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IMPACT OF NEW TECHNOLOGIES ON AIRCRAFT SYSTEMS

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Abstract

During conceptual and preliminary design an aircraft can be optimized by introducing innovative configuration or the use of new technologies. But the design in interdisciplinary project teams makes it difficult to estimate the impact of a technology on the aircraft. Especially in such an environment, it is difficult for developers to identify the impact of design decisions by changing system properties. To face this challenge feasibility analysis can be applied. In the following, a procedure is described to implement feasibility studies for identifying and tracking impacts on aircrafts. In the ATLAs project the procedure was used to investigate five different technologies. Using the example of the CO_2 controlled cabin, the procedure and its practical applicability in everyday project life is shown.

Keywords: conceptual and preliminary aircraft design, aircraft systems design, model based design, feasibility study

1. Introduction

New technologies enable aircraft to be used in a more ecological and economical way. In addition, passenger comfort can be improved. In order to evaluate innovative technologies, their impact on the aircraft must be analyzed and assessed. On the basis of these impacts, it can be decided whether these technologies should be retrofitted to existing aircraft or integrated into new ones.

At DLR, the Advanced Technology Long-range Aircraft Concepts (ATLAs) project investigated and evaluated new technologies in terms of feasibility for a mid-range aircraft addressing long range capability (352 PAX). In order to understand the used approach to evaluate new technologies in an aircraft, the CO_2 controlled cabin is used as an example. This technology was used to investigate what influence the control of the partial pressure of O_2 and CO_2 in the cabin air could have on the Environment Control System (ECS) and the aircraft. For this purpose, a procedure for conducting feasibility studies was investigated, which can deliver the required results in a short period of time.

There are different definitions of a feasibility study depending on the field of application. According to the Systems Engineering Handbook [8], the systems engineering process includes a concept phase. In this project phase, different system concepts will be designed and analyzed by a multidisciplinary team [14]. This analysis examines the realization of an idea and is called feasibility study. This study generates results that are used as a basis for decisions on the execution of a project. For traceability, the obtained results must be documented. Another definition implies that a feasibility study is generally an analysis that shows the feasibility of an idea. For this purpose, after Hofstrand [7], Matson [11], and O'Brien [15] a series of assumptions regarding technology, realization, financing and other aspects are made. These assumptions are used to examine the extent to which an application or business is possible. Furthermore, the idea is evaluated and a decision is made on how to proceed. Matson [11] recommend for a thorough analysis, background knowledge from the relevant fields is required. Also, if the study is being conducted for the first time, a consultant should be called in to lead the study. If many studies are carried out, a department could be set up like done at Microsoft (Hofstrand [7]), or the European Space Agency (Bandecchi [1]).

A special type of feasibility study is the "technical feasibility". This has a prototype character and carries out a "proof of concept" or "proof of principle". For our purpose, the analysis of new technologies, this type of feasibility study is very well suited. In addition, the following requirements are made for the analysis:

- Proof that a solution found, e.g. technical system, is feasible
- Examination of the solutions and comparing with alternative implementations
- Evaluating of different solutions as a basis for an objective decision-making
- During the analysis, requirements and application scenarios are identified and refined for later optimization

It will be shown that compliance with the following requirement simplifies the execution of feasibility studies. The creation of a feasibility study should be simple and quick. For this purpose, the necessary calculations should be reused or at least is already tested. During the execution there should be a quick feedback to the involved departments. This allows the influence of individual decisions to be understood more quickly. Thus the influence of boundary conditions, restrictions or problems of individual solutions can be identified earlier. In regard to experience made in model based development in space engineering [5] depending on the maturity of a solution, the inaccuracy of the calculation results in the conceptual design can vary between 5 ... 20 %.

1.1 Feasibility studies during the early system design

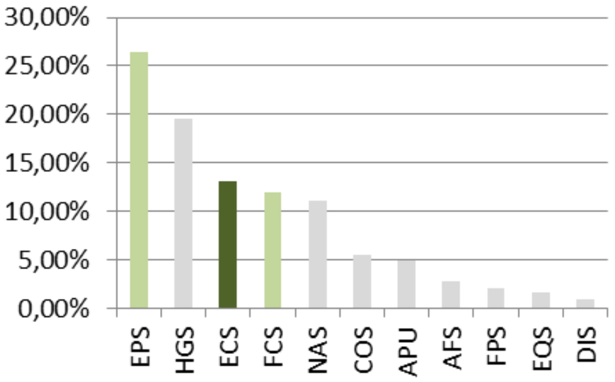
To assess whether a new technology appears suitable for integration, various system parameters such as mass, energy and the required installation space must be determined. The system mass is changed by the integration of a new technology. In addition to the change in aircraft mass, the energy consumption of a system can also have an effect. Both parameters, mass and energy consumption, have an effect on the fuel consumption of the aircraft. The fuel consumption can be determined by the parameters block and reserve fuel. Thus, the first question to be asked is whether it is possible to reduce fuel consumption. If the technology under investigation has the potential to reduce fuel consumption, it can be installed in a new aircraft or replace an old system by a retrofit.

If the interdisciplinary character of the concept design as shown by Moerland [14] is to be taken into account during the feasibility study, the challenge is to identify the relationships between system properties. Afterwards the effects on the system can be evaluated by changing these properties. This analysis is called impact analysis.

1.1.1 What are the challenges?

The impacts of a system like the Environment Control System on an aircraft depend on its capabilities. The impacts can be expressed by parameters. From the technical point of view, the mass, energy consumption and installation space have, derived from experience, a great effect on the system feasibility. Therefore, these parameters are examined in greater detail during an analysis.

In order to be able to understand which challenges occur during a feasibility study, the estimation of the system mass is described. Figure 1 System mass distribution shows the proportions of individual system masses in relation to the total mass of all aircraft systems. The mass of the ECS we are examining is about 12.5 % of all system masses sum. Also, Figure 1 System mass distribution shows the considered systems classification.



Name	System	CeRAS	ATA
AFS	Auto Flight System	38	22
APU	Auxillary Power Unit	30	49
COS	Communication System	40	23
DIS	De-Icing System	34	30
ECS	Environment Control System	33	21
EPS	Electric Power System	41+42	24
EQS	Electric Equipments	37	25
FCS	Flight Control System	36	27
FPS	Fire Protection System	35	26
HGS	Hydraulic Generation System	31+32	29
NAS	Navigation System	39	34

Figure 1 System mass distribution (left) and considered system (right)

Referring to Torenbeek ([24], ch. 8), Raymer ([21], ch. 15) and Roskam ([19], ch. 7), it was stated by Lammering [10] "system models commonly used in early stages of aircraft design are based on statistical approaches and regression analysis" and further, "this is due to the lack of correctly captured data for today's aircraft". If individual systems are modified, the associated system masses can only be determined to a limited extent and cannot take into account changes due to new technologies.

For a more accurate estimation of system parameters, the existing calculations for a more precise aircraft design were extended by Coeppen [9] as well as by Lammering [10]. Both approaches are model based and use a more detailed system description to calculate system masses and power output. The approach of Lammering is implemented in the design tool MICADO, which can cover the needs of early aircraft design. A restriction of the model-based approach of Coeppen and Lammering is that only the architectures specified by the implementation can be analyzed. The influence of new technologies that change the architecture cannot be investigated. To enable this, the existing implementation would have to be adapted manually for each new technology. This would exceed the resources of a feasibility study. Due to this limitation, an approach is needed that allows a flexible design of an architecture based on the desired system function. For such architectures, it should be possible to design a system that can optimally integrate the required system components into the aircraft in terms of mass, power consumption and space requirements.

1.1.2 *Old system out, new one in*

Before describing the approach to the analysis of flexible architectures using new technologies, an interface for the separation between aircraft and system level will be introduced. As interface the aircraft design parameters Operating Empty Mass (OEM) for the mass and the fuel masses block and reserve fuel respectively the specific fuel consumption (SFC) for the energy consumption can be used. Parts of the OEM are among others the masses of the individual aircraft systems. As already described, the OEM of an aircraft can be determined using statistical methods. These methods are implemented into the tool MICADO. MICADO provides an estimation of the mass break down, including the masses of the individual subsystems.

Based on a the internal developed reference aircraft D250 a next generation aircraft configuration (D250 NXG) integrating the new technologies is derived. For the D250 NXG the Electric Power System (EPS) is to be investigated on a model-based basis. First the OEM of the D250 is determined. If possible, the masses for each individual subsystem are estimated. Then, the EPS for the new D250 NXG configuration shall be calculated based on an A330-300 EPS. As the dimensions of the A330-300 and the D250 NXG are different, which can be easily understood by the different OEM, the calculated value for the EPS mass has to be adjusted. For this purpose a scale factor considering A330 and D250 OEM can be calculated. Using this provides a reference value for the EPS mass of the D250. Changes in the architecture of the EPS, e.g. changes in the distribution of electrical energy and new cabling technology, could save 479 kg for the A330-300 as shown in Table 1. Taking into account the previously calculated scaling, the mass of the EPS is reduced to 336 kg for the D250-NXG.

Table 1 Example calculations for aircraft systems

	OEM	Systems	APU	ECS	DIS	FPS	FCS	EQS	Auto	NAS	COS	EPS	HGS
A330-300	122780	12559	613	2449	1643	123	266	1507	211	342	1396	685	3322
D250	86180	8815	430	1719	1153	86	187	1058	148	240	980	481	2332
D250 NXG	84460	8478	430	1383	1153	86	187	1058	148	240	980	481	2332

A similar procedure can be used for the fuel mass respectively the SFC. The energy required by a system can be satisfied by bleed air or electric energy. Both energies are taken as power takeoff from the engines. Due to the engine thrust requirements additional fuel is needed to provide the energy for the systems. This fuel consumed by the systems can be calculated during propulsion system design. To improve the engine efficiency the power takeoffs need to be reduced.

After showing how statistical and model-based methods used system architectures, a detailed description of how flexible architectures and different system solutions can be considered follows.

2. Approach for evaluating new technologies

The following method for evaluating a new technology has been successfully applied in various projects. This procedure can be divided into two parts. First, the parameters that can have a significant impact on the system during design are identified. In order to be able to estimate and measure the impacts, a calculation model is required for the second part. Figure 2 shows the method to identify the calculation model and the significant parameters.

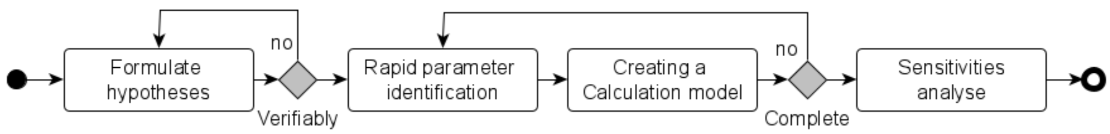


Figure 2 Process for determining design driving parameters

Then, the early design of various possible solutions using the calculation model can be continued. After a possible solution has been found and the feasibility study has been documented, the next development phase can begin. In the following, the example of a CO_2 controlled cabin is used to describe the methodology. This is followed by a short introduction to the ECS of an aircraft.

2.1 The environmental control system of an aircraft

The function of the ECS in the aircraft is to control the environmental conditions in the cabin in such a way as to preserve the health of passengers and crew. In order to achieve this goal, fresh air is continuously supplied, a cabin pressure of a maximum of 2438 m and a temperature of approximately 25°C is provided in regard to AMC 25.831 [4]. These conditions ensure the comfort of passengers and crew. In addition, cool air is provided for cooling electronic devices [17]. As shown in Figure 3 left, the ECS has the main functions *Air Conditioning* to adjust cabin conditions such as pressure, temperature, remove gaseous contaminants and *Distributing Air* for air distribution in the aircraft. In Hunt [6], the individual components, such as the Air Conditioning Pack (ACP), are described from an air quality perspective using the B767 shown in Figure 3 right.

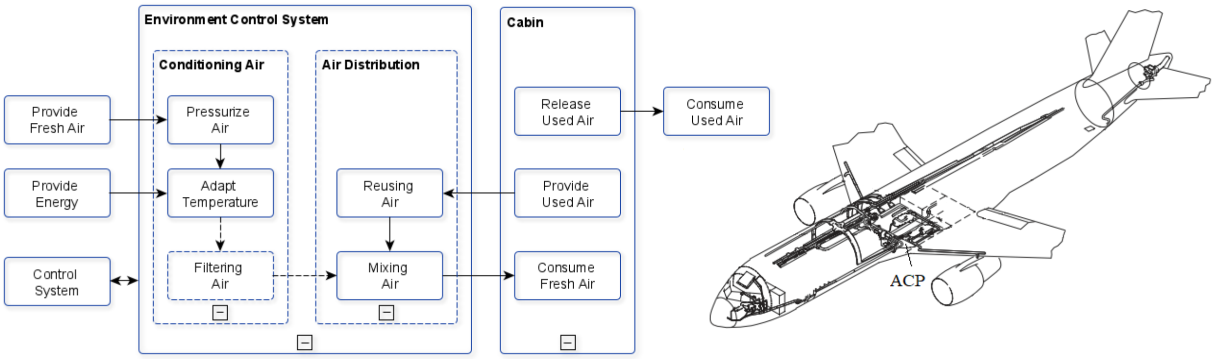


Figure 3 Functional architecture of ECS (left) and the implemented ECS of a B767 from [6] (right)

In the beginning, air from the atmosphere is directed into ACP. Typically two devices are installed. The ACP first regulates the pressure to the required cabin intake pressure (*Pressurize Air*). Then the temperature is adjusted to the specified value (*Adapt Temperature*). For this purpose, energy in the form of bleed air is supplied to the ram air via heat exchangers. To prevent possible contamination, the air is filtered (*Filtering Air*) before it is mixed with the used cabin air (*Reuse Air*) in the mixing unit (*Mixing Air*). After mixing, the conditioned air is fed back into the cabin.

In order to keep the CO_2 concentration within safety limits for the crew and passengers, the specified value for the supply of fresh air from certification specification [4] must be met. Further, the used cabin air is continuously vented to the atmosphere. This leads to a continuous renewal of about 50 % of the cabin air. To save energy, the ECS will be extended by the CO_2 controlled cabin concept. Therefore, the system depicted in Figure 3 is to be modified to include the functions "*filtering of CO_2*" and "*enrichment with O_2*". During the filtration, CO_2 is separated from the cabin air and released into the atmosphere.

The introduction of the CO_2 filtering functions is supported by the first hypothesis that filtering can save energy and thus reduce the SFC. During the enrichment of O_2 the oxygen partial pressure should be increased. This can be used to decrease the cabin pressure. The second hypothesis is that by increasing the oxygen partial pressure, structural weight can be saved and thus also SFC can be reduced. The described two hypotheses will serve as a starting point for the impact analysis.

2.2 Rapid identification of system parameters

Based on the observations and experiences made, the parameters system mass and energy consumption need to be determined for the evaluation. As a constraint for the feasibility of a solution, the required installation space has to be considered additionally. A calculation model is required to determine the parameters.

During the creation of a calculation model for the early development phase, the main impacts as shown in Figure 4 that contribute to changes in mass and energy consumption must first be identified. For this purpose we have conducted brown paper sessions. At a brown paper session, experts from the various disciplines met and discussed the impacts of the additional functions on the aircraft. During the discussions, the identified impacts were visibly documented on the brown paper for all to see. Figure 4 shows an overview of the identified impacts at the end of a session. The discussions that arose during the work also served to qualitatively assess an impact. If an impact was positively assessed, it was marked with a "+", negatively assessed with a "-". In case no clear decision could be made, no marking was made.

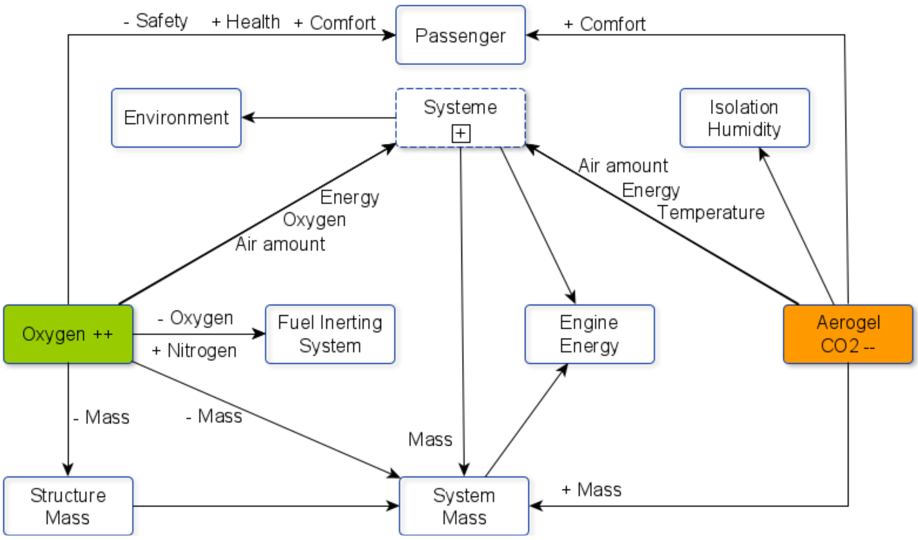


Figure 4 Impact of O_2 enrichment and CO_2 filter

According to experience made brown paper sessions should be conducted at the beginning of the development. Thus, a platform is provided to gather all participating domains to identify the dependencies among the aircraft systems. Since the project team is distributed and the assembly can be changed from project to project, these sessions enable a common understanding of the system to be reached quickly. During several sessions, it was observed that the overview shown in Figure 4 can usually be worked out in a 60-minute session. If the manufacturer is included in the sessions, the model also incorporates the background of the later use case. In further iterations, the model was adapted until the necessary relationships were identified for the calculation. The model is complete when it is clear which parameters are provided by functions or objects. It must also be determined who is responsible for the required calculation, since the knowledge is required for this.

2.3 Development of a calculation model

It is possible to verify the hypotheses, only when a calculation model has been created before. The model created in the brown paper session must be translated into a calculation. At first the identification of the parameters is started. In order to determine the impact on aircraft level in relation to system mass, the OEM is used. Parts of the OEM are systems masses, like the ECS mass that can be represented by the parameter *system mass* of the function *adapt environment conditions*. With this parameter the mass of the *CO_2 filtering* function can be taken into account. Furthermore, the parameter *remaining mass* can be used to consider additional masses that are not introduced by *CO_2 filtering*. Thus, the additional mass of the designed filter system can easily be considered in the OEM. This enables a successively creation of the calculation model.

Creating a calculation model requires practice and skills, since the quality of the calculation model and the quality of the analysis result depend on each other. If significant system dependencies are not taken into account, it may happen that a system for example is built that consumes too much energy, even though the analysis has identified a potential of saving energy. For this reason it is important to know or identify the significant dependencies.

By using a functional architecture, the degree of abstraction for individual functions or system elements can be determined and controlled. Defining the level of detail will also control the implementation effort for the calculation model. When developing the calculation model, it should be taken into account that the modeling depth can determine the precision, i.e. the more details are taken into account the more exact the calculations. Experience shows that a well planned development of calculation models improves the control over the resources used. Thus, the trade-off between calculation precision and the required resource input can be controlled by the level of detail in which the calculation should be performed.

Figure 5 shows the calculation model of the parameters OEM and SFC to trace the impact of the CO_2 filter function on the aircraft. To simplify the analysis and to support the development parameter dependencies are shown in different colors. The relationship between the adsorption capacity and the material mass required for filtering is such that the higher the capacity, more CO_2 can be adsorbed and less material is required. This relationship is referred to as the counter dependency and was displayed in red. A proportional relationship was marked green. Thus, the mass of the required filter material depends proportionally on the amount of CO_2 to be filtered. Relationships that cannot be clearly identified as proportional or counter-dependencies should be marked in yellow.

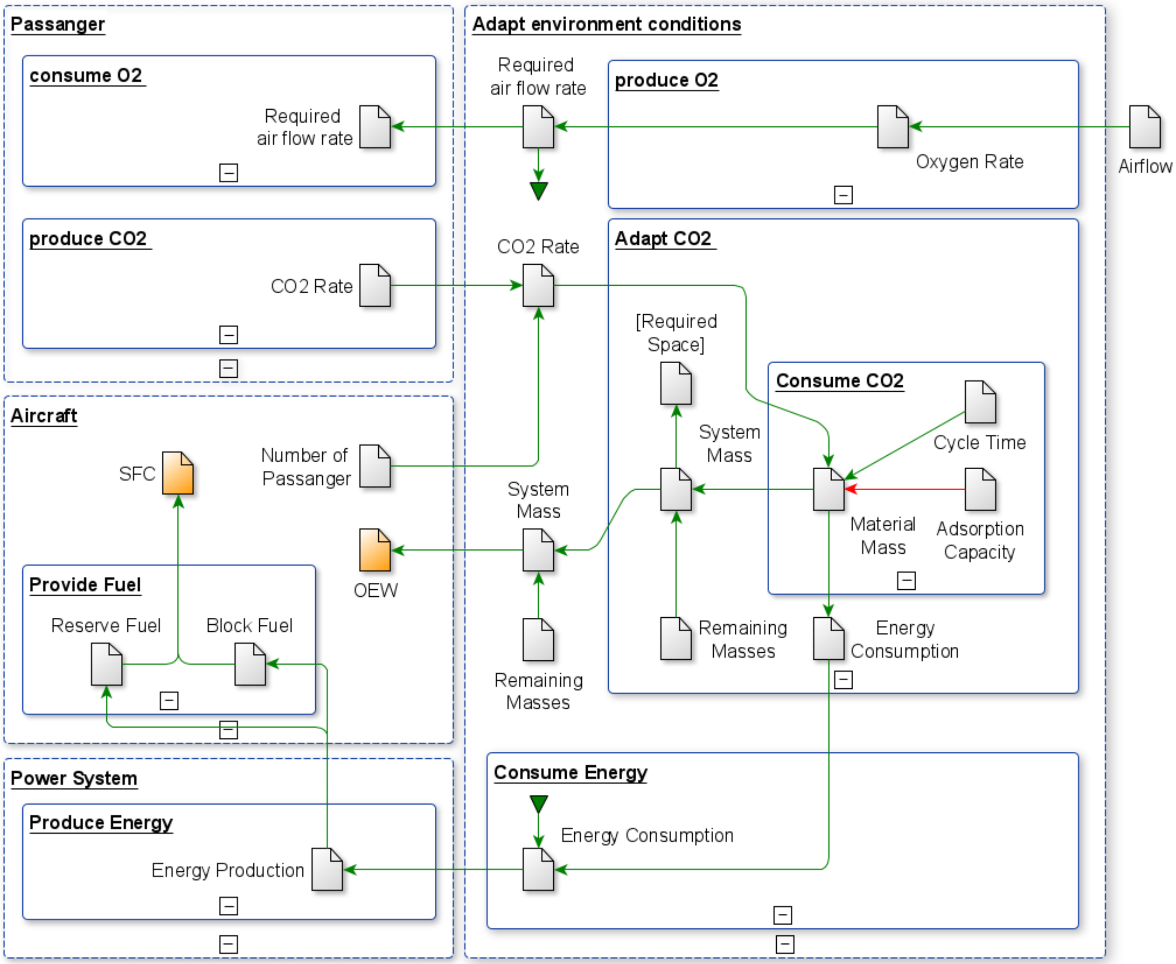


Figure 5 Calculation model of CO_2 filtering

Because of the novel concept, a new calculation model was needed and the reuse of existing calculation was not possible. For a minimal effort, the decision was made to realize the calculation in Excel. The implementation enables automatic update of the input values like number of passengers or cycle time directly into the Excel spreadsheet. Calculated values such as system mass and energy consumption will be read out and passed on for calculations at aircraft level. A detailed description of the process is given in the next chapter.

2.4 Sensitivity analysis

At the moment when a first version of a calculation model exists and useful calculations can be done, it is possible to perform sensitivity analyses continuously and automatically. The sensitivity analysis has exploratory character and with it the impact of design parameters can be investigated. If, for example, the adsorption capacity is changed by the use of different materials, this has an effect on the mass of the required filter material and the required desorption energy. However, parameter values always change within the corresponding ranges of validity. After a successful calculation, the sensitivity will be expressed by the ratio parameter change to parameter effect. Here, the change of the OEM or the SFC in relation to the change of the adsorption capacity.

Finally, the parameters can be sorted according to their sensitivity. The generation of this list can support the system engineer during system design. For example, if the question rises to optimize the cycle time or to change the filter material, then the sensitivity list supports a decision by selecting the parameter which has the greater impact in direction to systems optimum. It is important to consider the sensitivity and the effects related to the optimum of the system property to be affected.

2.5 The system architecture and possible variants

The quantitative evaluation of the system cause-effect relationships by means of a calculation model and the introduction of sensitivity analyses to support design decisions enables the design of different system solutions. By applying Trade off studies the designed systems can be compared. The following section describes possible architectures for the functions *CO_2 filtration* and *O_2 enrichment*. Therefore, the functions should be considered independently and effects that might have an impact on the other function should be considered in later work. The design of the different system variants is based on the architecture of the Environment Control System described in Figure 3.

2.5.1 CO_2 Filtering

To extend the ECS with the *CO_2 filtration* function, there is only one reasonable option. Part of the cabin air is continuously released into the atmosphere via a valve. The remaining cabin air enriched with CO_2 is mixed with conditioned fresh air in the mixer and returned to the cabin. The recirculation fans are integrated between the cabin and the mixer. These ensure that the cabin air and the fresh air are mixed in the right ratio. As shown in Figure 6, the CO_2 filter can be integrated before or after the recirculation fans. The additional flow resistance will increase the required power of the fans.

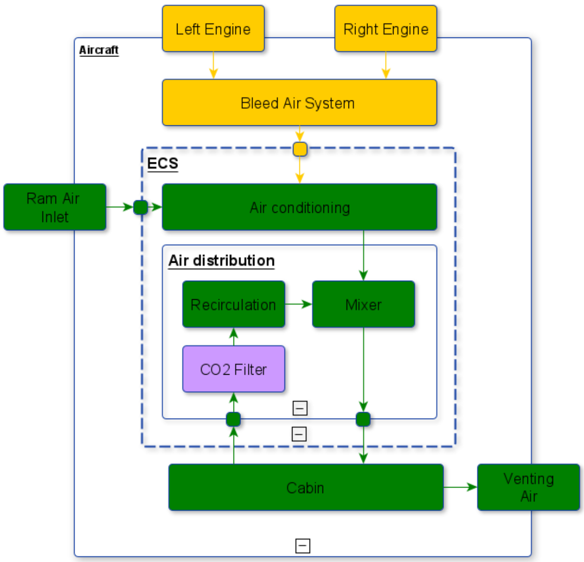


Figure 6 Integration of the CO2 filter

For the described calculation model, minor adjustments had to be made to take into account the additionally identified effects. Afterwards, the values for mass and energy consumption shown in the following table were determined for CO_2 filtering with the design driving parameter Persons on board (eq. 1).

$$Persons = n_{Passenger} + n_{Crew} + n_{Pilots} \tag{1}$$

Table 2 System parameters

Persons	**252 / 6 / 2**	**301 / 7 / 2**	**352 / 9 / 2**
Mass [kg]	373	446	522
Electric Power[kW]	13,3	15,8	18,5

2.5.2 O_2 Enrichment

The objective of enriching oxygen in the cabin is to increase the partial pressure of oxygen. Therefore oxygen should be taken out of the fresh air from the environment and the partial pressure should be increased so that the cabin pressure can be decreased from about 2500 to 4000 m without causing any damage to the passengers. Therefore, ram air can be used as source for oxygen as well as bleed air. While ram air is used for cooling the breathable air, bleed air may support the extraction process by reducing the energy consumption of the system. In contrast to the *CO_2 filter* system, four different variants were designed for *O_2 enrichment*. In the cases the design provides oxygen-reduced air, this air may be used for the inertization of the fuel tanks.

In Figure 7 the oxygen extraction "*Pre conditioning*" variant is shown. Therefore, high-energy air is extracted from the bleed air system. The basic idea is, that energy required for the extraction can be provided directly by the bleed air, thus may save energy. The extracted oxygen is then added to the fresh air through the ACP. Figure 8 shows the "*Bypass conditioning*" variant, which also extract oxygen from bleed air to possibly save energy. However, the extracted oxygen is introduced into the air distribution system and bypass the ACP's. This has the advantage that the extraction can be carried out as an independent system without adaptation of the ACP's.

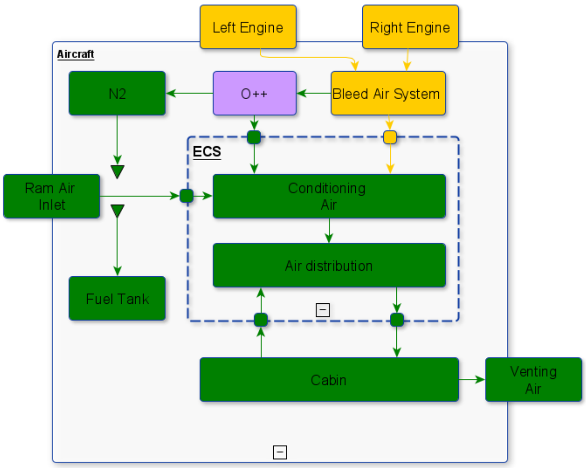


Figure 7 Pre conditioning

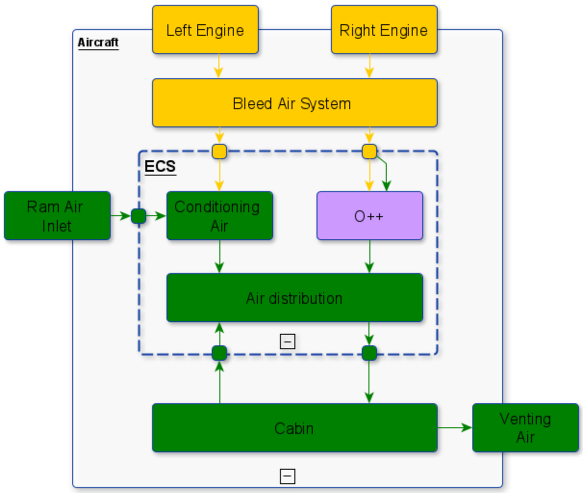


Figure 8 Bypass conditioning

Figure 9 shows the "*Post conditioning*" variant. Oxygen is extracted from the conditioned fresh air. Then, the extracted oxygen is introduced into the air distribution system. In this variant, the amount of conditioned fresh air must be increased. Figure 10 shows the "*In cabin enrichment*" variant. A system approved for use in medicine and ready to use, requires only access to fresh air.

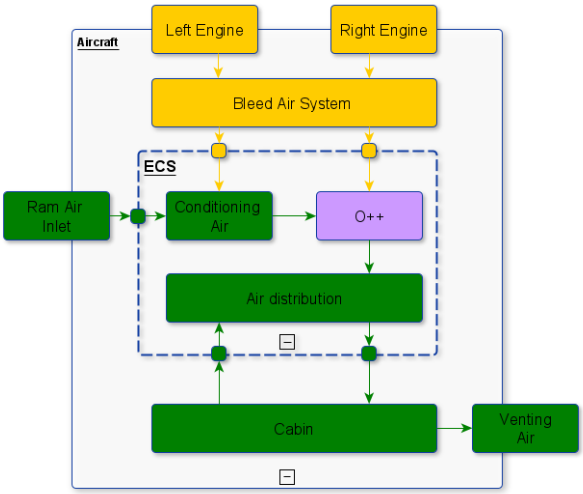


Figure 9 Post conditioning

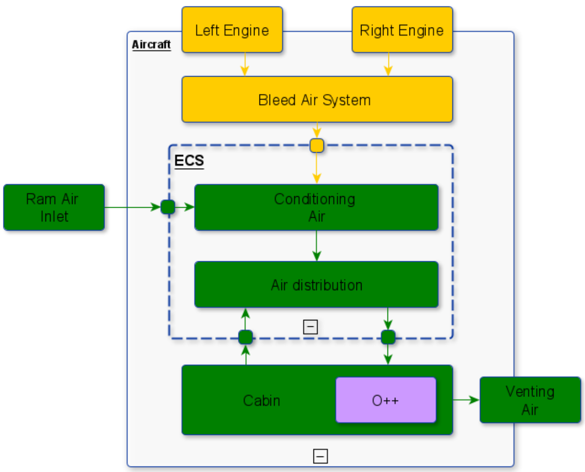


Figure 10 In cabin enrichment

Similar to CO_2 filtration, a calculation model of the effects had to be created. For this purpose the parameters system mass and required energy in regard to saving aircraft mass and energy were considered. A possible improvement of passenger comfort by generating additional income was not considered. The necessary assumptions could not be made because the necessary data could not be provided during the project.

2.5.3 Thoughts on a fast Implementation

In order to implement high-quality calculations quickly and with little effort, care must be taken in the early development. Since different ideas should be tried out and compared with each other. The quality of the calculation model should not primarily be evaluated according to the quantitative accuracy of the parameters, but whether essential correlations and significant parameters have been identified. The evaluation can be done by experts or by experience gained during the continuous work with the models. In addition, the quality can be assessed on the basis of expandability and maintainability.

To implement calculation models in a fast way, the foremost question to be answered first is, should the model be reused in different projects. If only smaller calculations are carried out, one time used models are suitable. These models should not be reused and can deliver the results you are looking for within a short time. If it turns out that one of these models are reused in several designs or projects, a redesigned must be done to meet the implementation quality of a reusable model. In order to be able to implement a calculation model quickly and with a minimal effort, an appropriate tool is required. If small calculation models need to be implemented on a regular basis, a spreadsheet based calculation with Microsoft Excel might be suitable. If the calculations are complex and should be reused, languages like Matlab or Python might be suitable. During implementation, care must be taken to ensure that data exchange is simple and needs small realization effort.

SysML [25] tools offer a further solution. With these tools, calculations or simulations of parameters can be made from the system description using parametric diagrams. From observations with the different SysML tools it has been shown the effort of creation and reuse of calculations is simplified if calculations can be done independently e.g. in Matlab and integrated in the parametric diagrams. Therefore external calculations should be supported by the SysML tool.

We have developed a tool for our purpose that simplifies the execution of feasibility studies and can meet all the requirements described. The ParadigmShift method developed by us is described in detail by Schumann [23] and is implemented in the tool PARADISE. In PARADISE calculation models are created in Excel, Matlab or internal calculations. The coupling between the system description and the calculation models is done via system parameters. Input parameters are used by the calculations and the results are transferred to output parameters. A coupling with simulation tools is possible via direct data exchange. For example in our project, the calculation model was implemented in Excel and the system architecture for CO_2 filtering with PARADISE was continuously evaluated.

2.6 Assessment on System level

For the oxygen enrichment of the cabin air a calculation model was implemented in Excel. It has been shown that with our conservative estimations regarding the benefits in aircraft mass compared to the additionally required system mass, the overall aircraft mass is increased. Furthermore, the energy required for the extraction increases the mass of the energy generating system. Thus, the SFC increases and thus we do not consider that this function currently has any potential for aircraft integration. For this reason, no further analysis of this technology was conducted in the project.

For the *CO_2 filtration* function, the first estimates showed that the use of aerogels shown in Table 3 leads to a high installation space, which also results in a high system weight. If alternatively zeolite is chosen as adsorption material, the required installation space and the resulting system weight are reduced. In order to give a recommendation for the integration of the filter function, the following question must be answered. Can the additional weight be achieved by saving energy consumption at aircraft level? The parameter that answers this question is the change of the SFC. If it is less than zero, the integration is worthwhile. The SFC is estimated during calculation of aircraft parameter, for this reason the calculated parameter of the systems level needed to be integrated into aircraft level.

Table 3 Trade-off filter material

Aircraft configuration	Volume [m³]	Mass [kg]
Zeolith	0,044	30,12
Chitosan Based Aerogel	4,842	387,33
Chitosan Aerogel	7,288	583,07

3. Integration into aircraft analysis

Up to this point the method described enables calculations and evaluations to be carried out at system level. The impact of a solution on the aircraft cannot be determined and the system solutions can only be compared. Currently the impact of mass and energy is considered, but for the decision making on system level the simple rule applies: Choose the system which has the least mass at the lowest energy consumption. Only when the considered dependencies between a system and the aircraft become more complex and the architectures take different effects into account, the decision making process requires an impact analysis at aircraft level.

In order to determine the impacts of a system on the aircraft, a closed loop calculation model must be available at aircraft level. Furthermore, the calculation of the system parameters must be integrated into calculation model of the aircraft.

3.1 Calculation at aircraft level

To design an aircraft configuration for the ATLAs project, closed loop calculation workflows were created using the Remote Component Environment (RCE)[1]. The RCE Framework is open source[2] and was developed especially for the distributed development of complex systems such as air- and space crafts or ships. The task of the framework is to link the distributed development and analysis tools using a workflow and to perform the needed calculations automatically. Figure 11 shows an excerpt from a calculation workflow.

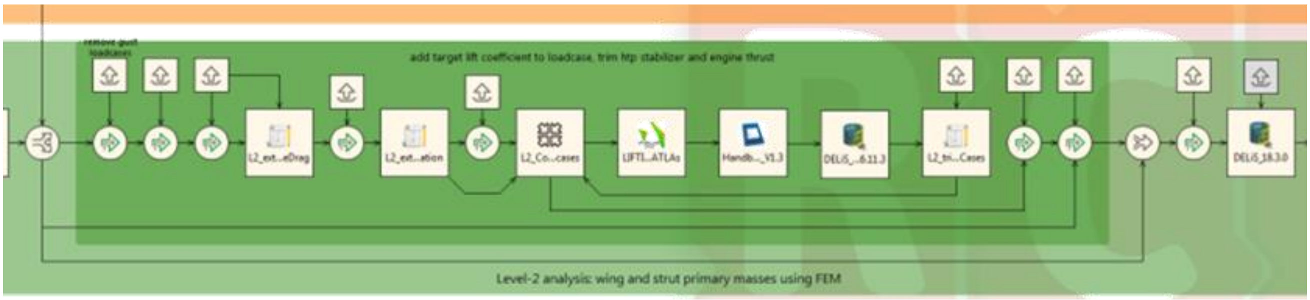


Figure 11 Excerpt from overall workflow

RCE enables partners and disciplines to use their own tools in a decentralized manner over a server network. The partners can provide individual servers for their tools. To use a tool, it must be configured as an RCE component and made known to the network. During the execution of calculations, the required data is exchanged in the network between the individual RCE components according to the workflow specifications. The calculation is then performed on the respective servers and, if successful, the results are forwarded over the network.

In order to use the calculations of the system parameters at aircraft level, an RCE component had to be created that can be used in the overall workflow. For this, a RCE component for system calculation incorporating the workflow shown in Figure 12 was implemented.

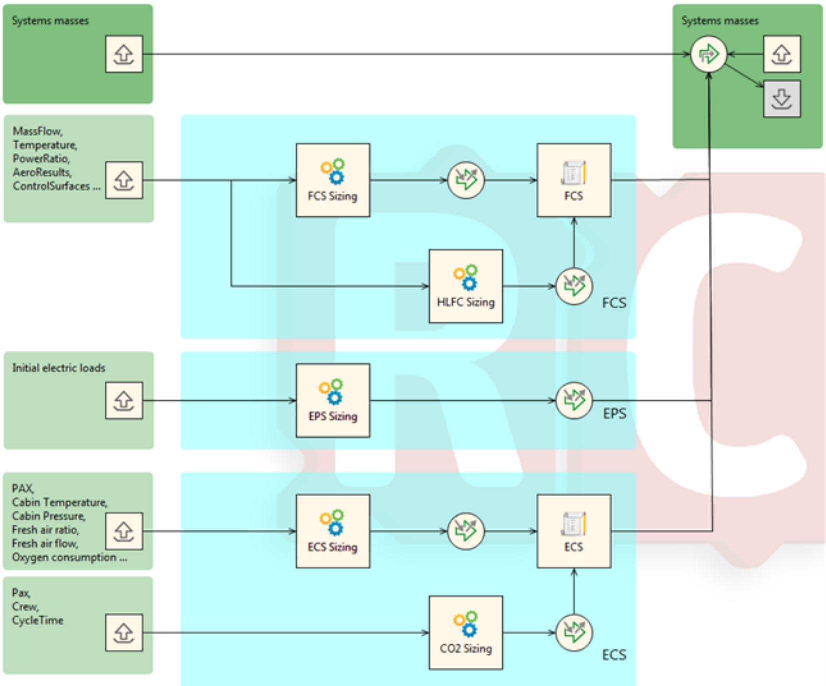


Figure 12 Calculation workflow of system parameters

A particular characteristic of the workflow used in the system RCE component is that it accesses five other components. This also reflects well the character of the system development. For the design of the Environment Control System (ECS), the Electronic Power System (EPS) and the Flight Control System (FCS) tools were developed by different project partners. Each tool was then provided as a component. In addition, separate tools were implemented to evaluate the technologies Hybrid Laminar Flow Control (HLFC) and *CO_2 Filtration* (CO_2 Sizing). The calculation model for

[1] https://rcenvironment.de/
[2] https://github.com/rcenvironment/rce

HLFC was quickly implemented in Python as the system was well known to a large extent. As described above, a model for CO_2 filtering was created and the calculations were implemented with Excel. The integration with RCE was done using our tool PARADISE.

The system RCE component for calculating the system parameters could be made available to the overall workflow very early in the project. However, the calculation models of the individual tools as well as the dependencies between the systems were continuously extended.

3.2 Data exchange using CPACS

To enable calculations between the different tools, an appropriate exchange format is required for data exchange. For this reason, the Common Parametric Aircraft Configuration Scheme[3] (CPACS) [16] was developed at DLR. This XML schema contains semantically detailed information for aircraft configuration and geometry description as well as process data for controlling parts of the design process.

3.2.1 Extensions of CPACS

For the data exchange between the aircraft and the system level the used CPACS version 2.3.1 offered design parameters like mOEM for the OEM and fuel for the fuel mass. Also the system masses like EPS, ECS, and so on could be specified as single values and considered in the OEM. Unfortunately, in the CPACS version used, masses were given which were neither specified by ATA Chapter shown in [1] nor by Central Reference Aircraft Data System[4] (CeRAS) [20], [3]. Additionally it was unclear which single masses were considered in the system masses, because the documentation was incomplete. Here an extension was needed to simplify the use.

For the current version 3.2 the described requirements have been partially taken into account. For example, the system masses were assigned directly to the mOEM node. In addition, the CeRAS and ATA Chapter description was taken into account. Unfortunately in the documentation which single masses are considered for the description of the system masses.

By converting the energy consumption using the energy density of the fuel, the power takeoffs could be roughly estimated in terms of fuel mass. However, the exchange or power takeoff of the individual systems or the energy flows between the systems cannot be taken into account. In order to enable this data exchange among systems, an XML schema was introduced, which allows the exchange of parameters. With this schema it was possible to consider the power takeoffs for example the EPS and thus improved the calculation of the system mass.

3.2.2 PREMISE and CPACS synchronization

For the design of the CO_2 filtering, the tool PARADISE we developed was used. PARADISE stores its data in its own data format PREMISE. This data format was developed specifically for the early design of systems and exceeds the syntax and semantics of a pure exchange format such as CPACS. In order to be able to synchronize the parameter values calculated in PARADISE to CPACS, the parameters to be transferred were specified in the PREMISE model. These parameters were then used in the calculation model. A tool was implemented to synchronize the parameters between PREMISE and CPACS. This tool carries out the synchronization by using a PREMISE, a CPACS and a file in which the mapping of the parameters is defined are used for this.

3.3 Results on aircraft level

In the ATLAs project, the design parameters were continuously calculated for different configurations of the medium-range aircraft by an overall calculation process. For the configuration (Baseline) the systems were calculated in the usual way without considering any new technologies. For the configuration + CO2 filter the procedure described above was used. Thereby the effects of the change of the ECS could be determined. It was enough to consider only the changes in system mass and energy consumption when calculating the systems. To identify the effects at aircraft level, the changes in system mass in the OEM and the changes in energy consumption using the power supply system were taken into account. These could then be converted into fuel consumption using the required propulsion power. The changes in fuel consumption were considered as mass. The design parameters calculated in the following table were determined for the configuration with the maximum number of 352 passengers.

[3] https://www.cpacs.de/
[4] https://ceras.ilr.rwth-aachen.de/

Table 4 Aircraft system parameter

Aircraft configuration	Baseline (D250)	+ CO_2 Filter	[%]
Block fuel [kg]	29418	28470	-3.2
Reserve fuel [kg]	3743	3636	-2.9
MTOW	137699	136830	-0.6

Table 4 shows the integration of the CO_2 filter system has the effect of requiring 1,055 kg less fuel. This effect alone can justify the additional mass of 522 kg. If the change in MTOW of 869 kg is also taken into account, the integration shows a positive effect in relation to the aircraft mass. Our observation is that by saving bleed air the performance of the engines is improved. This reduces fuel consumption and saves an additional 174 kg of engine mass. Using the 6160 kg dry mass of a Rolls-Royce Trent 772C-60 (A330) about 2,8°% weight can be saved. Therefore, our estimations indicate that the integration of a CO_2 filter system can offer an advantage for the operator by saving fuel as shown in Table 4.

4. Summary and Conclusion

In this work, a systematic approach to evaluate the impact of various system architectures was presented. It was shown that with this method it is possible to continuously investigate the impacts of a system. Thus, different system solutions can be examined simultaneously in the early design phase and the most promising solution can be identified by a trade-off analysis.

By using Brown Paper sessions in the beginning of a project the impacts of a system can be identified by domain experts. The identified impacts are represented as cause-effect relations in a system cause-effect graph. In addition, the identification of the impacts allows a better understanding of the system. In this work a cause-effect graph of the CO_2 managed cabin, incorporating CO_2 filtering and O_2 enrichment was derived from one brown paper session.

By implementing these identified impacts in a calculation model, the effects on the other parameters can be investigated at any time by changing one system parameter. This enables a fast feedback for previously made design decisions. So, it was possible to cancel the analysis of O_2 enrichment due to a great mass and energy consumption, in early stage.

The separation between system and aircraft level results in a loose coupling of the calculations between system and aircraft level. This simplifies the development of the calculation models and further developments can be made successively. Further, it enables a precise control of the resources needed for the calculation compared to the calculation accuracy. As shown in chapter 4.3, an accuracy of the results is achieved with that the decision whether a technology has the potential for integration is made. This was shown by the CO2 filter system example, by saving mass and fuels on aircraft level. Thus, the presented method can be used as a basis for decisions in the early design and evaluation of systems.

Based on our experience, the creation of the calculation model could be partially automatically generated. Thus, for the calculation of mass and energy consumption, an algorithm can be implemented which adds up the sub-masses or energies of all physical system components according to the Bill of Material. In addition, definitions for calculations of parameters could be derived from the cause-and-effect relationships. For these definitions, suggestions for implementations already existing in libraries can then be made.

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