A SYSTEMATIC APPROACH TO OPTIMISE CONVENTIONAL ENVIRONMENTAL CONTROL ARCHITECTURES

T. Giese
Environmental Control System, Airbus Operations GmbH, Hamburg, Germany

B. Oehler
Environmental Control System, Airbus Operations GmbH, Hamburg, Germany

M. Sielemann
Deutsches Zentrum für Luft- und Raumfahrt, Institute of Robotics and Mechatronics, Wessling, Germany

ABSTRACT

This paper presents an optimisation method to optimise environmental control system (ECS) architectures on aircraft level with respect to fuel consumption and/or weight. This optimisation is based on a library of parametric component models for current and future environmental control systems. Validation of the library has been performed using data for a Three Wheel Bootstrap Cycle. The presented optimisation method comprises a global aircraft system optimisation process coupled to a local system optimisation process. Both processes and their coupling are described in this work. The local system optimisation process described in this paper is applicable to any ECS architecture and allows comparing different technologies under the assumption of power optimised systems. Results of the local optimisation process for a Three Wheel Bootstrap Cycle architecture are shown.

1. INTRODUCTION AND OVERVIEW

Increasing prices for jet fuel have led to higher cost for airline operations. In addition with the increasing sensitivity for carbon dioxide as one cause of global climate change there is a high pressure for the airlines and for aircraft manufactures to search for the most fuel-efficient aircraft. Environmental Control Systems (ECS) contribute approximately 2-3% to the overall fuel burn with today's technologies. To reduce this share a worldwide search for new technologies has started. One way to meet this challenge could be an introduction of novel e.g. electric technologies instead of conventional bleed air driven air-conditioning systems.

To evaluate and assess innovative air-conditioning architectures early in the development phase a simulation tool was developed which contains all components to build up potential environmental control architectures. This library has been developed with the multi-physics simulation tool Dymola/Modelica and was presented in [1].

This paper will first elaborate on some recent improvements to the modelling and simulation library. An application of the library for simulation of a Three Wheel Bootstrap environmental control architecture is presented together with its validation versus available data.

Then, the focus shifts to the main topic of this paper, which is optimisation of aircraft systems in general and ECS in particular. To find a weight or fuel optimised environmental control architecture on aircraft level a global aircraft system optimisation with all consumer and power generating systems must be performed. Within this global aircraft system optimisation process a resize of the aircraft according to maximum take-off weight, wing area and fuel is possible. The result of such a global aircraft system optimisation process are dependencies for specific fuel consumption and minimum block fuel demand depending on weight, power off-takes for electrical and pneumatic power and ram air related drag. Based on these so-called exchange rates it is possible to perform a local system optimisation. The paper will illustrate the link between global aircraft level optimisation and local system optimisation to find a global optimum on aircraft level. Furthermore, the local system optimisation is described in detail for ECS.

2. MODELLING AND SIMULATION LIBRARY

The modelling and simulation library was developed further since the last publication. The changes that are relevant for the current subject are therefore reviewed. Furthermore, the library was validated against data on a conventional Three Wheel Bootstrap ECS. For more information on ECS in general and the modelling and simulation library the reader is referred to [1].

2.1. Parametric Component Models

An objective of the present work is to identify environmental control architectures that are optimal with respect to fuel burn on aircraft level. To do so, all components of such architecture must be parameterised with performance dependent parameters, relating component performance and weight.

The heat exchanger models fall into this category. Models were developed to establish heat transfer and component weight based on heat exchanger spatial dimensions and fin parameters. Most of them used the NTU effectiveness approach and pressure drop correlations outlined in [2]. The heat exchanger weight is established based on geometry and additional regression factors.

The turbo machinery is equally important for conventional ECS. Therefore, parametric radial turbo compressor and radial turbine models were developed. Both use characteristic maps that were established off line. They are scaled using two physics-based scaling factors each to modify the design point of these components. The weight of the turbo machinery assembly is established based on regression factors.

To cope for ECS architectures using vapour cycle technology for generation of cooling power, parametric condenser and evaporator models have been developed. The same principles as for air to air heat exchangers have been applied. In addition parametric models for refrigerant compressors have been developed. Those models use main geometric parameters and nominal performance as scaling factors. Weight estimation is performed on regression factors as for air turbo machine components.

2.2. The Three Wheel Bootstrap Architecture

The general concepts of different air cycles have been introduced in[1]. This work focuses on a particular Three Wheel Bootstrap Cycle with high pressure water separation as shown in FIG 1. In order to provide the reader with a self-contained article this cycle is discussed in this work. For further details the reader is referred to [1].

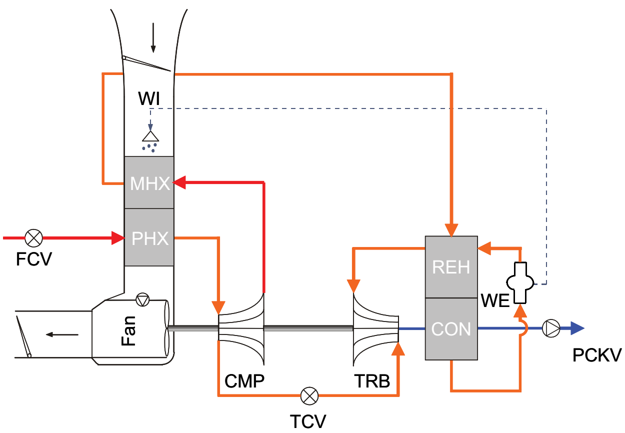

FIG 1. Three Wheel Bootstrap ECS, schematic

In the Three Wheel Bootstrap Cycle ECS, a Flow Control Valve (FCV) restrains the amount of bleed air going to the packs and the temperature control system (not shown in the schematic). In the Primary Heat Exchanger (PHX) the bleed air flow is cooled by ram air. In the Compressor (CMP) it is then compressed. The Primary Heat Exchanger keeps the compressor outlet temperature within the material constraints of aluminium alloys. After compression the air flow enters the Main Heat Exchanger (MHX) where it is cooled further by ram air. The air flow then enters the high pressure water separation loop, which consists of the Reheater and Condenser heat exchangers (REH and CON) and the Water Extractor (WE). In both heat exchangers the air flow is cooled down such that the water in the moisture laden air condensates before entering the Water Extractor. In order to lower the adverse effect on ACM performance of cooling the air flow with the turbine outlet air flow, the Reheater is used to recover energy. The air flow is expanded in the Turbine (TRB) and passes the cold side of the Condenser. Through the Pack Check Valve (PCKV) the conditioned air flow is discharged towards the mixing unit. The pack discharge temperature is controlled via the Temperature Control Valve (TCV).

2.3. Validation

Model validation is conducted on the basis of the Three Wheel Bootstrap Cycle ECS in a two step approach. In the first step model parameters are purely based on fixed performance characteristics for heat exchangers and turbo machines, as the major components of the air cycle. Those data have been taken from lab test performed at supplier benches. Ram air channel performance data are based on empirical data as well.

TAB 1 shows relative deviations for major properties from existing air cycle data for 2 cases:

Case 1): normal flight case (C35H2)

- Altitude: 35,000 ft
- Mach Number: 0.78
- Ambient temperature: -31.5°C
- Ambient pressure: 238 hPa
- 100% Air Cycle Flow
- Pack Discharge Temperature: -11.8 °C

Case 2): maximum performance flight case (C39H1)

- Altitude: 39,000 ft
- Mach Number: 0.78
- Ambient temperature: -33.5°C
- Ambient pressure: 197 hPa
- 120 % Air Cycle Flow (single pack operation)
- Pack Discharge Temperature: -38.8 °C

	P_FCV [hPa]	T_PHX_ out [°C]	T_MHX_ out [°C]	Ram Flow [kg/s]	Pi_cmp [-]	1/Pi_trb [-]
Case 1 Rel err [%]	-6.9	-0.8	-1.8	8.5	0.7	- 5.7
Case 2 Rel err [%]	-5.3	1.0	-1.0	4.4	-3.9	-10.6

TAB 1. Comparison of existing air cycle data with mapped heat exchanger models

In the second step all four heat exchanger models are replaced by models based on geometrical data taken from the original equipment. Internal heat exchanger surface is a function of the fin density of the heat exchanger. This parameter is not directly available and is correlated to available air cycle data using a larger number of flight cases than the two cases shown here. Turbo machine models are unchanged.

TAB 2 shows relative deviations for major properties using geometric heat exchanger models.

	P_FCV [hPa]	T_PHX_ out [°C]	T_MHX_ out [°C]	Ram Flow [kg/s]	Pi_cmp [-]	1/Pi_trb [-]
Case 1 Rel err [%]	-7.5	0.2	-0.3	-2.8	-3	- 2.8
Case 2 Rel err [%]	-10	0.2	-0.2	-7	-2.7	-6.5

TAB 2. Comparison of existing air cycle data with geometric heat exchanger models

For heat exchangers relative errors are below 2%, for FCV pressure and turbine ratio, relative errors are between 3% and 10%. Those two properties are linked, because turbine inlet pressure is mainly determining the FCV pressure. Overall range of errors is acceptable, as this library is used during early concept phases of aircraft system design.

Accuracy between first and second step is comparable with the exception of flow control valve outlet pressures. This is related to the difficult pressure drop description for finned heat exchangers, which needs to be improved. As a conclusion parameterised models could be used without loosing too much accuracy. This is a prerequisite for using the described library in an optimisation framework.

3. INTERACTION OF AIRCRAFT SYSTEM AND LOCAL SYSTEM OPTIMISATION

The focus of this work is on elaborating the local system optimisation process outlined in section 4. But local optimisation processes for systems not linked to optimisation on aircraft level will fail to reach optimal aircraft system configurations. Thus it is crucial for the local system optimisation to take the influence of design decisions and system sizing on aircraft level into account.

Optimising all aircraft systems in a single process with a single tool is beyond current capabilities. In this work, the complexity of this task is addressed via a heterogeneous optimisation process, separated into two major processes. Some steps in this task include classical numerical optimisation; other steps include selection of the best alternative among a given number of combinations.

The core of the task is an energy system sizing step followed by the assessment of the resulting energy system.

3.1. Global Aircraft System Optimisation Process

The objective of the global optimisation process is to optimise energy systems on aircraft level in terms of fuel consumption, weight, costs and finally net present value for the customer. Briefly it consists of the following steps.

1) *Consumer systems* like actuators, ECS, Wing Ice Protection System (WIPS) and Commercial Loads are sized to aircraft high level requirements. Input to this process is an energy system configuration, which comprises feasible combinations of system architectures. The topology of such architecture is fixed but design parameters shall be changed during the process. For simple consumer systems (e.g. WIPS) system sizing can be conducted in the frame of the global aircraft system optimisation process. For complex systems a local process is conducted to find optimised system architecture, because a trade off between important design parameters has to be done. This is the Local System Optimisation described in section 3.2. The trade off between design parameters is described in more detail in section 4.1.
   The results of this step are the sizing power requirements and the weight of the consumer systems, where complex systems are already pre-optimised. Additional data for cost assessment are provided for each system architecture/technology.
2) Depending on power requirements of consumer systems, *distribution systems* are sized. If required, a local optimisation process is conducted to find pre-optimised distribution system architectures. This results in power requirements and weight of distribution systems. As for consumer systems additional cost data are provided.
3) Based on reference aircraft weight, aircraft performance and updated energy system power demand, weight and drag count estimation, the required thrust is determined.
4) Based on thrust, noise, installation and other requirements and secondary power off-takes the aircraft engine as major *generation system* is optimised in a local process. As a result a model of the sized engine, its weight and cost data is available.
5) Power demands are calculated for an evaluation mission based on sized consumer and distribution systems.
6) With given power demands, drag counts and weights required thrust for evaluation mission is determined.
7) Finally, mission fuel burn can be computed for the evaluation mission.
8) Then, the aircraft is resized to meet aircraft

performance requirements due to updated fuel capacity and system weights and the process is continued from step 3) until convergence.

As a result, (updated) values for SFC and Mission Block Fuel sensitivities for power off-takes, weight and drag counts can be provided to local system sizing or optimisation processes. Those data ensure proper consideration of aircraft aspects on local system level.

3.2. Local System Optimisation Process

Consumer, distribution and generation systems are sized or optimised in local processes, which consider details of the respective systems and provide an optimisation environment for multi objective optimisation of complex systems. To optimise systems taking aircraft constraints and dependencies into account, sensitivity data for SFC and Mission Block Fuel are provided by the global aircraft system optimisation process. For distribution systems and energy management systems like electrical or thermal management systems peak power and power profiles from consumer systems are provided.

1) The system technology and the topology of the system architecture are provided as input to the local optimisation process. The most promising system architectures are modelled in the required level of detail to cover the relevant system design parameters.
2) Relevant design points are combined with the evaluation mission into combined mission, which is evaluated during the optimisation process.
3) To start the system architecture optimisation, parameters, which are sizing the architecture like geometric data are selected. Resulting weight for this architecture is calculated.
4) For a given set of architecture parameters the operational system parameters, which can be controlled by the system, are optimised with respect to power consumption for each point of the evaluation mission. For new technologies power optimal system control is not known in the beginning. Optimisation is therefore also utilised to find the best control strategy and to compare different technologies under the assumption of power optimised system control. Power demands for all points of the combined mission are calculated. It is checked whether design constraints and performance requirements are met with the current set of architecture parameters.
5) From all points of the evaluation mission the mission block fuel is calculated.
6) Based on mission block fuel values and design constraints the optimisation algorithm chooses a modified set of architecture parameter values and continues from step 4) until convergence.

As result an energy optimised system architecture is available, which reflects the impact of power off-takes on aircraft level. This architecture is used as input to the global aircraft system optimisation process. The resulting power demands for consumer systems have to be made available to local optimisation processes of distribution and generation systems, to ensure consistency of data for all involved systems.

The global optimisation process and the related local system optimisation processes are repeated until systems and global aircraft system configuration converge to a stable state. As a result the most energy efficient system architecture on aircraft level is found. A high number of system architectures and possible combinations are assessed and optimised in terms of fuel efficiency. Snowball effects are considered and system configurations are evaluated under comparable conditions. Additional data like cost figures are available to assess the net present value of the different aircraft configurations.

In the present work local system optimization is performed directly minimising fuel consumption on aircraft level. Based on constructal theory [4] methods for optimizing ECS on aircraft have been proposed [5]. Such methods are aiming at minimizing entropy generation of involved components, leading to fuel optimized systems. The intended outcome of such methods from aircraft perspective is comparable to the method presented here. The advantage of the present work is the direct re-use of performance models and the easy introduction of arbitrary additional design constraints, which don't require model changes, because they are handled in the optimisation framework.

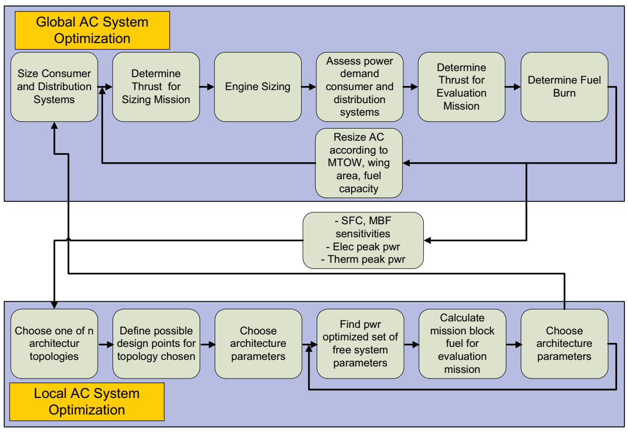

FIG 2. Link between global aircraft system optimisation and local system optimisation process

4. OPTIMISATION OF ECS ARCHITECTURES

According to the terminology introduced in section 3, the optimisation of ECS is performed on a local system optimisation platform. In this section, some formal characteristics of the optimisation problem and associated challenges are discussed. Then, typical elements of an implementation of such a platform are reviewed. Finally, illustrative results are presented.

4.1. Implicit Sizing

A challenge in optimisation of ECS architectures lies in the sizing process of the components, which is not explicit. That is, a given set of functional requirements does not lead *directly* to a sizing of the system components. In some domains, this is different. For Wing Ice Protection Systems (WIPS) for example, explicit sizing is possible via the Extend of Protection and technology parameters. For architectural models of Electric Power Generation and

Distribution Systems, performance metrics such as power or current to be provided by a given component lead to an explicit sizing of said components. Dealing with systems, where explicit sizing rules exist for the level of detail under investigation, a more direct approach for global aircraft system optimisation could be used, compared to the one presented in section 3. Such a method has been published in a recent paper [6].

For ECS design such explicit sizing rules are only available for a set of conventional architectures (e.g. the one illustrated in FIG 1). The methods discussed in this work need to scale up to unconventional architectures however, for which such explicit sizing processes are not established. Furthermore, an additional aspect has to be considered.

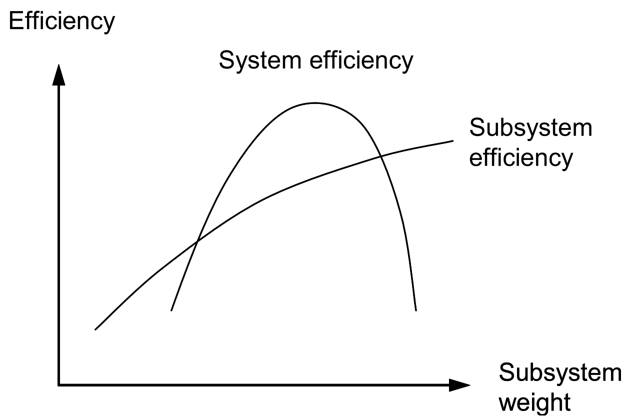

FIG 3. System efficiency has a maximum at optimum trade-off between subsystem efficiency and weight

In reality, the sizing process of an airborne system involves a trade-off between sub-system efficiencies and sub-system weights. As illustrated in FIG 3, maximum subsystem efficiency (e.g. ECS energy efficiency) does usually not correspond to maximum system efficiency (i.e. aircraft fuel burn). For the systems, which are sized explicitly, this trade-off can be factored out of the design process. This may be the case, because efficiency is more a technology parameter than a question of the size of a component. For ECS architecture, this is different. A heat exchanger becomes, independently of the particular technology employed, more efficient if the heat transfer surface and thus its size increases.

For the applications considered here, the conclusion is obvious. The trade-off between subsystem weight and its efficiency for maximum system efficiency cannot be found *a priori* but has to be investigated for each design separately. This leads to an implicit sizing process and the requirement for an elaborate optimisation process to design ECS architectures.

4.2. Control Variables

Before providing a somewhat formal definition of the problem to be solved, the scope of the optimisation problem shall be investigated. For this purpose, it has to be noted that a simulation problem of an ECS plant model *by itself* is not a well-defined (i.e. square) problem, because control variables need to be defined (e.g. the valve position of the Temperature Control Valve of the Three Wheel Bootstrap ECS shown in FIG 1). The question arises of how to choose these control variables during optimisation of ECS architecture. It is noted that if some control logic for a specific architecture is known, it is obviously possible to establish the control variables based on this logic. Whenever unconventional architectures are investigated, such control logic is not known. Then, a sequential approach of first establishing and implementing appropriate control logic and then optimising the architecture is considered time-consuming. Therefore, an obvious choice is to do so in parallel. Consequently, the optimisation problem has to cover both the actual architecture optimisation and the definition of control logic.

4.3. Optimisation Problem

Formally, an optimisation problem is described by a set of design variables (also called tuners), inequality or equality constraints, and objective functions. These are discussed step by step in order to define the problem to be solved herein.

Based on the remarks made in the preceding section, the set of *design variables* consists of variables describing the architecture and ones defining the operation of the system on a given evaluation or sizing mission. Architecture design variables can be continuous variables (e.g. heat exchanger dimensions) or discrete (e.g. Engine Bleed Air System (EBAS) stages, the number of the compressor stage at which intermediate or high pressure air is bled from the engine). The set of potential architecture design variables is defined by the architecture itself and by the modelling hypotheses of the components used in the simulation model (c.f. section 2.1).

The set of design variables defining the operation of the system on the evaluation mission similarly depends on the architecture. For the Three Wheel Bootstrap ECS shown in FIG 1, these are the position of the Temperature Control Valve and of the Ram Air Channel actuators (RAC). Additionally, the precise set of control variables depends on whether a direct model (calculating in performance direction) or an inverse model is used. For the former, usually the whole set of control variables has to be established, for the latter only a subset. In this work, only direct models were used for optimisation, because they can be evaluated for architectures, which do not fulfil all performance requirements. As the optimiser reduces the excess performance available in a design in order to reduce weight, such infeasible designs are routinely suggested by the optimiser. If, however, an inverse model is evaluated with, e.g. a pack discharge temperature below the minimum discharge temperature, the evaluation will fail and the optimiser cannot be returned a value quantifying how infeasible the architecture is. A direct model in turn will return the minimum discharge temperature and its deviation from the demanded discharge temperature is an exact means of quantifying how infeasible the architecture is.

Constraints are typically present with respect to the operation of the ECS system. When establishing the control strategy, inequality constraints have typically to be respected (e.g. on maximum temperatures due to the usage of aluminium alloys or on maximum water content of the pack discharge). Additionally, equality constraints may be present in optimisation problems utilizing direct models (e.g. on pack discharge temperature).

The top-level *objective* of the optimisation problem is, for example, aircraft level energy efficiency expressed by mission block fuel. Additionally, ECS system weight is usually of interest. As illustrated in FIG 3, ECS system weight is not an aircraft level optimisation metric. Nevertheless system weight is an important issue during system development. Therefore, the given objectives can be understood as a trade-off between aircraft and system level criteria.

Formally, the resulting problem is a Mixed Integer Nonlinear Programming problem (MINLP). Furthermore, it is typically a multi-objective problem, for which the entire Pareto Front has to be established. Then, management has to agree to a compromise between the top level objectives (i.e. a point on the Pareto Front). Finally, the problem is expected to exhibit multi-modal behaviour (i.e. be non-convex). The given three properties of the problem, together with the high number of design variables (approximately ten to 20 architecture variables plus two to five control variables for ten to 15 mission segments, that is, 30 to 95 design variables) yield an optimisation problem, which is prohibitively expensive to evaluate using state of the art algorithms.

4.4. Implementation

Analysis reveals that some of the properties of the problem that make it difficult to solve are either related to the architecture design variables or the control design variables. For example, the set of discrete design variables contains only architecture design variables. Furthermore, the criteria that are exclusively a function of the control variables are mostly convex (even though local extrema were observed in some cases). Due to these distinct properties and the complexity of the problem no direct solution of the problem was attempted. Instead, it is suggested to re-factor the problem into two parts: First, the architecture optimisation problem itself, and second, an optimal open loop control problem of the architecture for different operating conditions. It is possible to do so, because the trade-off between ECS energy efficiency and weight, which shall be balanced by the architecture optimiser for best possible aircraft energy efficiency, is not affected by the particular choice of the operating point of the ECS in the open loop control problem. This is directly visible in FIG 3. The architecture design variables cover all factors sizing the components of the ECS (e.g. heat exchanger dimensions). Therefore, as soon as a vector of design variables has been suggested by the architecture optimiser, the value on the abscissa is already fixed (ECS weight). The open loop control problem does not need to know about the multi-objective nature of the optimisation problem. It may simply search for operating point with maximum aircraft level energy efficiency (ordinate value). As metric for aircraft level energy efficiency in a specific mission segment the authors use specific fuel consumption (a typical aircraft level energy efficiency objective is mission block fuel, which is minimised when minimising the specific fuel consumption of the mission segments).

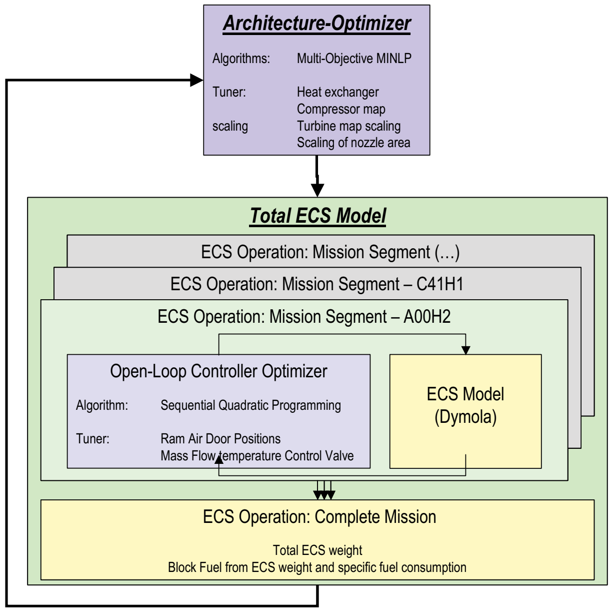

FIG 4. Bi-level approach to ECS optimisation

The suggested procedure is as follows: The optimal open loop control aims at finding the lowest specific fuel consumption for each segment of a predefined flight mission by varying the actuators of the ECS (in FIG 4, this is the inner loop of the open-loop control optimiser and the ECS model). This problem has to be solved for all segments of the mission. Afterwards, the results are used to establish the mission block fuel based on the ECS weight and the specific fuel consumptions (in FIG 4, this is the mission evaluation model on the lower right). Then, the complete ECS architecture model ("Total ECS Model" in FIG 4) is run by the architecture optimiser. This algorithm varies the architecture design variables to search for the Pareto Front of the given objectives in general and the global minimum of block fuel consumption in particular. This process is repeated until convergence.

The problem was implemented utilizing the Multi-Objective Parameter Synthesis software [3], MOPS. The software provides several key features such as state-of-the-art optimisation algorithms and transparent parallelisation for High Performance Computing clusters. The open loop control problem is implemented as a normal multi-case model in MOPS. The mission assessment and computation of mission block fuel is realized as a final model. Finally, the architecture optimisation is implemented as a normal model.

4.4.1. Optimal Open Loop Control Problem

In order to discuss the implementation in some detail, the conventional Three Wheel Bootstrap ECS shown in FIG 1 is taken as example for the remainder of this section. The plant model is called semi-inverse, as the pack discharge temperature is calculated as in a direct model and the pack discharge pressure is prescribed as in an inverse model.

Following the reasoning outlined in the last section, the generic open loop control problem solves for minimum specific fuel consumption (SFC). It is solved for all regular mission segments. For the Three Wheel Bootstrap ECS, the architecture parameters (e.g. the geometry, the compressor stages of the HP and IP bleed ports) have to be known. These data are furnished by the architecture optimisation discussed below. Additionally, several parameters describing the ambient conditions have to be provided. Furthermore, the aircraft altitude and the demanded pack discharge pressure have to be provided (the latter for example may be established from the models of the mix manifold, air distribution network, and cabin or be prescribed via tables calculated separately). Therefore, the optimisation problem is as follows.

MINIMISE	Specific fuel consumption
GIVEN	Architecture parameters EBAS stages Ambient conditions $T_{dis,demanded}$
SUBJECT TO	$T_{cmp2} \leq T_{cmp2,max}$ $x_{dis} \leq x_{dis,max}$ $T_{WE} \geq T_{WE,min}$
AND	$T_{dis} = T_{dis,demanded}$
BY VARYING	Ram air channel actuator (RAC) Temperature Control Valve (TCV)

Here, $T_{dis,demanded}$ is the demanded pack discharge temperature. T_{cmp2} and $T_{cmp2,max}$ are the actual and the maximum compressor outlet temperatures (these constraints are due to material properties of aluminium alloys). Similarly, x_{dis} and $x_{dis,max}$ are the actual and the maximum water content at pack discharge. Variables T_{WE} and $T_{WE,min}$ are the actual and the minimum permissible temperature in the water extractor. Finally, T_{dis} is the actual pack discharge temperature.

During the architecture optimisation of the Three Wheel Bootstrap architecture, this generic open loop control problem is solved for most regular cases. Alternatively, two other set-ups are used to establish control parameters. One of them is solved for all failure cases. These are the cases with only one engine operational. It is considered important that the ECS is able to provide the required performance in these cases, but the specific fuel consumption is not relevant. Consequently, in this open loop control problem, the objective function is not the specific fuel consumption but the deviation of the actual discharge temperature from the demanded pack discharge temperature. The other set-up is used for top of descent to ensure minimum pressure for cabin pressurisation.

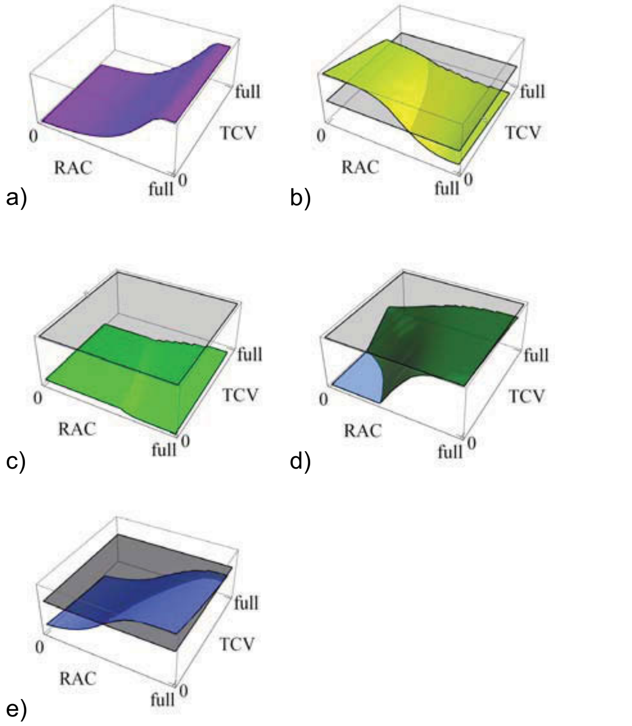

FIG 5. Exemplary topology for C35H2, three dimensional illustrations: Criteria on a) SFC, b) compressor outlet temperature, c) water content at pack discharge, d) water extractor inlet temperature, e) pack discharge temperature

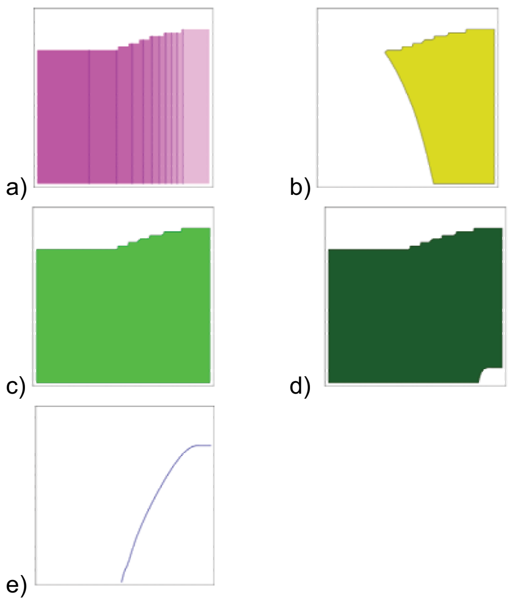

FIG 6. Exemplary topology for C35H2, two dimensional illustrations: Criteria on a) SFC, b) compressor outlet temperature, c) water content at pack discharge, d) water extractor inlet temperature, e) pack discharge temperature

In order to accelerate convergence, and due to the mostly well-behaved topologies observed for the open loop control problems, a sequential quadratic programming (SQP) algorithm of [3] is used. In order to deal with the mildly non-convex topologies a multiple starting point approach is used, which seems to offer a suitable compromise between computational expense and robustness.

In FIG 5 and FIG 6, an exemplary topology is shown for the optimal open loop control problem. It refers to a cruise case at 35,000 ft altitude, hot ambient conditions and normal operation. Figures a) to d) show the objective to minimise SFC, the inequality constraint on compressor outlet temperature, water content at pack discharge, and temperature in the water separator are shown, e) shows the equality constraint on pack discharge temperature. All these values are shown both in three dimensions (FIG 5) and in two dimensions (FIG 6). In three dimensions, the objective or, respectively, the normalised constraint value (coloured) is shown together with the reference value (grey). The constraint has to maintain a value below of (for inequality constraints) or equal to (for equality constraints) the reference value. In the two dimensional plots, a contour plot of the objective (the lighter the worse), or the region in which the constraint is fulfilled is shown.

The equality constraint on pack discharge temperature shown in e) effectively restricts the subspace to be considered by the optimiser to a one dimensional manifold. Only the line shown in e) of FIG 6 fulfils this criterion. The inequalities on water content at pack discharge and water separator temperature are not relevant for flight cases due to low ambient humidity in high altitudes. However, the compressor outlet temperature may not grow beyond a specific value, which renders the lower left of the one dimensional manifold fulfilling the equality constraint infeasible. Comparing the objective to be minimised to the latter, one can infer that the optimum for this particular optimal open loop control problem is at precisely this location, namely, at medium RAC mass flow and nearly zero mass flow rate through the TCV (upon a further reduction of the TCV flow, the compressor outlet temperature would then grow beyond the prescribed limit).

This behaviour exactly mimics the established Three Wheel Bootstrap ECS control logic. In a normal cruise case, the ram air channel doors are closed as much as possible while maintaining the maximum allowed compressor outlet temperature.

4.4.2. Architecture Problem

When solving the optimal open loop control problem for each of the mission segments involved and establishing mission block fuel based on the results, all top-level optimisation objectives are available for a given architecture. The outer loop shown FIG 4 contains the complete ECS architecture model, which is driven by the architecture optimisation algorithm. This is typically a global, gradient-free algorithm suitable for MINLP optimisation problems.

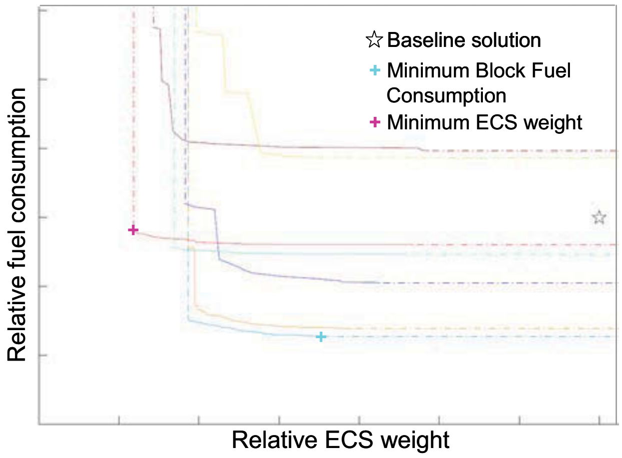

FIG 7. ECS architecture optimisation Pareto Front

An exemplary result of this ECS architecture optimisation is shown in FIG 7. This figure illustrates the trade-off between the aircraft level energy efficiency metric mission block fuel and the system level metric ECS weight in terms of a Pareto Front. Between the two extremes of minimum block fuel consumption (cyan) and minimum ECS weight (magenta), many other compromises are possible. However, in order to improve one metric of the ECS, one has to deteriorate the other (Pareto Optimality).

The typical wall time on a 32 node HPC cluster at DLR Institute of Robotics and Mechatronics is four to five weeks for a solution to a problem like the one illustrated in FIG 7.

With the availability of these results, the local system optimisation is complete. The results obviously depend on the exchange rates provided for the baseline aircraft by the aircraft optimisation platform discussed in section 3. Optionally, the global aircraft system optimisation platform could now be used to conduct a re-sizing of the aircraft and thus to provide updated exchange rates.

5. CONCLUSIONS

Based on parameterized component models for environmental control systems a powerful method for direct optimisation of ECS architectures has been developed. The presented optimisation method is using the component models without modifications or simplifications. Component models and model topology used during performance assessment of a given ECS architecture are directly used for optimisation of such architecture. The resulting optimisation method provides a flexible and comprehensive way of improving ECS architectures based on new technologies. In addition to the optimum parameter sets found by optimisation and the resulting Pareto fronts for the multi-objective optimisation problem, the tool provides a powerful method for detailed exploration of the design space. This supports better understanding of the sensitivities of design parameters, especially important for new architectures.

The presented bi-level local system optimisation approach includes design variables determining system operation, which ensures comparison of different ECS architectures in their respective operational optimum. Furthermore this supports development of an optimal control strategy for new systems in early development phases.

The developed method of local system optimisation has been coupled to optimisation of global aircraft systems by using exchange rates for energy and weight calculated at the global platform for local system optimisation and by providing pre-optimised system models from the local optimisation platform to the global one. This leads to local system architectures, which are optimised on aircraft level. An overall iterative process has been presented, which considers snowball effects due to aircraft re-sizing and provides a framework for comprehensive optimisation of energy system on aircraft level.

6. ACKNOWLEDGEMENTS

This research is performed in collaboration between Airbus Operations GmbH and Deutsches Zentrum für Luft- und Raumfahrt.

This project has been performed within LUFO IV project EFFESYS, funded by German BMWA.

The third author proposed and implemented the ECS optimisation method discussed in section 4.

REFERENCES

[1] M. Sielemann, T. Giese, B. Oehler, M. Otter (2007): “A Flexible Toolkit for the design of environmental control system architectures”. In: Proceedings of the First CEAS European Air and Space Conference. CEAS 2007, September 10th to 13th 2007, Berlin.

[2] W. M. Kays, A. L. London, Compact Heat Exchangers, Krieger Publishing Company, 1998.

[3] H.-D. Joos, J. Bals, G. Looye, K. Schnepper, A. Varga: “A Multi-Objective Optimisation-Based Software Environment for Control Systems Design”, Proceedings of the IEEE CADCS Symposium, 2002, Glasgow, Pages 7-14.

[4] A. Bejan, “Shape and Structure, from Engineering to Nature”, Cambridge University Press, Cambridge 2000.

[5] J. Vargas, A. Bejan, “Integrative thermodynamic optimization of the environmental control system of an aircraft”, Int. Journal of Heat and Mass Transfer, 44 (2001), p. 3907-3917.

[6] S. Liscouet-Hanke, S. Pufe: “Simulation Framework for Aircraft Power System Architecting”. Journal of Aircraft, Vol. 46, No. 4, July-August 2009, p. 1375-1380.