A engines on the A320neo aircraft.

The optimum number of DFs that was found is 26, i.e. with total fan area of 26m^2 (Figure 20). With the 26 DFs, the fuel burn for the 1500km mission is about 3316kg. This translates in about 10% reduction in mission fuel burn compared to the initial BWB with 6 DFs which has about 3696kg fuel burn for the same mission. The mission fuel burn reduction is about 11% compared to the A320neo @EIS2035 reference aircraft, which has about 3734kg mission fuel burn for the same mission.

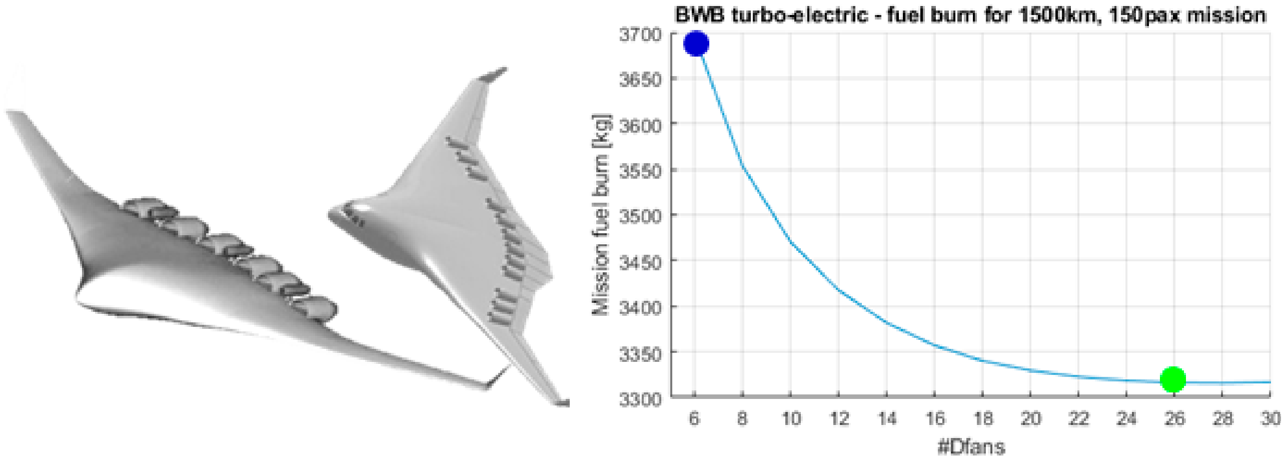

Figure 20: Illustration of the results of the case study 3: For the BWB aircraft, the optimum number of DFs that was found is 26, i.e. with total fan area of 26m^2. With the 26 DFs, the fuel burn for the 1500km mission is about 3316kg (green dot in the graph). This translates in about 10% reduction in mission fuel burn compared to the initial BWB with 6 DFs which has about 3696kg fuel burn for the same mission (green dot in the graph).

Some more details of this study have been published in [20]. This study is still ongoing as part of the IMOTHEP project [6], where among others the investigations are looking at DF placement on the aft body of the BWB aircraft and at the turboshaft-generator modelling in more detail.

10 Conclusions

This paper presents an overview of methods and tools for conceptual level aircraft design that are under development and currently in use at NLR. Flexibility, versatility and efficiency are key aspects of these tools for the concept design phase. Various of these tools have been combined together in the MASS tool, for aircraft level design and mission evaluation.

The MASS tool and its related methodologies allow for quick and versatile modelling for the development of future low-emission aircraft. Enhancements of aircraft configurations and propulsion architectures can be investigated in cooperation with European research partners and airframers such as Airbus. Besides quick analyses of the aircraft design, also design optimizations can be explored. Evaluations of new propulsion technologies can give valuable insights in emerging requirements and component developments to achieve the envisaged benefits.

Some example applications of the methodologies have been presented. The example applications come from different R&D projects and HEP is an important driver for these investigations. For low-emission aircraft there seems to be different potential for the various HEP configurations that were considered. Indications are found for the most promising concepts, which were evaluated in the present studies mostly with quick evaluations and lo-fi analyses.

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