A FLEXIBLE TOOLKIT FOR THE DESIGN OF ENVIRONMENTAL CONTROL SYSTEM ARCHITECTURES

M. Sielemann[†], T. Giese[‡], B. Öhler[‡], M. Otter[†]

[†] German Aerospace Centre (DLR)
Institute of Robotics and Mechatronics
82234 Wessling
Germany

[‡] Airbus Deutschland GmbH
Air System Technology and Processes
21129 Hamburg
Germany

OVERVIEW

One of the core systems in a conventional or More Electric Aircraft (MEA) is the environmental control system (ECS). It is either the key consumer of pneumatic power or draws a substantial load from the electric power system. Therefore, it is crucial for the trade-off between aircraft and engine design and an important element of a tool to assess system architectures at aircraft level. Drawing on these findings, this paper presents the development of a dedicated simulation tool to evaluate potential ECS architectures in conceptual design with respect to system weight and performance metrics such as electrical power demand or engine bleed air mass flow.

1. INTRODUCTION

In the quest for reduced operating costs and environmental impact of commercial aircraft the potential of reducing *system power usage* has become apparent. For various reasons, electrification of those systems is considered as a promising route. Due to the substantial impact on related systems and the need to improve overall platform performance, such technology infusions have to be assessed from a perspective that is as global as possible.

Current industry practice for this type of problems is the trade study. Using functional requirements and, for example, a morphological matrix, candidate configurations are synthesised. Then, a mathematical model is developed to represent the system behaviour for each candidate configuration and optimization algorithms are used to size components. This leads to systems that are optimal with respect to certain figures of merit and operational conditions. Then, the most advantageous system architecture is selected.

The implementation of mathematical models requires a large portion of the resources available to such trade studies and the limitation of these resources restricts the number of candidate configurations that can be evaluated thoroughly. This research aims at creating a tool that allows the creation and adaptation of such models at reduced turn-around times. Using the object-oriented modelling and simulation language Modelica, highly modular models can be formulated in an acausal fashion. The user can change model assumptions, architecture features, model causality and the like. Based on the modelling and simulation kernel, an interactive environment providing GUI elements such as sliders, control lamps and plots are provided. This supports the project engineer in gaining a thorough understanding of the architecture he is looking at and to investigate the implications of control strategies and operational modes of the architecture. Additionally, Modelica provides an open platform in which, due to standard connector definitions, an ECS model can later be plugged together with another one modelling, for example, the electric power system.

2. THE ENVIRONMENTAL CONTROL SYSTEM

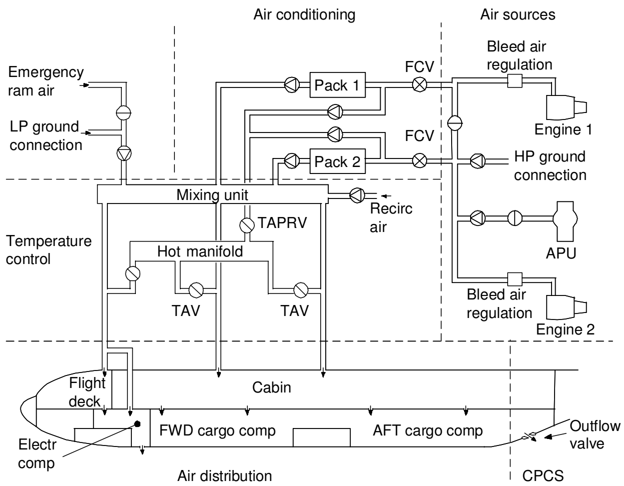


FIG 1. Conventional ECS architecture [1]

A conventional ECS consists of the following subsystems (see FIG 1): Air conditioning system (ACS), temperature control system (TCS), ventilation control system (VCS), air distribution system, and cabin pressure control system (CPCS). Additionally, optional systems such as combined ozone / VOC converters (VOZC), humidification systems (HUM), or dry air generation systems (DAGS) can be installed on an ECS.

The primary function of the environmental control system is to establish an environment that addresses the physiological needs and comfort requests of the passengers and crew. These tasks require the following functions: Control temperature and humidity and regulate cabin pressurization. Provide de- or anti-icing capabilities. Ensure sufficient ventilation and fresh air and remove pollutants.

2.1. Overview

The central component of the ECS is the air generation unit (also called pack), which is the device used to condition the air flow. Usually, two air generation units are installed in an aircraft. Traditionally, they use engine bleed air as power source. At the start of the jet engine age, thrust was created by high exit velocity. The total mass flow passed through the core of the engine and the engine cycle itself was not very efficient. Consequently the cost of bleeding air for use in systems such as the ECS was small.

The compressor stage, at which bleed air is extracted, is selected based upon the maximum pressure requirement of the ECS and the wing ice protection system (WIPS). Due to the disparate segments of the aircraft mission, the pressure at the different stages varies remarkably and a single bleed port design would be rather inefficient. Therefore, two bleed ports are typically installed in the engine compressor (high and intermediate pressure). The system implementing the bleed air off take is called the engine bleed air system (EBAS). It provides bleed air primarily to the ECS and pneumatic WIPS.

The pack provides conditioned air to the flight deck, cabin, and cargo compartment. In the different classes of the cabin, in the flight deck, and in the cargo compartments the number of passengers and the amount of payload vary more and more as the commercial aircraft become larger and more sophisticated. In order to provide conditioned air to all of those compartments, the conditioned air flows from the packs are mixed in a dedicated volume. This is called the mixing unit. From there, supply ducts carry the conditioned air to the compartments. Herein, the design principle is to maintain a constant volume flow rate. Therefore, every supply duct is calibrated with a fixed orifice. Large commercial aircraft divide the cabin in up to eight zones per deck. The packs are controlled such that the mixing unit temperature fulfils the most demanding cooling requirement of the cabin zones. To meet the exact temperature requirements of all zones, hot trim air is mixed to the supply air in tappings. The system that implements and controls this process is the TCS.

The CPCS maintains the cabin pressurisation at a value, which depends on altitude and mission phase. It controls the outflow in the under-floor by means of dedicated outflow valves (OFVs). Here, a certain time derivative of pressure may not be exceeded in order to avoid irritation of the human ear.

Another important consumer of pneumatic power is the WIPS mentioned earlier. Currently, hot bleed air is used to heat the wing leading edge which prevents ice build-up.

Starting at the end of the 1960s, turbojet engines were superseded by turbofan engines. That is, the paradigm to create thrust by high exit velocities was surpassed by the concept to move larger mass flows using a bypass to the engine core. Engines drawing on this concept provided considerably improved propulsion efficiency but increased the cost of extracting bleed air from the engine core. In an effort to reduce these drawbacks, recirculation systems were designed. The approach is to use highly efficient filters to reduce the bleed air off take from the engine without compromising the cabin air quality. As a result, the fresh air and not the ventilation requirements drive the amount of pack air flow in modern ECS designs.

Nowadays, a general trend towards even higher bypass ratio engines is perceived. This development, together with the well-established inherent inefficiencies of bleeding air from the compressor stages (throttling of pressure and reducing the temperature below the auto-ignition temperature of fuel in the pressure regulating valve and the pre-cooler respectively) provides the main argument in favour of electric ECSs and reduced usage of pneumatic power on energy efficient aircraft in general.

To implement an electric ECS, two different approaches can be employed or combined. One option is to use ambient air instead of bleed air in air cycles and drive the associated turbo machinery electrically. This involves so called motorized compressors and motorized turbine compressors. The natural competitor to the air cycle is the well-established vapour compression cycle, as it almost generally has a higher efficiency (coefficient of performance, COP). Traditionally, vapour cycle systems are however associated with larger weights. In addition inlet air temperature on the condenser side varying over a wide range results in reduced COPs. Therefore vapour cycle systems are currently not used extensively in commercial aviation (an exception is supplemental cooling).

2.2. Air Cycles

As mentioned above, the air generation unit is the core component of the ECS. This section provides information on different conventional approaches (thermodynamic cycles) to implement an air cycle in such a device.

All air cycles are inspired by the reverse Joule cycle (also called reverse Brayton cycle) for open systems. They employ air compression (at least in the engine compressor), heat rejection at high temperature, and air expansion to cool below the ambient temperature. FIG 2 illustrates four classic air cycles. They are or were all used in conventional ECS consuming bleed air and represent different levels of sophistication. To the left, the simple air cycle is shown. It features a heat exchanger (HX), in which bleed air is cooled by ram air (this is generally reasonable for subsonic commercial aircraft). Then, the bleed air flow is expanded in a turbine (T) to meet the temperature requirements imposed on the pack. The mechanical power obtained in the expansion process is used to drive a fan (F), which propels the ram air flow across the heat exchanger, which is vital for ground operation. The simple air cycle requires high bleed pressure. At the same time the turbine is not well loaded, unless the fan is made inefficient. From today’s point of view, the simple air cycle is inefficient. This approach is used for the ECS aboard the Fokker 100, for example.

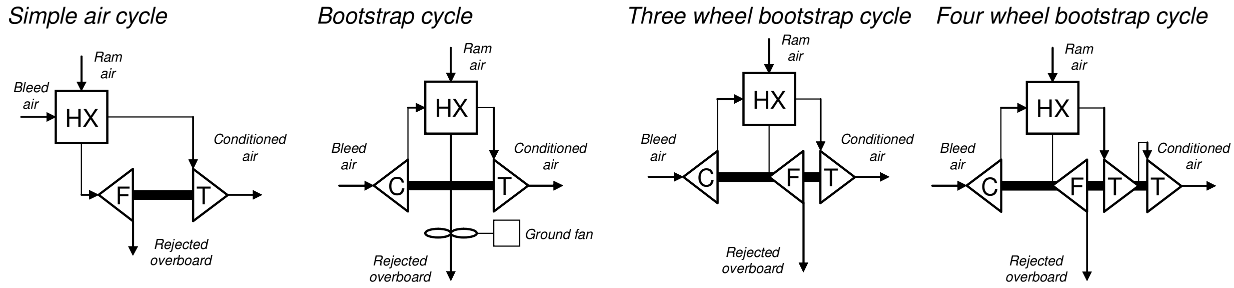


FIG 2. Typical air cycles used to condition air aboard commercial aircraft [8]

Next, the bootstrap cycle is shown. Before cooling the bleed air flow using ram air as heat sink, the hot engine air is compressed (C). Due to the higher temperature on the hot side of the heat exchanger (HX), the cycle becomes quite efficient. After cooling the bleed air, it is expanded in the turbine (T) and cooled below the ambient temperature. On ground, a fan is used to drive the ram air over the heat exchanger. It is usually driven electrically (e.g. Boeing 727) or pneumatically (e.g. Boeing 737 Classic).

Before continuing the discussion of the air cycles shown in FIG 2, the fundamental effects of water content in ambient air shall be addressed. As the ECS is concerned with conditioning air, which, in many cases, involves cooling, the temperature can sink below the saturation point. This results in condensation and free water in the moist air flow, which can theoretically happen in any ECS component (e.g. ice build up) or the cabin (e.g. fogging). Consequently, the function to control the humidity level mentioned in section 2.1 is vital for the reliable operation of the aircraft.

In determining candidate locations for the extraction of water, the question for the location of condensation comes up. It cannot be answered generally, as it depends on the specific cycle and exact operating conditions. One prediction can be made, however. As the lowest temperature is encountered downstream of the turbine, free water can certainly be found there. The placement of a water extractor at this location led to so called low pressure water separation designs. Usually, in the case of condensation, ice build up cannot be prevented by other means than limiting the turbine discharge temperature to 0 °C. The cooling capacity of such pack designs is therefore restricted. The apparent alternative is to install a water extractor upstream of the turbine. These designs are called high pressure water separation loops. The cooling capacity of a pack is not limited by ice build up and the higher pressure level supports the condensation of sufficient free water in the air flow. The only drawback of this layout is that a pair of additional heat exchangers is required to ensure high pack performance (the reheater and condenser).

An important technique to recover performance lost in the separation of water is to spray the extracted water in front of the heat exchangers into the ram air channel. The latent heat to evaporate the liquid water is extracted from the surrounding material, lowers the temperature of the ram air and thus increases pack performance.

This takes the discussion back to the air cycles shown in FIG 2. The three wheel bootstrap cycle combines the simple air cycle and the bootstrap cycle in that it features three wheels, the compressor (C), turbine (T), and ram air fan (F) on a single shaft. Even though the efficiency of this arrangement is slightly lower than that of the bootstrap cycle, this design has the advantage of being self-contained and not dependent on any other power source. The three wheel bootstrap cycle was first used on the Boeing 747 with low pressure water separation and is, using high pressure water separation, probably the most common pack configuration today (it is in use on the Airbus A320 and A330 / A340 families, the Boeing 757, 737NG, and on later versions of the Boeing 747 and early versions of the 767).

The four wheel bootstrap cycle (also called condensing cycle) shown to the right of FIG 2 is probably the most sophisticated conventional design to date. The general arrangement of components is similar to that of a three wheel bootstrap cycle. The main difference stems from conflicting requirements on the turbine of a three wheel bootstrap cycle. The high altitude cruise conditions mandate a different turbine design than the ground cases, in which the water separation is pivotal. In a four wheel bootstrap cycle, these two requirements can be emphasised in one turbine each. The first turbine is laid out such that it expands the air flow to a temperature a little above the freezing point (minimizing the required de- and anti-icing provisions). In the condenser heat exchanger, the latent heat of vaporisation required to condense water content on the hot side is injected to the cold air flow. The energy not recovered in the first turbine plus the latent heat of vaporisation is then retrieved in the second turbine. Additionally, the reheater heat exchanger is not required anymore. The four wheel bootstrap cycle provides different bypass paths to adapt the cycle to different ambient and operating conditions. Most prominently, at high altitudes, low pressure and humidity, an altitude valve can be opened to bypass both the high pressure water separator and the first turbine. This operates the cycle as a three wheel bootstrap cycle with an increased turbine nozzle area and decreases the restriction of the flow in the air cycle machine (ACM).

Even though the four wheel bootstrap cycle can be more efficient under certain conditions it seems to be a matter of philosophy whether to use a four or three wheel bootstrap cycle. The advantages of one cycle have to be traded off against the ones of the other on a case to case basis. This cycle is used today on the Airbus A380, the Boeing 777 and later 767 versions, and the Embraer EMB 170 / 190 family.

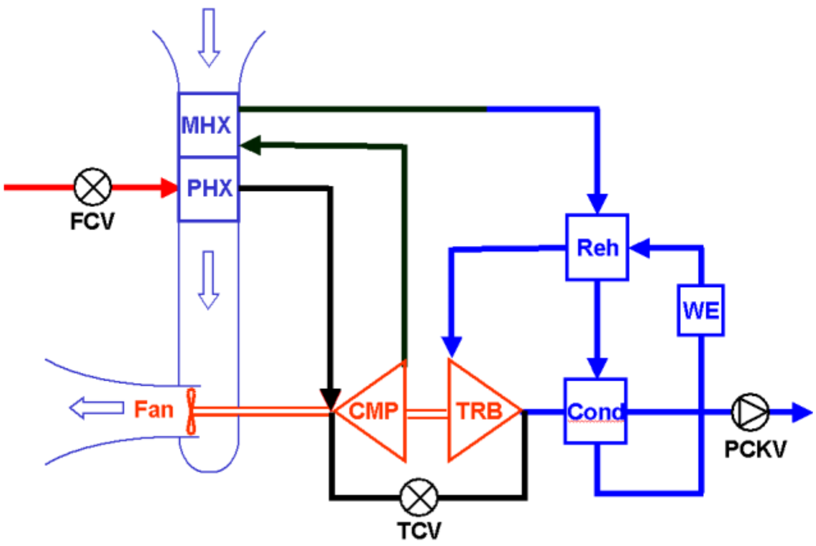


FIG 3. Components of a typical three wheel bootstrap air generation unit with high pressure water separation

2.3. Three wheel bootstrap Air Generation Unit

The general concepts of different air cycles have been introduced. To illustrate the components of an actual air generation unit, FIG 3 shows an exemplary three wheel bootstrap pack with high pressure water separation.

A flow control valve (FCV) controls the amount of bleed air going to the packs and the temperature control system (not shown in FIG 3). 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).

3. THE MODELING AND SIMULATION KERNEL

A purpose-built model library is at the very core of the toolkit for the design of ECSs presented herein. It is being implemented in the object-oriented modeling language Modelica and contains physical models in an acausal formulation. The library is modular and hierarchically structured. Therefore, basic component models are composed of elements of minimal complexity, such as control volumes or fluid inlets and outlets. In turn, they constitute component assemblies such as compressors, heat exchangers or cabin heat loads. Similarly, sub-system and system models are put together. All in all, they span five different domains of a complete ECS architecture model. These are the *Fuselage* domain covering the cabin, flight deck, and under-floor, *Air Mixing and Distribution*, the *Air Generation*, the *Ram Air Channel* and *Vapour Cycle and Electric Heating*. Using this toolkit, users can plug together various conventional and advanced ECS architectures using the graphical user interface of a Modelica environment. Here, much effort lies in providing a robust and flexible implementation that does not restrict the user to certain "allowed" combinations.

In architecture design of ECS it is natural to establish model causality starting with the functions to fulfil. Casting them into requirements allows the formulation of derived requirements for all other parts of the system. In comparison to earlier works such as Figliola et al. [5] or Vargas and Bejan [6], this approach is followed more rigorously, starting with, for example, a detailed cabin model.

Ordonez and Bejan [7] do consider a simple cabin model, which contains a lumped heat generation and heat transfer element. Based on that, they derive requirements on a mostly idealized pack model (reversible compression and expansion, no pressure drops on the heat exchanger). While their work is very interesting from a theoretical perspective, the presented trade-off between pack outlet temperature and pack mass flow is of limited practical value as it does not consider all relevant constraints. As highlighted in section 2.1 the pack mass flow rate is directly driven by the fresh air requirements due to the high cost of bleed air in terms of specific fuel consumption. These requirements are imposed by the certification authorities in JAR/FAR 25.831a.

New in comparison to earlier publications is that the model covers off-design performance. This is highly important in design as the system can only be optimized for a limited number of working conditions. It has to be evaluated however in a rather large number of different scenarios, in which certain performance goals have to be met, too. While other works (such as [5], [6], and [7]) present models based on constant efficiencies, the toolkit presented in this research uses either component performance maps or geometry based performance estimation.

3.1. Library Implementation

In this work, the connector definition of Modelica_Fluid [1] is used. Consequently, the following quantities are provided at the fluid interfaces: Absolute pressure, mass flow rate, specific enthalpy, enthalpy flow rate, mass fractions, and substance mass flow rate.

Most component models contain a number of control volumes. The most generic type of the latter has a heat and two fluid ports. The governing equations are the mass balances and the energy balance. A flag is used to specify these equations for transient or steady state conditions. Additionally, pressure is set to be equal on both sides of the control volume (a simplified momentum balance).

A second type of basic component is the pressure loss model. Currently, distributed friction coefficient, concentrated pressure drop and flow resistance based implementations are provided. There are no universal pressure loss models that cover both laminar and turbulent flow regimes. As it is known on a component to component basis whether laminar or turbulent flow will be encountered, the applicable pressure loss model will be selected to reduce model complexity.

The media models were implemented using the Modelica.Media [1] structure. As humidity is considered an important factor, a detailed moist air model was implemented for this work. It considers dry air and H_2O in gaseous, liquid and solid phases and uses pressure, specific enthalpy, and mass fraction as independent variables. It is implemented as a gas vapour mixture with temperature dependant specific heat capacities.

For the vapour cycle, a two-phase medium model of the coolant R134a is used. It implements the equation of state suggested by Baehr and Tillner-Roth [3] and was developed outside of this research.

As mentioned in the introduction of the present section 3, off-design calculations are routinely made with the library. Components can be modelled at three different levels of detail. They can utilize constant efficiencies, contain characteristic maps, or use geometry-based performance estimators. Characteristic maps are created in high-fidelity codes for individual geometries. Two or more variables are used to establish component performance and efficiency. Geometry-based performance estimators are algorithmic routines implemented in Modelica as `functions`. Based on handbook methods and proprietary data, they use geometric data and transport properties to establish performance and efficiency based on typical key parameters such as the number of transfer units for a heat exchanger. Currently, the library does not consider elements that were discretized in Modelica models using approaches such as the finite volume or finite element method due to the computational cost. In the present first iteration, the prospect of being able to study large design spaces is judged more valuable.

Due to the nature of early ECS architecture studies, mainly quasi-steady-state results are of interest. Here, the chosen formulation allows the execution of large numbers of scenarios at relatively low cost of computational time. To support this type of calculation, “perfect control”-logic is used in the library. Using the latter, different strategies for components can be defined. The behaviour is assumed to be ideal, and the architecture problem is simplified in that the design of the respective closed-loop control algorithms can be postponed to a later stage in the preliminary or detailed design process.

When building models using quasi-steady-state assumptions redundant equations can appear. Typically, a Modelica environment does not recognize the redundancy and protests that a model is overdetermined. In this case elements labelled line breakers are used. A simple example is the model of a closed loop with, say, three components A, B, and C. Three connections (AB, BC, CA) result in mass flow rate equality. At the same time, the mass flow rate into and out of each component has to be identical due to the steady-state assumption. Then, two mass flow rate equalities (say AB and BC) can be combined to yield the third one (CA). A line breaker removes such an equality equation but asserts its compliance. Similar elements are required in other occasions (e.g. for pressure in branching of ducts).

Robustness of the library is a major concern. Several provisions have been made to accomplish this goal. To understand them, it is important to keep the mathematical nature of the formulated problem in mind. Each component using steady-state assumptions is based on algebraic, not differential equations. Connecting them directly to each other creates systems of nonlinear equations. Usage of the present library to study complete ECS architectures results in models with medium to large systems of nonlinear equations. Some of the provisions made to ensure robustness are listed below.

- Explicit junctions are used to enforce coupling between the flow variables such as mass flow rate and substance mass flow rate.
- Complex thermodynamic systems might require laws that cannot be formulated explicitly, as various components have to contribute to their compliance. If a system additionally contains various loops, it might be advantageous to introduce constraints on, for example, the mass flow directions, if they are known in advance (e.g. bypass in a pack model).
- The `semiLinear` operator is ambiguous in specific enthalpy for zero mass flow. Consequently, it is not used in all model domains. Wherever it potentially affects robustness negatively (and no flow direction reversal has to be permitted), this operator is removed (e.g. trim air system). This improves robustness at events.
- The user is provided with template models containing replaceable sets of guess values, which serve as starting point for the nonlinear equation solver. The templates are exemplary system models that can be used as departing point for user models.
- During the development of each model, the complete range of all variables of a model were considered and it was made sure that it provides at least moderate results for all of them. This includes, for example, avoiding unreasonable extrapolation: As the nonlinear equation solver iterates, it potentially uses input values that are beyond the validity range of the model (even though the converged solution complies with the latter). To allow for robust convergence, it was made sure that the results always are at least in the correct order of magnitude.

3.2. Fuselage Package

The fuselage domain covers the flight deck, cabin, and under-floor. The models depicting them contain heat loads and sources of dissipated water. Based on temperature control logic and a demanded zone temperature the required blown temperature of the ventilating air flow is established.

FIG 4. A380 Cabin

The cabin is discretized into n control volumes (“areas”) along its longitudinal axis. Each of them is subject to the convective and radiative heat flow and the water dissipated by its occupants (passengers and cabin attendants). Additionally, external heat loads (such as conduction through skin, windows, and floor and radiation) and internal heat loads (such as reading and cabin lights, inflight entertainment devices, and galleys) have to be considered. In the cabin model, the pressure is typically set and, based on pressure loss elements, propagated from there to the other system components.

As an example of a load model, the inflight entertainment system (IFE) heat load model will illustrated. It models the heat dissipated by the IFE to the cabin ambient. Generally speaking, an inflight entertainment system is either completely switched off, in standby mode or operational in a given configuration. Additionally, a passenger might choose to operate a personal computer. The heat flow rates for the different operational states of the IFE and a typical portable computer are given as parameters among the global inputs discussed in section 3.7. Similarly, usage factors of the different modes are provided. Pulling these terms together brings about equation (1).

(1)
$$\dot{Q}_{IFE} = n_{seats} \cdot \dot{Q}_{pseat\_IFE\_standby} + n_{pax}\left(usage_{IFE} \cdot \dot{Q}_{ppax\_IFE\_operational} + usage_{PC} \cdot \dot{Q}_{ppax\_PC}\right)$$

The flight deck is represented by a single control volume. Similarly to the cabin, heat flow and water dissipation of the occupants (flight crew) are considered. The external heat load models implement similar physical phenomena but require slightly different assumption (e.g. conduction through the floor to the avionics compartment, variable transmission of radiation through the flight deck windows etc.).

The under-floor covers cargo and avionics compartments. In the present first iteration, it is modelled as boundary condition without a dedicated heat balance (i.e. no control volumes). At a later stage, it might be advantageous to model the heat transfer phenomena and include control volumes for the under-floor.

3.3. Air Mixing and Distribution Package

The mixing unit is the entity that joins the recirculation and pack air flows. Then, they are split into the ones running towards to the flight deck, cabin areas, and cargo compartment. Before entering all but the latter, the air must be heated or cooled to the required blown temperature using a conditioner. In a conventional architecture, this is a TAV.

The mixing unit is implemented using two different models; one is the mix manifold, the other the mix control. In the mix manifold, the actual mixing takes place, while the mix control sets the demanded pack mass flow rates and pack outlet temperatures. According to the mixer temperature strategy and the required blown temperatures of cabin areas and flight deck, the mix manifold chooses a certain temperature as manifold temperature. In a conventional architecture, this is the minimum required blown temperature (trim air can only be used to heat, not to cool).

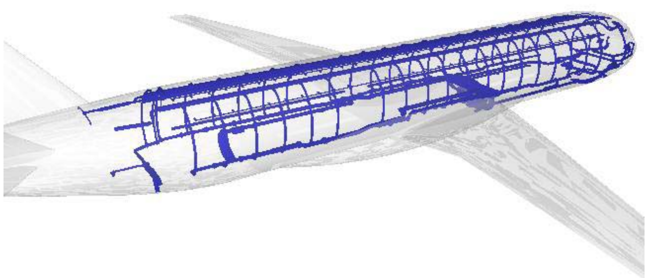


FIG 5. Air Distribution System

Conditioners generally read the required blown temperature signal provided by the respective cabin area or flight deck model. They sense the temperature of the air flow provided by the mixing unit and heat or cool the material to the required temperature. Based on that, the derived requirements in terms of the energy demand from the source used by the conditioner are developed (as mentioned before, in a conventional architecture, the conditioner is a TAV and it establishes the required mass flow of trim air). Obviously, not every conditioner is capable to both heat and cool.

Additionally to generic pressure loss models provided in the library (see section 3.8), this package offers dedicated duct models with sizing logic based on the flow requirements (see section 3.7) and the design philosophy mentioned in section 2.1.

An additional feature of the ECS architecture is the recirculation system. Nowadays, two different types of recirculation systems are in use. One is the proven recirculation system (also called central or lower recirculation system) and the other the local recirculation system (or upper recirculation system). In a central recirculation system, air is extracted from the under-floor and fed into the mixing unit. On large commercial aircraft, it is advantageous to recirculate only a fraction of the recirculation air flow centrally and use a local recirculation system for each cabin area. This allows for weight savings. The recirculation system models contain primarily pressure loss and air-cooled fan sub models.

3.4. Air Generation Package

As mentioned before, the air generation unit is the device that provides a conditioned air flow meeting the demand of the mixing unit using an air cycle. In unconventional architectures, it may use only compressed ambient air or, in reduced bleed designs, use both engine bleed and ambient air.

As indicated above, most air cycles rely upon turbo machinery. In the present library, performance maps are typically used for this purpose. They provide pressure ratio and isentropic efficiency as a function of two or more parameters each. For the compressor, corrected speed and corrected mass flow rate are used (they translate the actual shaft speed and mass flow to the values that the compressor would experience if it was operated under standard conditions at sea level). Additionally to the corrected speed, the turbine maps use a velocity factor and a speed factor, which relates the actual turbine mass flow to the maximum nozzle throughput.

To reject excess heat to the ram air flow, heat exchangers are used. They can be implemented based on given efficiency maps or using geometry and configuration information. Based on the latter approach, one to three pass cross flow, single pass counter flow, and cross-counter-cross flow heat exchangers have been tested.

FIG 6. Air Generation Unit

Air generation units based on the cycles discussed in 2.2 use an additional fan in the ram air channel to compensate the lack of dynamic pressure and ensure sufficient cooling on ground. In the present library, this type of fan is typically modelled using performance maps in a similar fashion to the turbo machinery components discussed above.

The Air Generation package additionally includes models of water extractors, which are based on the cyclone principle, and components to model different types of bypass fluid paths.

3.5. Vapour Cycle and Electric Heating Package

In a reverse Clausius-Rankine vapour compression refrigeration cycle, heat is extracted from a low temperature reservoir and rejected to a high temperature sink employing work from an external source. The process is located in the two-phase region of the refrigerant to take advantage of the constant temperature of a single substance gas-liquid mixture under heat load.

In the most basic configuration, a vapour cycle system consists of an evaporator, compressor, condenser, and a thermal expansion valve. The evaporator has an air and a coolant side and is currently implemented using a given fixed thermal efficiency and degree of super heating. This is the component that extracts heat from an air flow, which has to be cooled. Due to the possibility of surface temperatures below the dew temperature of water, the separate extraction of condensed water is implemented based on an empirical psychrometric relation. The compressor uses an isentropic efficiency parameter, which has to be supplied as constant, too. It has to be connected via a flange to a motor model, which accounts for electrical and mechanical losses. Heat is dissipated either to the ambient, a specific other component or to a fluid flow (air or refrigerant). The condenser is implemented similarly to the evaporator; it has a given fixed thermal efficiency and a degree of super cooling. Here, the heat absorbed in the evaporator plus the losses incurred over the compression process are rejected to a second air flow (e.g. ram air). The thermal expansion valve finally expands the liquid refrigerant. It cools down significantly and enters the evaporator again.

While these components currently use constant efficiencies, they were designed such that characteristic maps or geometry based performance estimators similar to the ones presented in 3.4 can be introduced quickly.

Again, the location of the process in the ph-diagram is found from functional requirements imposed on the vapour cycle system.

Finally, the package provides conditioner models that rely on electric power to heat an air flow.

3.6. Ram Air Channel Package

In the ram air channel, ambient air is decelerated during flight and used to reject heat flows from the air generation unit or vapour cycle. The ram air channel consists of a ram air inlet, water injector, and ram air outlet. The other components such as heat exchangers for different types of applications and fans are included in the other model domains and already cover their respective pressure losses and waste heat rejection.

In flight, the ram air inlet establishes the pressure recovery factor based on inlet opening area and flight conditions. On ground, the conditions downstream of the ram air inlet are established based on a pressure loss model, which scales with the inlet opening area.

Downstream of the inlet, a water injector is typically placed to recover performance lost due to the extraction of water in the air generation unit. The water injector sprays the liquid water into the moist air. The latent heat required to reach phase equilibrium is extracted from the surrounding.

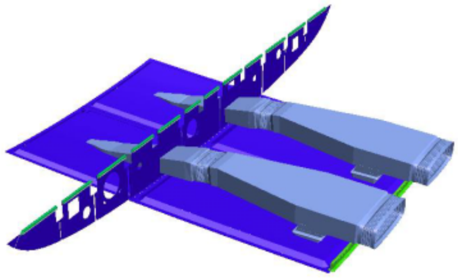


FIG 7. Ram Air Channel with NACA Inlet

Following the flow direction, the users of ram air rejecting waste heat come next. Typically, these are air-to-air heat exchangers of the air generation unit and / or evaporators of the vapour cycle system (see sections 3.4 and 3.5).
The amount of ram air is controlled to maintain a specific compressor outlet temperature.

Finally, a fan is usually included. It is used to pull the air through the ram air channel on ground. Afterwards, the ram air is disposed to the ambient via a ram air outlet model, which is basically a specialised pressure loss element.

3.7. Data

For an ECS architecture model, several global parameters are required. They are, for example, related to the definition of the ambient environment, or to the aircraft geometry and cabin configuration. Based on them, several derived quantities can be established (e.g. based on the mission profile and atmosphere settings, the solar radiation can be established for any point in mission time). These two purposes are fulfilled by the elements in the data package; they provide a means to specify constant input parameters and to establish derived quantities based on them.

The constant input parameters are grouped into general, cabin, and flight deck parameters. The general parameters capture requirements with regard to the amount of fresh and total air, local and central recirculation ratios, flow selector settings and such. Additionally, the ambient conditions are defined based on an atmosphere model (such as ISA plus optional offset or hot day), a solar flag to activate or deactivate the influence of solar radiation, attenuation and relative humidity parameters. Lastly, a mission profile in terms of altitude over time has to be specified. Typically, it is read from a file.

The cabin parameters carry information on the numbers of seats and passengers as well as flight attendants in vectorized form. Like this, each element of the respective vector corresponds to a single area within the fuselage. Additionally, the heat loads are specified in more detail. Heat loads per device and usage factors of different systems are included. Last of all, geometry data such as the number of frames per area and some overall heat transfer coefficients have to be specified. The flight deck parameters are similarly structured.

Based on these global input parameters, several derived quantities can be established. This is done using different calculators. A group of calculators determines the ambient conditions (ambient temperature, pressure, mass fraction of H_2O, and solar radiation), a second one the external boundary (Mach number, aircraft skin temperature, and cabin pressure), a third one the fuselage geometry (lengths and floor, skin, and window areas of the different cabin areas), and a last one the flow requirements.

The flow requirements cast the parameters specifying the demand of fresh and total air for cabin, flight deck, and cargo compartments into mass flow rates for use in different models such as the mixing unit and recirculation system. Typical input parameters are the mass flow rate of fresh air per passenger, the volume flow rate of total air per aircraft frame, and the flow selector (a means for the attendants to increase the total cabin ventilation). Combining them with specific strategies such as maintaining a constant volume flow of outside air below 31 kft altitude and a constant mass flow rate between 31 kft and 43 kft, yields the flow requirements in terms of mass flow rates. They can be used to specify the demand in the respective models.

All calculators can be replaced easily when required. In some scenarios, the impact of reducing the maximum cabin altitude shall be studied as a comfort feature. Using the features of the object-oriented modelling language Modelica, the standard calculator of cabin pressure can be replaced with a single click in the graphical user interface by any class derived from the common super class such as a different calculator considering a given maximum cabin altitude.

3.8. Miscellaneous Models

Additionally to the models discussed so far, several other components are included in the library. Pneumatic and electric wing anti-ice devices fulfil important functions that should be included in trade-off studies between pneumatic and electric power usage for airframe subsystems. The pneumatic power package contains implementations of a conventional EBAS. It also covers the trim air system (the TCS in a conventional ECS) for the distribution of bleed air to TAVs and such.

On top of the above, a large set of generic models is included in this library. Among them are different types of fluid and heat sources, control volume models, junctions and splitters, generic pressure loss elements, heat transfer elements, valves, and electric motor models.

Finally, a weights package is included to establish and sum up component masses. The component masses themselves can be calculated using fixed parameters such as component dimensions (such as length, width, height, rotor diameter) or simulation results (such as average or peak component power). Using a flow connector in a specialised construct, the component masses are summed up and propagated to the system level only by instantiating components – no explicit connections or similar steps are required from the user.

4. APPLICATIONS

The tool provides a powerful instrument for analysis and optimization of ECSs. It can be used for limited parameter studies analyzing, for example, system behaviour for bleed air extraction at different compressor stages, and for fully blown optimization studies of reduced bleed or all-electric ECSs. To support the user in gathering a thorough understanding of the problem he is looking at, the tool additionally provides a means for interactive experiments on any modelled architecture.

4.1. Exemplary ECS model

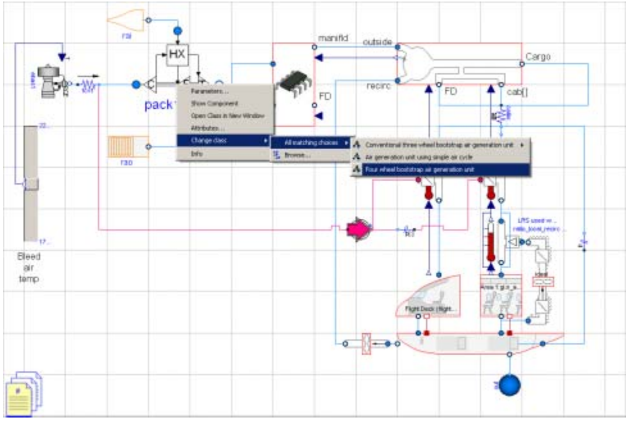
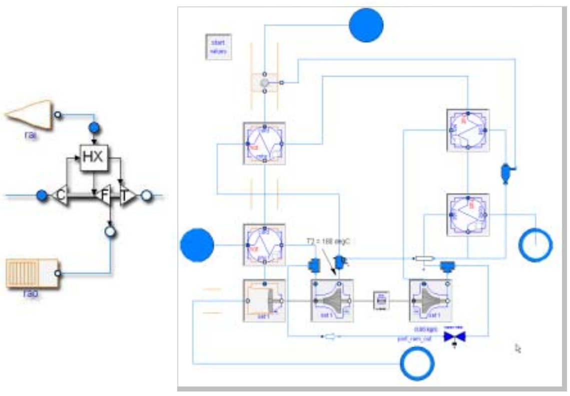


FIG 8. Example of a simple ECS model

In FIG 8, a simple ECS model is shown. It features n vectorized cabin area models that are connected to vectorized trim air conditioners. A central and a local recirculation system are implemented, too. The mixer is fed by a conventional pack, which is driven by bleed air. The three wheel bootstrap pack can easily be replaced by a different one (FIG 9 shows conventional pack models).

4.2. Interactive Environment

The library can also be used in an interactive mode. The user can change parameters using sliders for example and receive feedback from indicator lamps and plots. Each relevant component optionally provides runtime displays of key metrics such as pressure ratio, efficiency, temperatures, mass flow rates etc. This allows the user to study and fully understand the model he has built including the implications of the chosen control strategies.



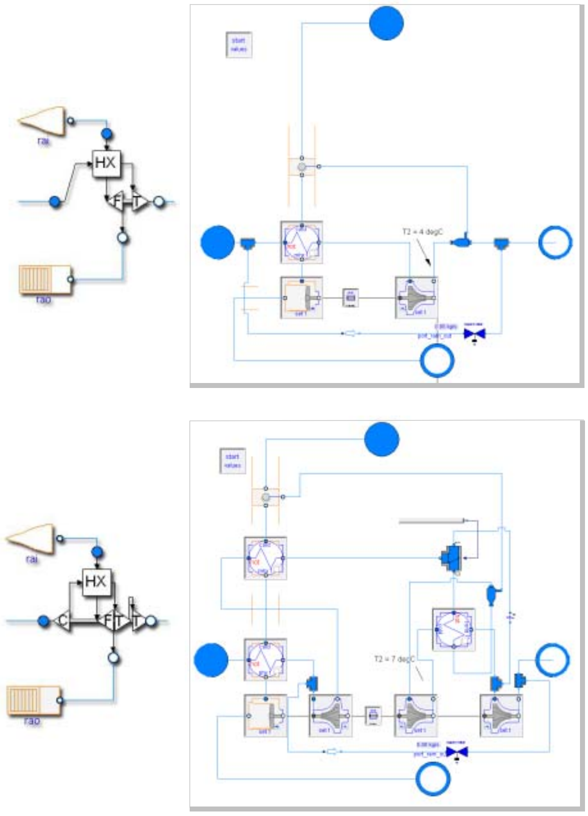


FIG 9. Different available pack models with diagram of the contained components (three wheel bootstrap, simple air cycle, four wheel bootstrap)

5. CONCLUSION AND OUTLOOK

The presented tool provides a powerful instrument for analysis and optimization of ECS architectures with respect to system weight and performance metrics. During concept phase of the design process a large number of architecture candidates can be assessed and a more thorough trade off between possible solutions can be performed.

The acausal formulation of equations allows for different calculation directions giving the user the possibility to design his system according to requirements and assess a designed system within its operational range without changing model topology.

Much effort has been made to provide a robust and flexible library, that does not restrict the user to certain ‘allowed’ combinations. Existing and new unconventional ECS architectures can be modeled and investigated.

Implementation of an interactive mode helps the user to gain a better and quicker understanding of the system under investigation.

Future work will incorporate methods to create performance characteristics for turbo machinery from geometric data, generic ice protection systems and parametric weight assessment of ECS architectures.

The library will be used to assess future ECS architectures in detail and compare results with existing systems.

When parameterized models for all major ECS components are assembled in the library the library will be linked to Matlab and the optimization software MOPS (Multi-Objective Parameter Synthesis) [4]. Using this setup, an ECS architecture model can be optimized for any objective composed of performance and weight metrics.

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