Modeling and Simulation of novel Environmental Control System for a combat aircraft

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Division of Machine Design

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Modeling and Simulation of novel Environmental Control System for a combat aircraft

Master Thesis in Dynamic System Simulation and Design Optimization
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Linköping, June 2017
Abstract

The present thesis deals with the analysis of Environmental Control System (ECS) as a part of the aircraft conceptual design. The research focuses on developing methods for modelling, simulation and optimization of current and future cooling technologies suitable for aircraft applications.

The work started with a pre-study in order to establish the suitability of different cooling technologies for ECS application. Therefore, five technologies namely, Bootstrap (BS), Reverse-Bootstrap (RBS), vapour cycle system (VCS), magnetic cooling (MC) and thermo-electric cooling (EC), were assessed from a theoretical point of view by the method of benchmarking. This resulted into the selection of three most suitable technologies that were further modelled and simulated in Dymola. In order to compare the optimum designs for each technology, the models were optimized using the modeFRONTIER software. The comparison was performed based on the optimum ratio of maximum power of cooling and minimum fuel penalty. The results showed that VCS has the “best” performances compared to BS and RBS. In addition to the active technologies, passive cooling methods such as liquid cooling by means of jet-fuel and poly-alpha-olefin were considered to address high heat transfer rates.

In order to apply the cooling technologies in the ECS, concept system architectures were formulated using the functional analysis. This led to the identification of basic functions, components and sub-systems interaction. Based on the comparison carried out previously and the functional analysis, two ECS architectures were developed. Design optimization procedure was applied further in order to assess each concept and also to study the differences between the two concept architectures. The results depict the complex interaction of different key parameters of the architectures and their influence on the outcome. The study culminated with a proposed methodology for formulation of systems architecture using information from the optimization results and a robust functional analysis method.

To sum up, the thesis proposes a simulation-based optimization method that allows inclusion of ECS system in aircraft conceptual design phase. The study also proves the complexity of the conceptual design stage for ECS architectures which highly influences the design of the combat aircraft.

Keywords: ACD (aircraft conceptual design); ECS (environmental control system); design optimization; functional analysis; modeling & simulation.
UPPHOVSRÄTT

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Linköping, June 2017

Răzvan-Florin-Rainer Gagiu Abin Kakkattil Paulose
"In today’s world of high-speed computer programs, sophisticated analysis, and computer-aided-design, the need still remains for quick, cursory methods of estimating weight, especially for early conceptual studies. One might say that there is still a need to take a quick look at the forest before examining a few of the trees”

-D.P. Marsh (1982)
# Nomenclature

## List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta T$</td>
<td>Temperature drop</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Pressure drop</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>$\gamma_v$</td>
<td>Flight path angle</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>$\dot{m}_b$</td>
<td>Mass flow rate of bleed air</td>
</tr>
<tr>
<td>$\dot{m}_r$</td>
<td>Mass flow rate of ram air</td>
</tr>
<tr>
<td>$a$</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>$A_f$</td>
<td>Free flow area</td>
</tr>
<tr>
<td>$b$</td>
<td>Gap width hot side</td>
</tr>
<tr>
<td>$br$</td>
<td>Gap width cold side</td>
</tr>
<tr>
<td>$C_P$</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$e$</td>
<td>Heat exchanger effectiveness</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Heat transfer coefficient for cold side</td>
</tr>
<tr>
<td>$h_h$</td>
<td>Heat transfer coefficient for hot side</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$k_p$</td>
<td>Gradient for power-off take</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Bleed air factor</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Number of gaps in the heat exchanger</td>
</tr>
<tr>
<td>$n_E$</td>
<td>Number of Engines</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>Volume flow rate</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$T$</td>
<td>Thrust force</td>
</tr>
<tr>
<td>$T_{TO}$</td>
<td>Take-off thrust</td>
</tr>
<tr>
<td>$U$</td>
<td>Overall heat transfer coefficient</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of system</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$W$</td>
<td>Mass of system</td>
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACD</td>
<td>Aircraft Conceptual Design</td>
</tr>
<tr>
<td>ACM</td>
<td>Air Cycle Machine</td>
</tr>
<tr>
<td>CAVE</td>
<td>Collaborative Aircraft Vehicle Engineering</td>
</tr>
<tr>
<td>CD</td>
<td>Conceptual Design</td>
</tr>
<tr>
<td>CE</td>
<td>Conceptual Engineer</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CMDO</td>
<td>Collaborative Multidisciplinary Design Optimization</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>DO</td>
<td>Design Optimization</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiments</td>
</tr>
<tr>
<td>ECS</td>
<td>Environmental Control Systems</td>
</tr>
<tr>
<td>EC</td>
<td>Electric Cooling</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>HEX</td>
<td>Heat Exchanger</td>
</tr>
<tr>
<td>LC</td>
<td>Liquid Cooling</td>
</tr>
<tr>
<td>MHE</td>
<td>Main Heat Exchanger</td>
</tr>
<tr>
<td>MC</td>
<td>Magnetic Cooling</td>
</tr>
<tr>
<td>MDO</td>
<td>Multidisciplinary Design Optimization</td>
</tr>
<tr>
<td>MOGA</td>
<td>Multi Objective Genetic Algorithm</td>
</tr>
<tr>
<td>NTU</td>
<td>Number of Transfer Units</td>
</tr>
<tr>
<td>PAO</td>
<td>Poly-Alpha-Olefin</td>
</tr>
<tr>
<td>PHE</td>
<td>Primary Heat Exchanger</td>
</tr>
<tr>
<td>RBS</td>
<td>Reverse-Bootstrap</td>
</tr>
<tr>
<td>RHE</td>
<td>Regenerative Heat Exchanger</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>SFC</td>
<td>Specific Fuel Consumption</td>
</tr>
<tr>
<td>TMS</td>
<td>Thermal Management System</td>
</tr>
<tr>
<td>ULH</td>
<td>Uniform Latin Hypercube</td>
</tr>
<tr>
<td>VCS</td>
<td>Vapour Cycle System</td>
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1 Introduction

The first chapter of the thesis intends to present a brief description of the content and motivation of the project. Within this section, the environmental control system background is described, followed by specific information of the thesis work flow and challenges.

1.1 Motivation

Environmental control system is the term used for the systems associated with heating, cooling, pressurization, ventilation and humidity/contaminant control in an aircraft. It also supports other functions like demisting and deicing. The ECS design is a challenging task insofar as it has to operate under a wide range of ground and flight conditions in a reliable and efficient manner. Modern aircraft designs are relying on an increased amount of control electronics and electrical actuation systems for better performance. In addition to this, advanced electronic attack devices and weaponized laser systems are also important considerations for future designs as discussed in A. Donovan[19]. This trend poses tough design challenges for thermal management of the aircraft along with increased demands for stealth and efficiency. At the same time, the thermal management of systems are critical in the total safety and function of the aircraft. Using the traditional methods of cooling for the increased load and reduced space would result in unacceptable levels of drag and fuel consumption. These concerns call for an early consideration of thermal management in conceptual design phase of a combat aircraft. Therefore the idea of considering the most suitable cooling technology for a specific aircraft design gains good grounds. The focus of the thesis refers to the analysis and optimization of various cooling technologies using dynamic system simulation, being intended for aircraft conceptual design.

1.2 Background

The conventional method of conceptual design, in general, utilizes low fidelity models for estimation of top level specifications like power consumption, range and overall dimensions of vehicle systems. As Edris et.al states in [20], these estimates are rather vague. The authors of [20] study the use of higher fidelity models early in the concept design phase to reduce the uncertainty and increase the efficiency of the design process. As part of this initiative, different aircraft subsystems are taken into consideration using the tool named CAVE. The environmental control system is one of these subsystems and it utilizes three cooling technologies and an arbitrary distribution of cooling load between them to form different ECS architectures. In CAVE, a particular technology used and a specific fraction of cooling load it handles together forms the desired concept for the cooling system. Since both of these choices hugely influences the the power consumed and also the performance of the system, it is decided to detailed study into the technologies to be used in ECS systems and the architecture which can be formed with them for optimum results during the course of this project.

1.3 Objectives

The main objective of the thesis is to propose an improved methodology in aircraft conceptual design for the development of environmental control systems. In addition, the secondary objective is to propose a semi-generic solution in conceptual design of an ECS architecture. This objective will give a direct implementation of the methodology proposed, resulting in at least one suitable ECS architecture that can be investigated in later design stages, as preliminary design.

Apart from the objectives stated above, the following goals were defined:

- Study the state of the art cooling technologies and appropriate future technologies that can be used in the aviation sector.
- Modeling and simulation of various cooling technologies utilized in a combat aircraft.
- Optimize various cooling technologies with respect to the aircraft specification and a predefined flight profile.
- Evaluate the performance of various technologies, system, and system architectures with respect to power consumption, cooling power generation, mass, volume.
1.4 Research Questions

The thesis’ objectives aforementioned will help in understanding other important topics that are further enunciated in form of research questions as it follows:

- **RQ1:** To what extent does the fidelity\(^1\) of the models affect the conceptual design process?
- **RQ2:** Is the selection of tools adequate regarding their availability, compatibility, and fidelity?
- **RQ3:** To what extent CAVE capabilities can be improved?

1.5 Tools description

The software selection depends on the discipline needed to fulfill the thesis objectives but also on the aforementioned limitations. Therefore, Dymola is used for modeling and simulation of the dynamic components and systems, modeFRONTIER is the software chosen for the optimization process, and Visual Basic Application, i.e. the programming language from Microsoft Excel connects Dymola with modeFRONTIER. Likewise, a more detailed description of each tool is presented.

**Dymola** or dynamic modelling laboratory by Dassault Systemes is a simulation environment based on modelica language. Dymola enables simulation of multi-domain dynamic systems by solving a system of equations defined by component models of the system. The models can be customized using programming interface in modelica language [21]. The programming language used in Dymola is **Modelica**, i.e. an object-oriented, equation based language used for developing systems within the mechanical field, electrical field, fluid field, etc. The main goal of this programming language is to model the dynamic behavior of different components in a convenient way [22], by making use of differential, algebraic and discrete equations. The modelica language is used within this project to generate components (e.g. compressor) and also to create the connections between them.

**modeFRONTIER** by ESTECO is a software developed for the multidisciplinary design optimization field, by enabling coupling between various engineering tools (e.g. CATIA, Excel, Matlab). The tool also enables automation of design simulation process and simplify the analysis of the results through a large amount of data visualization, statistical analysis and decision making tools [23].

**Microsoft Excel** is used within this project for its Visual Basic programming feature that helps coupling modeFRONTIER with Dymola. The coupling is necessary because there is no connection between the two softwares, therefore an interface created at Linköping University for the Collaborative Multidisciplinary Design Optimization course is used. The parameter values generated in modeFRONTIER are sent to the excel sheet, followed by running a macro (i.e. generation of a sequence of instructions) that generates a C (i.e. a programming language) code. The C-code is sent to Dymola in order to run the models created and to retrieve the outputs desired back to the Excel sheet for further evaluation.

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\(^1\)Where fidelity refers to the accuracy of the models with respect to the physical systems, E. Safavi [2]
1.6 Thesis work flow

A sequential work flow for the thesis is presented, in which the focus and the basic methods used in different steps of the project are indicated.

Figure 1: Thesis work flow

1. **Defining Objectives:**
   - This phase involves understanding the objectives and defining measure of success in the form of a main objective.

2. **Pre-study:**
   - The development of technical knowledge on the systems involved, previous research and related tools

3. **Modelling and Simulation:**
   - Study of the existing Dymola models of different technologies and building improved models based on the pre-study.

4. **Optimization and comparison:**
   - Optimization of each cooling technology using the modeFRONTIER optimization framework and comparison of different technologies based on the results.

5. **Formulation of architectures:**
   - Functional analysis of ECS based on the pre-study and formulation of candidate ECS architectures with combination of technologies using the comparison study done in previous step.

6. **Optimization and comparison of architectures:**
   - The optimization of formulated candidate architectures using the modeFRONTIER optimization framework for comparison and discussion

7. **Proposal:**
   - Final proposal of methodology and suitable ECS architectures based on the previous steps.
1.7 Limitations

The limitations of the thesis are related to information access, software lack of modules and inaccessibility to physical experiments for validation.

- Lack of information access arises due to restrictions coming from SAAB AB, meaning that confidential information cannot be provided or presented to open public. Besides restrictions from the company, finding reliable experimental data in the open literature is challenging and alternatives as straightforward logic and empirical formulas will be used.

- Dymola software used at SAAB AB contains cooling libraries developed by specialized engineers. However, the software provided by Linköping University contains the basic libraries, meaning that most of the components and connections have to be created.

- Appropriate validation of models created in Dymola should be performed versus physical models, however, this is not possible, the aforementioned alternatives will be used.

- The models provided and used as reference, were created in Dymola, hence they restricted the software used for dynamic simulations. Another tool that could have been used is LMS Imagine.Lab Amesim developed by SIEMENS.

- Development of models, such as the one for the flight profile require, specific data at certain stages. However, due to lack of information an approximation based on the models created in CAVE and the literature was considered.

- Investigation of other tools developed for the conceptual design phase was not possible due to time constraints.

1.8 Report Outline

The present thesis is divided into six chapters, each containing several sub-chapters. Furthermore, the schematic of the report outline is presented in Figure 2.

![Figure 2: Outline of the report](image-url)
2 Frame of reference

The information presented in this section will highlight the study conducted to gain adequate knowledge in the field of aircraft conceptual design, system engineering, dynamic modeling and design optimization. Moreover, this section intends to give a broader perspective of the thesis’ needs in terms of knowledge and understanding.

2.1 Literature review

The literature review section will give insights of previous work done regarding the study of the ECS, aiming to show the continuous research being carried out on this subject.

Xiong Peng discusses in [10] the importance of ECS optimization for passenger aircraft and presents a detailed yet clear schematics of different types of Air-cycle ECS systems. Here a clear methodology of formulating and testing the mathematical model in reference to an actual aircraft is carried out. The modeling platform used is Matlab/Simulink. The work concludes HPWS as better in terms of ram air mass flow, lower expansion ratio, lower weight and higher reliability for a specific aircraft model.

Chen Long et.al investigates a mechanism of energy recovery on a HPWS of a passenger aircraft [24]. The energy recovery mechanism is considered as an augmentation to electric ECS system to reduce its main energy consumption which is compressing the intake air. The paper concludes that there is approximately 36% increase in COP and 8.9% decrease in weight penalty.

Rolando Yega Díaz in [25] presents an elaborate study of ECS systems in both fixed wing and rotary wing aircraft to propose an electric ECS model and compare it with a conventional ECS. The paper draws out a systematic approach to study the ECS systems ensuring that the models under study meet the necessary basic performance requirements. It presents a thorough analysis of the models with Matlab/Simulink as platform. The paper also proposes a method of converting the system penalties in terms of additional fuel weight required and compares them in terms of these fuel penalties. The work concludes that there is a slight increase in total weight penalty with electric ECS but a significant 60% reduction in ECS fuel penalty.

Javier Parrilla in [26] presents a very detailed study of various configurations ranging from conventional to fully electric ECS for a passenger aircraft. The method utilizes a detailed numerical engine model to analyses the effects of various hybrid ECS models. The paper concludes that the hybrid ECS systems are better than both conventional and All-electric systems considering system efficiency together with life cycle costs.

John Fin et.al in [27] presents an analytical methodology for optimization of cyber physical system with ECS system as example. The process is carried out by two step algorithm. The first part named as SELECTION finds a set of discrete combinations which are optimized for cost and weight. Then the next part named as SIZING carries out a continuous sizing optimization for required elements of the system based of the output of the selection program. The sizing algorithm utilizes Modelica based simulations to compare designs.

Rahul Agarwal et.al in [28] presents a study of Conventional, Electric and hybrid ECS systems for combat aircrafts. Different working fluids are investigated for the vapor cycle cooling pack included in the electric and hybrid system. The paper also compares the different system clearly with pros and cons of each. It concludes that hybrid ECS with R136a VCS fluid and fuel as heat sink as the best solution. This suggestion will be investigated in this thesis with one of the ECS architectures.

David Braid et.al in [29] presents a detailed account of the lessons learned during the implementation of liquid cooling units in recent combat aircraft models by Lockheed Martin, mainly F22. Main takeaway from this literature would be the advantages of PAO based on standard MIL-C-87252 in contrast with older liquid coolants used for avionics cooling in ECS systems.

Randy Ashford et.al in [16] presents the detailed architecture of F22 ECS/TMS system. TMS has ram air and fuel as the main heat sinks. It uses two separate liquid loops to transport the heat in a cascading manner to the final heat sink which is fuel. And uses both air cycle and vapor cycle refrigeration. The overall aircraft temperature management or TMS approach present ands opportunity to analyses the interaction of various systems affect ECS function.

Yu-Wei Chang et.al [30] presents an investigation into the effectiveness of thermoelectric cooling device for electronics cooling application in conjunction with another heat sink which is actively cooled. The research findings lead to the conclusion that the participation of the thermoelectric device in the cooling process is limited by both the power of cooling and the maximum input current. This is attributed
to the effect of joule heating of the device which is proportional to input current/power.

2.2 Aircraft conceptual design

The requirements of a design process in the aviation sector, and not only, are divided into two perspectives the manufacturer and the customer’s perspective. Therefore, according to D. Böhneke in [5] the manufacturer strives to obtain a product that generates high income and low cost, whereas the customer seeks for a product with high performances, low-operating costs and, especially for commercial airplanes, high range.

In order to provide a product that fulfills the requirements aforementioned, the product development process has to be divided into clear stages as seen in Figure 3.

- **Conceptual design** stage is based on predefined requirements and targets to generate and evaluate a variety of concepts, resulting in multiple concept proposals that require investigation in the later stages as in E. Safavi [2].

- **Preliminary design** aims to find the properties (e.g. lift over drag) of the concepts proposed in the conceptual design stage [5], culminating with a better understanding of concept capabilities.

- **Detailed design** is the stage where the preliminary concept is analyzed and optimized with respect to certain requirements, thus preparing for prototyping [2].

![Figure 3: Classification of design stages and their impact and tool availability, adapted from L.Wang et.al[1] and E.Safavi[2]](image)

E. Safavi states in [2] that any minor mistake in the CD phase will result "in high design costs and time overruns", therefore continuous research and development of the CD stage is essential. In Figure 3 it can be observed that the greatest impact on the product development process is given in the conceptual design stage and the impact of decision decreases as the product maturity increases. Even though the importance of CD is clear, the amount of tools available for this stage is relatively low. Wang et. al. states in L.Wang, [1], that the lack of tools in CD phase is due to the large variety of unknowns that are present in this early stage. Wang continues to assess the problem of unknowns being influenced by the "product’s life cycle is usually imprecise and incomplete".

2.2.1 Systems engineering in aircraft conceptual design

I. Staack presents a simple and comprehensible description of systems engineering, modeling and simulation concerning the field of aircraft conceptual design in I. Staack [31]. In chapter 3.1, the author gives an explicit guidance that the conceptual engineer should take into consideration, i.e. the process has to be efficient 2, flexible 3, transparent 4 and multi-modal 5. The guidance is confirmed by Daniel Böhneke in [5], with a clear account on transparency, whereas transparency, according to the author, refers to the

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2I.e. low-effort.
3I.e. easy to adapt to certain situation in CD.
4I.e. easy understanding by the user.
5Referring to the ability to enable automation or manual mode
capability of tracing the qualitative and quantitative physical dependencies. Böhneke adds to the list also extensibility, referring to the ability to further incorporate more physics into the system.

From a different perspective, I. Staack states that systems engineering in ACD is a complex stage that can not be performed by experts on a topic (e.g. CFD expert), the work being more appropriate to one person or a small team. An adequate conceptual design phase is described by Staack as low-effort, short-term tasks, vague and incomplete requirements formulation. Knowing this, one can understand that conceptual design phase is a remarkably difficult stage for any engineer due to the "thin line that one must walk on", where not sufficient information given to the concept can result in discarding a potentially good concept and too much information will restrain the conceptual engineer to explore various fields.

2.2.2 Functional analysis in systems engineering

Functional analysis is an important tool for examining new concepts and forming their architectures, being applicable in all design phases, especially in conceptual design. Likewise, N. Viola et.al. noted in [3] that one can use functional analysis to refine product functional requirements, understand relations between components or verify if components used are sufficient.

In order to reach the project’s objectives, the process depicted in Figure 4 presents specific tasks that one must follow. Moreover, the tasks presented in Figure 4 are defined by N. Viola et. al. as it follows:

- **Functional tree** allows splitting the higher level functions into lower level and then to basic functions that are to be performed by the newly created concept. By higher level functions it is referred to complex functions that are formed through the means of multiple other functions. This stage is essential in the functional analysis as it gives the engineer important information about what does the product do. Moreover, a physical view will be complementary to the functional view as it will reveal what is the new product.

- Functions/components matrix is "to map functions to physical components" as in N. Viola et. al. [3]. This task is performed by assessing the basic functions and finding which component does that function, resulting in the end with at least one component for each function.

- The product tree will result by adding the basic components through a bottom-up process.

- Connection matrix is used to map functions to physical components through creating either a triangular or a square matrix. In addition, the rows and columns of the matrix will show how the components are connected and which components exchange information.

- The functional block diagram is another mode of representing the connection matrix, this time by using a schematic that connects different functions.

![Functional analysis process chart](image_url)

Figure 4: The functional analysis process chart, adapted from N. Viola et.al[3]
2.3 Modeling and simulation

A system is a whole formed by a set of components that interact continuously releasing within certain boundaries an outcome. S. Steinkellner defines the model in [32] to be the simplification of a system or a component and the experiment made on a model being labeled as a simulation.

2.3.1 Causal versus acausal

The causality is defined by Steinkellner in [32] as the property of cause and effect in the systems, in other words causality is the approach taken to solve an equation or a system of equations. Therefore, the solution of a system can come from a causal approach, i.e. a conventional way of solving the problem, or through an acausal approach. In order to gain a better view of the terms, let us consider the examples in Figure 5. In Figure 5a, X is the unknown, hence it is a simple conventional form of solving the problem, however when C is the unknown and X is known (see Figure (5b)), one must solve the problem in a acausal mode, i.e. a more unconventional mode.

![Figure 5: Example of a causal and acausal systems/problems](image)

In modeling and simulation, the causality will give a better view upon the modeling technique and tool selection. In acausal models, the causality is not specified thus the simulation tool has to sort the equations within the model, whereas in causal models the inputs and outputs have to be declared by the user.

As observed by I. Staack in [31], it is preferably to have an acausal implementation, with a clear view upon the entire system and with more flexibility in varying the parameters. The statement is confirmed also by S. Steinkellner, adding that one can let the tool to sort out the equations order for finding the unknowns.

2.3.2 Modelling techniques

Moving on to the modeling techniques, M. Eek makes a classification of modeling approaches in [4], separated as seen in Figure 6 into two branches single-flow modeling and power-port modeling respectively.

![Figure 6: Classification of modelling approaches adapted from M.Eek [4]](image)
• **Single-flow modeling**, where the engineer has to define the causality, i.e. inputs and outputs. The information flow in this approach is *unidirectional* at each node, being mostly used in Simulink (a block diagram environment for multidomain simulation and Model-Based Design[33]).

• **Power-port modeling** is a more compact approach, where the component-based modeling is used due to the *bidirectional* information flow which allows a more real match to the physical connections. The complexity of this approach stands within the possibility of choosing the type of solver, i.e. *centralized* solver also called lumped parameter modeling, or a *distributed* solver further called distributed modeling. The difference between this two solvers is that in the first one the equations are collected in one ordinary differential equation (ODE) or differential algebraic equation (DAE) and further solved, whereas for the distributed solver is based on bilateral delay lines meaning that each component solve its own equations independent of the system due to a time delay introduced.

2.3.3 Trade-offs

M. Eek discusses in [4] about the necessity of finding and implementing the "exact" amount of details in order to simulate the "correct" physics. Moreover Eek talks about the structural trade-offs when modeling dynamic systems. Knowing this, the author states that the conceptual engineer should identify the following trade-offs:

• **Generality between domains**, meaning that one component can be used in more than one domain (e.g. a pipe can be used for both liquid cooling and inserting air in the combustion chamber [4])

• **Generality inside the domain** (e.g. pipe resists for both laminar and turbulent flow)

• **Level of inheritance**, where the engineer should think in advance whether the model will be used in other applications so that more time will be invested in its details or not.

• **Graphical or textual modeling**, where the CE should know if the model will be used as a block or if it should remain as code.

2.3.4 Calculation structure

This sub-section takes the conceptual design phase onto a higher level of complexity and it should be treated as a recommendation that can be taken into consideration when models are created to be further optimized. Therefore, besides the trade-offs proposed by M. Eek, D. Böhnke states in [5] that a clear decomposition of components and disciplines involved in an a/c has to be performed. The author discusses about two different calculation structures, **sequential** and **cascade**, the later being the one used in [5]. The calculation structure will provide the conceptual design software with more information regarding the dependencies between the parameters. For that reason, achieving a good understanding of the calculation flow, one can make use of it in its favor.

![Figure 7: Calculation structures adapted from D. Böhnke[5]](image_url)
• **Sequential** structure depicted in Figure (7a), is a rigid calculation with a large uncertainty within the convergence of the parameters. This type of structure monitors only certain parameters concluding with fast but debatable results.

• **Cascade** structure illustrated in Figure (7b) computes all parameters at once, therefore it requires a dependency between them. The main disadvantage with this structure are the difficulty to provide adequate relations between parameters and considerably higher computational cost.

### 2.3.5 Modelling strategies

In design engineering obtaining an accurate model starts with selecting the right information processing and order. Therefore, depending on the knowledge and purpose of the project one should choose between the following approaches:

• **Top-down** approach is widely used in many fields and especially in conceptual engineering field, starting from an abstract idea and project needs to a more rational design and then to a physical implementation [34]. This approach requires extensive planning and a structured control of the project in order to achieve the desired outcome.

• **Bottom-up** approach starts with a focus on lower-lever components and how they can be interconnected and only after the components have been validated, one can attempt to form a concept. In [34] this approach is said to be used for reverse-engineering, due to the helpful information that can be gathered about the process by studying the components.

  Proceeding even further into the strategies adopted in CD, S. Chiesa et. al. noted in [35] that a typical top-down approach is mostly used for developing a new product and in order to integrate it, a bottom-up approach is used. This can be transposed into a V-diagram, also known as a V-model which depicts the development of a product from conceptual design, to preliminary design and lastly to the detailed design.

![Figure 8: V-diagram of system processing](image)

In Figure 8, a V-diagram adapted for the conceptual design phase is presented, showing the strategy that should be taken for achieving the needs. Therefore, within the *system design* phase one should start understanding the system requirements through a thorough pre-study, followed by system and sub-systems strategic development, the phase being ended with the design of the components. The process is continued during the *system integration* phase, where validation and verification is required, giving a better understanding of the components and sub-systems capabilities, followed by the assembly of components into sub-systems that further form the system architecture. The final step of the phase is to verify to what extent the system fulfils the requirements and through what means they can be achieved.
2.3.6 Validation and verification

The last stage in design engineering is to assess the models and the concepts created. According to S. Steinkellner in [32], the validation answers if the right thing was build, and verification shows if the model was build right. Steinkellner continues by stating that the verification is done firstly when the code written is error-free, followed by verifying if the programming language has been used accordingly. Contrariwise, validation cannot be done within the early phases because of the lack of data, however one can use sensitivity analysis to perform validation once enough information has been accumulated. Sensitivity analysis will give the user a good understanding of what are the most influential parameters, how they affect the final result and also to what extent they influence other parameters.

It is essential to mention that validation and verification is a difficult procedure for early stages as the conceptual design, being argued and exemplified by both S. Steinkellner in [32] and I. Staack in [31].

2.4 Design optimization

Design optimization is the process done by engineers to achieve the most adequate design parameters of a model, under certain constraints and boundaries. This procedure is done by using a mathematical process that will try to fulfill the condition of minimization or maximization of a specific function. DO is a decision making tool that strives to obtain the best possible solution when contradicting objectives and conflicting constraints appear. Therefore, one should understand that there is no perfect solution for a design problem but a solution that meets objectives considering the time and funds available [8].

2.4.1 Optimization process

The first aspect observed in an optimization process is the behavior of the system within modeling and simulation. Equally important to the behavior of the system is to recognize the expectations, because very often the expectations are not feasible or "not imaginative enough" [8].

Furthermore, a generic optimization process is depicted in Figure 9, from which one should gain a better understanding of the steps performed and the factors of interest. Within this steps the design variables play a significant role as they represent the starting values of the problem, that are changed continuously within the optimization process. Contrariwise, the operating variables are those variables that can be changed by the user after the design is finished, and environmental variables represent the environmental factors that affect the design (e.g. wear). Moving on to the system characteristics, within the optimization process is represented through dependent variables or design characteristics, i.e. variables that the designer cannot influence. The system characteristics are further influenced by state variables, referring to those variables that are required to connect the design variables with the design characteristics, that often acting as constraints. In the end of the process, the optimization method "tries" a new set of design variables, based on the objective fixed by the user, hence formulating the objective is as mentioned by J. Ölvander in [8] "a vital part of design optimization".

Figure 9: Generic optimization process, adapted from J. Ölvander [6]

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6 Different conditions or bounds of the design variables represented through numerical values. The constraints are usually represented as an equality or inequality.
### 2.4.2 Problem formulation

The most important phase of any optimization process is the problem formulation, thus one should determine the number of design parameters, type of problem, dimension of the design vector and objectives vector. The aforementioned formulation is represented in the generic example seen in equation (1).

\[
\begin{align*}
\text{min} & \quad F(x), \quad \text{i.e. Objectives} \\
\text{s.t.} & \quad g(x) \leq 0, \quad \text{i.e. Inequality constraints} \\
& \quad h(x) = 0, \quad \text{i.e. Equality constraints} \\
& \quad x_{\text{LB}} \leq x \leq x_{\text{UB}}, \quad \text{i.e. Variable bounds (Lower and Upper bound)}
\end{align*}
\]

where \( F = [f_1(x) \ldots f_z(x)]^T \)

\[
x = [x_1 \ldots x_i \ldots x_n]^T, \quad \text{i.e Design vector}
\]

Additionally, the most important features that influence an optimization problem are presented according to [2].

- The type of problem may require a local or global optimization, where local optimization refers to finding the minimum or maximum point (depending on the objective of the problem) in a certain region. On the other hand, global optimization searches for the minimum or maximum point in the entire design space (i.e. combination of design variables and the objective function). The difference between the two types of problems is that not all algorithms can provide a global optimum (i.e. the "best" point) from the beginning, yet all algorithms are capable to provide local optimum and then "try" to search for the global optimum.

- The number of objectives is important because a single-objective problem aims to find the "best" solution for one pre-defined objective, hence that can be one objective or a gathering of objective functions into one objective. Contrariwise, the multi-objective problem is encountered more often in practice when multiple objectives are opposing, therefore a compromise solution will be searched, titled as a Pareto-optimal solution.

- The variables of the problem can be continuous meaning that the variable can take any value between two values, or discrete variables may be encountered, being those variables that can take only certain values (e.g. only integers).

### 2.4.3 Optimization algorithms

The optimization methods are, according to M. Tarkian in [7], used to "effectively automate the iterative and time-consuming process of design that involves finding a suitable trade-off. As seen in Figure 10, there are many optimization methods, however, the focus will be on the numerical optimization methods as they are widely used within the design engineering field.

J. Ölvander et.al. remarks in [36] two families of optimization methods, gradient and non-gradient, or zero-gradient as defined by Tarkian in [7]. The gradient method is mainly used "where the gradient of the object function can be calculated explicitly at each point", whereas non-gradient method are for more general use because the gradient is not generally available to be calculated for each point. From a different perspective, J. Ölvander et.al. describe the gradient based methods as local optimizers focusing on finding the optimal point close to the starting point, and non-gradient method as global optimizers.
A wide investigation of the optimization algorithms is not the purpose of this paper, therefore two relevant non-gradient methods will be described, those being the blocks colored with blue in Figure 10. The methods chosen are related to the algorithms found in the optimization software used for the project, i.e. modeFRONTIER.

A. The simplex method is a single objective method developed by J.A. Nelder and R. Mead more than 50 years ago, and its use is described by the authors in [37] as "not to estimate parameters in a regression equation but to guide the direction of the next move". Moreover, the method is described as being highly opportunist because any past information from previous position is discarded and only the necessary information is used at each stage. Taking into consideration that this is a minimization method, false convergence can appear at a point other than the minimum for surface applications as to a domain with high steeps, long and fluctuating shape.

An updated simplex algorithm is used in modeFRONTIER, therefore it is important to mention its main features as in S. Poles [38].

(a) Obey boundary constraints on continuous variables.
(b) Allows user defined discretization (base).
(c) The number of variables + 1 independent points of the initial simplex can be evaluated concurrently.

The first n+1 entries in the DOE table are used as the initial simplex for the local optimization problem.

B. Genetic algorithm is an evolutionary algorithm, meaning that it is based on natural evolutionary processes. The GA creates a random population of possible solutions (called individuals), from which only the fittest survive over time after a process based on Darwinian theory of natural selection. The method distinguishes through its particularity of using a binary encoded genome that evolved using selection, recombination and mutation [8]. A simple representation of a GA process can be seen in Figure 11, where after the population has been initialized the fittest individual is selected for mating, the result being new a child. The child is produced by a process called crossover, to which mutation may appear that can result into a fitter child. The process is ended after a new generation is formed with the created children and then the process starts over again until the population converges or if the maximum number of generations is achieved. J. Ölvander describes in [8] the end of the process as "an artificial Darwinian environment", due to its similarity
with the Darwinian theory where it is said that only the strongest individual will survive in a certain environment.

![Simple process of a genetic algorithm, adapted from [8]](image)

There are many genetic algorithms available in modeFRONTIER, however only the description and features of the **Multi Objective Genetic Algorithm II** will be presented further. First of all, MOGA-II is known for its efficient use of multi-search elitism that is able to preserve good solutions without premature convergence into a local-optimum as in S. Poles[39]. Moreover, the algorithm has few-predefined user parameters, however one should take into consideration that the number of DOEs should be more than \(2 \times \text{number of variables} \times \text{number of objectives}\). Likewise, the main features of MOGA-II are the following:

(a) Supports geographical selection and directional cross-over.

(b) Implements elitism for multi-objective search.

(c) Enforces user defined constraints by objective function penalization.

(d) Allows generational or Steady State evolution.

(e) Allows concurrent evaluation of independent individuals.

The number of individuals (N) entered in the DOE table are used as the problem’s initial population.

### 2.4.4 Design of experiments

Design of experiments is a technique used to generate samples that fulfill several conditions strictly related to the objectives of the analysis that will be performed. In Figure 12, one can observe what is meant by a design space, thus selecting the suitable sampling technique is extremely relevant for any optimization process. The main factor that determines the difference between a poor and a good design space filling is that one can explore different variables in a stochastic way, the user affecting this procedure only by inputting boundaries for the design variable.
The DOE techniques are divided into two types, **deterministic** and **random** [5]. The deterministic technique ensures an even distribution of samples over a domain, one example of such algorithm being the **full factorial**. Contrariwise, the random technique is the procedure of selecting random samples using probability and statistics, thus each sample having the same probability of being selected when the process starts. Two common random sampling techniques are **Monte Carlo** and **uniform latin hypercube**.

Table 2 presents a comparison between three different types of DOE sampling. Additionally, one can understand that the "best" technique is problem related, however from a design optimization point of view the **ULH** has proven to be satisfactory in other papers, such as in [2] by E. Safavi [2] or in [5] by D. Böhnhke.

### Multidisciplinary design optimization

**Multidisciplinary design optimization** is an engineering practice that incorporates interaction between multiple disciplines and makes use of different design optimization methods to find the optimum parameters. In Figure 13 an example of how the disciplines are interacting can be seen, hence one can observe that all disciplines are dependent on a 3D model, i.e. a CAD model, while dynamic modeling (DYM) and CFD are dependent on both CAD and Finite Element Method. On the other hand, MDO is not compatible with this project because there is only one disciplines involved, i.e. dynamic modeling, however a brief explanation is required as its capabilities can be further used for later projects or the later stages as preliminary design and detailed design.
The main reason for using MDO in any engineering project is that the performance of a system in real life is given by the interaction of several disciplines. Moreover, MDO requires careful preparation of the discipline analysis models and of the software used. Thus, a combination of problem formulation and organizational strategy is best known as MDO architecture \[40\], where one can observe the coupling between models and the approach taken to solve the optimization. Joaquim et al. discusses in \[40\] about two different architecture types monolithic when a single optimization problem is solved and distributed where the same problem is divided into sub-problems each having their own variables and constraints.

2.5 Pre-study

The pre-study intends to present the background information required for developing and implementing a methodology for the study of an environmental control system in conceptual design phase.

2.5.1 Mission profile

Mission profile refers to breaking down the mission as in S. Gudmundsson\[41\] that has to be fulfilled by the pilot (e.g. survey a conflict area) into specific stages. The typical stages breakdown are represented as it follows: taxi\(^7\), takeoff, climb, cruise, loiter\(^8\), cruise, descent and landing. This typical mission is called a high-low-high mission \[41\], where “high” and “low” terms represent the altitude of the aircraft during the flight.

In addition to the altitude fluctuation during a mission profile, another important factor is the velocity of the aircraft. The velocity is measured using the Mach number, i.e. a ratio of the speed of a body with the speed of sound in the surrounding (e.g. in dry air at 20\(^\circ\)C, \(a=343\text{[m/s]}\)). In Figure 14, some common examples are presented in order to gain a better understanding of this dimensionless quantity. Therefore, one can see that a super car (e.g. Lamborghini Aventador) has the top speed, converted into Mach number, close to 0.3 (Top speed 350\text{[km/h]}, i.e. Mach=0.28 as in C. Florea\[42\]), whereas an Airbus A320 exceeds Mach number 0.8 \[43\] but as seen in Figure 14 it does not reach supersonic speeds as a fighter-jet (e.g. Gripen developed by SAAB AB).

The altitude and the velocity of the aircraft are extremely important factors that influence the behavior of an aircraft system. For an ECS these factors influence quantities such as pressure, mass flow rate, temperature and density, that are extremely important in the operation of the system.

2.5.2 Collaborative Aircraft Vehicle Engineering

Daniel Böhnke discusses in \[5\] about the existence of many CD codes as AAA (Advanced Aircraft Analysys \[44\]), FLOPS (Flight Optimization System \[45\]), MICADO \[46\], PASS\[47\]. However, due to lack of information and time-constraint, the focus will be on a tool developed at Linköping University to assist aircraft systems design, i.e. Collaborative Aircraft Vehicle Engineering CAVE is a tool developed in Visual Basic Application on the Microsoft Excel platform where dynamic models of the aircraft systems are developed in Dymola and integrated further \[2\]. In Figure 15 one can see the work-flow performed by CAVE in order to deliver the desired outputs, i.e. power of cooling for example. The philosophy behind CAVE is to ease the collaborative design by adopting a modeling strategy that is required to be generic and parametric. This can be represented through a main entity

\(^7\)i.e. driving to the designated area for departure and driving away from the landing area

\(^8\)i.e. performing the mission)

Figure 14: Mach number examples for different vehicles

2.5.2 Collaborative Aircraft Vehicle Engineering

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\(^7\)i.e. driving to the designated area for departure and driving away from the landing area

\(^8\)i.e. performing the mission)
that is required by the conceptual engineer and even though the systems communicate through power, the communication of lower level components “is defined by the characteristics of the system” [2] (e.g. temperature, pressure and mass flow rate). Another important characteristic of CAVE is the possibility of using inverse models, i.e. models where one can transform inputs into outputs and reciprocally.

In Figure 15, the methodology of CAVE is presented. In the beginning the tool computes the power consumed by the heat loads (actuator system), further part of the total power is given as heat load to the cooling architecture and in the end the average power required by the architecture is simulated in the electrical generation system.

In order to make use of CAVE and its capabilities the conceptual engineer has to pursue the following steps:

- Select actuator type and number of actuators to be simulated. Further the conceptual engineer has to select the amount of cooling in percentage, which has to be catered by the ECS.

- The tool proposes three cooling technologies, i.e. Bootstrap, Reverse-Bootstrap and Vapour Cycle System. Here the user has to specify the amount of cooling that has to be done by each technology in percentage. Moreover, if the user wants the cooling architecture to cool itself one might give values above 100%.

- Related to the previous step, the user has the possibility to change various parameters at a component level, for example one can change the effectiveness and dimensions of the heat exchangers used.
2.5.3 Technology

The following section will give the reader a good understanding of the cooling technologies and corresponding components used nowadays within the aviation sector. Moreover, one can read about future cooling technologies that should be considered at least in the conceptual design stage.

2.5.3.1 Description of components

This section defines the components and their names in the context of the thesis, being required for a better understanding of the actual work.

1. Heat exchangers

Heat exchangers facilitate the heat transfer between two fluids separated throughout the entire process by a solid or between solid particles and a fluid, having the capability to provide cooling or heating depending on the need. They are used in many industrial applications such as: power plants, petrochemical plants, aerospace, etc., and are classified as seen in Figure 17, into two groups recuperative and regenerative. The main difference between this two classes is that within the recuperative HEXs the fluids flow simultaneously transferring the heat from one side to another continuously. On the other hand in a regenerative HEX the hot and the cold fluids pass alternatively through the same path as in R. J. Brogan[48], "washing" the solid surface independently, thus transporting the energy from one fluid to another.

![Figure 17: Flowchart for the classification of heat exchangers](image)

Another important consideration is the type of flow arrangement. Thus the flow inside a HEX can be counter (see Figure 18a), concurrent (see Figure 18b), cross (see Figure 18c) or hybrid. The recuperative heat exchangers are typically designed to have a cross-flow or a counter-flow, being normally used within the air supply and exhaust applications. Contrariwise, the regenerative heat exchangers are mainly used in large gas/gas heat recovery applications, as they provide considerably better heat recovery than the recuperative [49].

---

[48] i.e. a combination of the aforementioned types [48]
Plate-fin heat exchanger

The need for lightweight and compact components is extremely important in the aerospace sector, therefore a plate fin heat exchanger is normally used. The plate-fin heat exchanger is a compact HEX made out of blocks of fins and flat separators. The fin geometry is chosen depending on the fluid flow and on the performances desired. In Figure 19 the geometry of a straight fin is represented along with the influencing parameters, i.e. width, height, length and thickness ($\delta$).

Regenerative heat exchanger

It is a type of HEX where the heat from a packing that has the required thermal capacity is stored temporarily (see Figure 20) by using a matrix disc that rotates at low speeds. The main advantage of using the regenerative HEX is that it achieves a higher pressure drop and the surface area is considerably larger, hence more cooling produced. On the other hand, when there is more surface it means that there is more material thus more weight is added to the system and besides this disadvantage, there is also an issue of leakage of the gases.
2. **Compressor**

Compressor is used to increase the pressure of a fluid. In general, it consumes work and raises pressure and temperature of the fluid. In this document, it can be a centrifugal compressor used in air cycle systems or a reciprocating compressor used in vapour cycle systems.

![Compressor schematic](image)

**Figure 21: compressor schematic**

3. **Turbine**

Turbine is used to harvest energy by expanding a high pressure gas. In general, it provides useful work and reduces pressure and temperature of the fluid. Here, turbine is a radial inflow turbine used in air cycle system to expand the compressed air to recover energy used in compressor.

![Turbine schematic](image)

**Figure 22: Turbine schematic**

4. **Pump**

Pump is used to induce flow of fluids. Here, it is used in liquid cooling to circulate PAO oil in the system or used in fuel system to supply fuel to engine.

5. **Avionics**

Avionics refers to the electronic package essential for the flight control of an aircraft. Here, it represents all essential electronic hardware needed to be temperature controlled during flight.

6. **Evaporator**

The evaporator is a component used in refrigeration systems having the purpose to heat the refrigerant until it reaches the boiling point transforming its phase from liquid to vapour. The evaporator depends on the type of convection\(^{10}\). Therefore, there are two types of evaporators depending on the method of applying the convection process:

\(^{10}\)Heat transfer due to diffusion (i.e. random molecular motion) or by fluids motion F. Incropera et. al. [50]
• **Natural convection** appears when the buoyancy forces induce the flow. The forces are generated when there is temperature variation in the fluid, causing density differences [50].

• **Forced convection** appears when the flow is induced by external forces, generated by a fan, a pump or wind [50].

Generally speaking, an evaporator is basically a heat exchanger, thus it has similar construction and principles. The only difference being, there is a phase change of medium due to the heat transferred. There are three types of evaporator constructions [51]: plate surface, bare-tube and finned. Within the aviation sector, finned evaporators are common because of its extended surface area that results in better heat transfer capabilities. The extended surface gives better advantages because it reduces the size, weight and cost of the component.

7. **Expansion valve**

The expansion valve plays a significant role in a refrigeration system, because it reduces pressure of the refrigerant before entering the evaporator. By reducing the pressure the refrigerant also loses its temperature [51].

8. **Condenser**

The condenser is the component used in a refrigeration system to change the state of the refrigerant from vapour to liquid, utilizing the vapours increased pressure and temperature. Similar to the evaporator the condenser is a type of HEX, that uses forced convection to produce cooling of the refrigerant.

Within the aviation sector, the condensers used are multi-pass due to the smaller sizing and higher efficiency obtained. From a fluid perspective, a concurrent flow arrangement (see Figure 18b) is typically used, requiring a manifold tube on each end to allow the free flow of the refrigerant.

9. **Jet engine**

A brief description of a typical engine used in airplanes is required, as it is highly important when it comes to investigation of an ECS. Furthermore, because there are many types of jet engines (e.g. Turbojet, Turbofan, Turboprop, etc.), the turbo-fan engine process is described due to the fact that it is commonly used in a combat aircraft.

In simple terms, a jet engine is the system that produces enormous thrust\(^{11}\) causing the aircraft to fly. In order to generate thrust the engine absorbs a large amount of air that is increased by using a fan, sending it forward to the compressor where the flow is slowed down and pressure increased by "squeezing" it. Along with the increase in pressure, the temperature is increased as well, and part of the air flow is sent to the ECS as **bled air**. Moreover, the compressed air is sent in the combustion chamber where it is mixed with the fuel and ignited, reaching temperatures up to 3000 °C. The high energy airflow is sent to the turbine making it rotate and because the turbine and the compressor are connected through a shaft it rotates compressor also. The last part of the engine is the nozzle, or the exhaust of the engine, i.e. the part that produces the thrust.

2.5.3.2 **Bootstrap system**

Bootstrap system utilizes air cycle refrigeration and atmospheric air as working fluid. It is the most common technology used in aircraft ECS systems as in X. Peng [10]. Even though the COP of air cycle system is comparatively lower than that of other refrigeration systems such as VCS, the Bootstrap system provides weight advantages, as the working no additional heat exchanger is needed to cool the air for ventilation. In addition to those, the facts such as, it is power saving as the expansion power is harvested using turbine, heating and cooling can be controlled using the same system and it provides integration of pressurization and air conditioning makes it more suitable for the application as in E.L. Zaparoli et. al. [52].

\(^{11}\)i.e. the forward force that pushes an airplane to move forward.
Figure 23: Schematic of Bootstrap system, adapted from X. Peng [10]

Figure 23 depicts a simple Bootstrap system where bleed air from engine compressor is used as input charge air. The bleed air is cooled with a primary heat exchanger and then fed to a compressor. The compressed air is again cooled using the ram air flow. The cooled pressurized air is then expanded through turbine and sent to the mixing unit where it is mixed with hot air streams to maintain the required temperature before sending it to cabin/cockpit.

2.5.3.3 Reverse-Bootstrap System

In the paper published almost three decades ago by Gregory L. DeFrancesco [53], the Reverse-Bootstrap refrigeration system is described as an alternative for the Bootstrap system that can be used under certain circumstances. According to DeFrancesco, RBS is a technology that has less components resulting in a lower weight and a smaller volume, good cooling capabilities under limited heat sink and in low pressure applications. On the other hand, because of its low pressure these advantages are impractical when the cooling technology is required to deliver suitable pressure and temperature to the cabin or when the aircraft is on the ground. The RBS process starts similarly to the Bootstrap system, the bleed air being cooled in a primary heat exchanger. Furthermore, the configuration changes completely and one can see that the air is expanded through a turbine first, being sent over the avionics (or a loop that requires cooling) and further it is compressed overboard. The main difference between the BS and RBS, from the flow perspective, is in the usage of the turbine immediately after the PHE that by expanding the air results in a decrease in temperature but also a decrease in pressure.

DeFrancesco describes an improved RBS system, i.e. B-1 regen pack re-configured into a RBS, where one makes use of a regenerative heat exchanger as a secondary heat exchanger. However, the usage of a secondary heat exchanger will increase the weight and the size of the cooling system considerably, more than that, the regenerative heat exchangers are substantially heavier than a normal heat exchanger. Overall, this approach neglects the main advantages of the Reverse-Bootstrap system, resulting in a more complex technology than desired at first.
Ian Moir et.al adopts a totally different approach when describing the RBS in [11]. What was described as an improved RBS, Moir describes as the conventional RBS and the system described as a Reverse-Bootstrap by DeFrancesco is considered to be a “Ram-Powered Reverse Bootstrap”. Taking into consideration the technological advancements in both military and commercial aviation sectors, it is obvious that the heat loads have increased considerably and the RBS described in [53] can be used mainly in locations where air supply from the main ECS maybe deemed impractical.

2.5.3.4 Vapour cycle system

Vapour cycle system is considered to be one of the most efficient refrigeration system used in aircrafts nowadays, with a efficiency up to five times higher than a conventional air cycle machine. On the other hand, the main disadvantage of the VCS is the weight of the system (almost 50% heavier than ACM) due to the refrigerant used, i.e. Freon, which is also toxic. Moreover, even though its efficiency is very good the temperature range is limited (maximum temperature of refrigerants up to 70 °C). In Figure[12], the schematic of the VCS can be observed. The process is similar to the system used in the home refrigerators, where the high pressure refrigerant is expanded in order to reduce its pressure before being sent to the evaporator that is in contact with the heat source, the heat being sent over the evaporator coils generating forced convection and changing the phase of the freon from liquid to vapour. After the process is finished in the evaporator, the low pressure vapour is compressed where the temperature and pressure increases before being sent to the condenser where the vapour is cooled by the air from the atmosphere changing the phase of the Freon from vapour to liquid.
2.5.3.5 Liquid cooling system

Liquid cooling refers to using a compatible liquid as coolant for certain specific systems such as aircraft electronics which produces a significant heat load to be removed in close spaces where the performance of air as coolant becomes limited.

Figure 26 presents a simplified representation of liquid cooling system. The avionics is vetted by the coolant which is driven continuously by the pump. The liquid rejects the heat through a heat exchanger to another coolant. Dedicated research has been carried out in the past regarding suitable liquid coolant and this technology is utilized in a cascading manner to transport the heat load from different electronic subsystems to the fuel, which acts as the final heat sink as in S. Brown et.al[16].
2.5.3.6 Magnetic cooling system

The magnetic refrigeration is a type of cooling discovered almost a hundred years ago by a French physicist P. Weiss and Swiss physicist A. Piccard. This type of refrigeration was the first one to be used to reach temperatures close to the absolute zero, being based on the magnetocaloric effect. The effect is a property of magnetic materials where the heat is absorbed or emitted through the force generated by a magnetic field [14]. The principle is straightforward, the magnetocaloric material "enters" the magnetic field and heats up due to its properties that attracts all molecules towards it.

Figure 27: Schematic of Magnetic refrigeration system, adapted from H. Bouchekara [14]

In Figure 27 one can observe a schematic similar to the one presented by Houssem et.al. in [14], where the fluid flow from the cold HE (external) is sent to the magnetocaloric material which is further delivered through adiabatic demagnetization to the hot HE which dissipates the heat in the surrounding.

The main advantages of this type of technology are related to its capabilities of reaching low temperatures, ability to reach up to 80% of Carnot efficiency (single stage refrigerator without all losses considered) and is also a silent system which is a very important factor that will decrease the amount of noise pollution. Despite all these advantages, the MC is a very slow cooling process compared to the ACM, which is due to the turbulent motion transports heat very fast and efficient. Whereas in MC, the transport mechanism for heat is slow molecular diffusion, being dependent on the temperature and viscosity of the fluid. Moreover, according to Ezan et.al. in [54], the material that has the best capabilities is gadolinium which is an expensive material (approx. 485 $/kg) with high melting point (1300°C). Additionally, Ezan et.al. discusses about two practices used for generative magnetic fields:

- Use of electromagnets or superconducting magnets. However, they are expensive, heavy, require electrical current and occupy a large volume which is undesirable in a combat aircraft.
- Use permanent magnets that produce a lower magnetic field which will be an issue in the aviation sector, where the cooling demand is elevated. The advantage in using this type of generating magnetic field is that there is no need of electrical current.

Even though magnetic refrigeration is an old technology, its study is still not mature enough to be implemented on other fields than a home refrigerator. According to Egolf et.al. there are three types of magnetic refrigerators (see [55]): axial, rotary and rectilinear.

2.5.3.7 Thermo-electric Cooling

Thermo-electric cooling makes use of Peltier effect which can be stated as the reversible change in heat content at junctions of dissimilar conductors when an electric current is passed through them. The cooling power produced is proportional to the electric current passed through the couple and the difference between their Seebeck coefficients as in H. King et. al. [56].
The module consists of several units with two different types of semiconductors places in series electrically and in parallel thermally. Upon passing current through the unit, heat from cold side is transported to the hot side. Application of a thermoelectric module in cooling avionics essentially involves a secondary convective cooling system to transport heat from TEC hot side. The participation of TEC unit in the cooling process is limited to certain cooling power and input current range H. King et. al. [30].

2.5.3.8 Media

The main types of media considered in models described in this project are air, fuel and poly-alpha-olifien oil(PAO).

i. Air
Air is used as a thermal medium as well as necessary material for cockpit environment. The two main sources of air for the ECS are the compressed air or bleed from engine and the ram air flow created by the motion of aircraft. The bleed air is at high temperature and pressure and used for both cockpit air supply and also for other functions such as deicing and demisting after cooling down to suitable temperatures. The ram air is generally at low pressure and temperature at flying altitudes and is used only as a heat sink at different heat exchangers. For use as a thermal medium, standard air properties are used for model computations.

ii. Jet fuel
The jet fuel used for propulsion is also considered as a thermal media and heat sink. Due to its large volume and heat loss to outside, the fuel source form the tank generally has large amount of heat capacity. The fuel is passed through a set of heat exchangers before being sent to the engine. There is a temperature limit for the fuel to be sent to engine for combustion while used as heat absorbing medium, and the return flow to the tank also is to be maintained below a specific tank temperature limit which are considered to be 100°C and 90°C respectively. The thermal properties of JP-4 fuel [57] are used for computation in the models.

iii. PAO
The PAO as per MIL-C-87252 is a specially developed coolant. It has superior properties to be used as dielectric fluid as in J. Ferentinos [29] and hence used to immerse aircraft electronics for a better direct heat transfer. The PAO oil is stored in a reservoir and circulated between source
and sink heat exchangers in a closed loop. The temperature and heat absorbing capacity of PAO is controlled by the heat transferred in the sink heat exchanger. The thermal properties of PAO-2 as in L. R. Rudnick [58] is used as reference for computations in the models.

2.5.4 Benchmarking

The method of benchmark has its use in different fields as it allows a satisfactory comparison between different products with a reference product (K. Ulrich and S. Eppinger [59]). One of the objectives of this project is to propose most suitable cooling technology to be used in the ECS of a combat aircraft. Therefore a first step, the available technologies are bench marked against the most common technology used, i.e. the Bootstrap system.

The comparison process in general makes use of a scoring matrix where different candidates are scored against a number of influencing factors based on the pre-study. Subsequently the weighted sum of the scores are used for the purpose of comparison.

2.5.5 ECS Architecture of competitors

The ECS system of Lockheed Martin F22 Raptor is studied to understand the functions of the ECS of a combat aircraft. F22 is one of the most advanced combat aircraft in service currently. The Thermal management system or TMS in F22 is observed to be well developed and suitable to be considered as a competitor or benchmark for the ECS architecture study.

Figure 29: F22 TMS system simplified representation, adapted from S. Brown and R. Ashford [16]
A simplified representation of F22 ECS architecture is considered for reference in Figure 29. F22 designers used a cascaded network of liquid loop systems to transfer heat from certain loads such as avionics to fuel and then finally to ram air, as indicated by S. Brown and R. Ashford in [16].

- The cockpit and the flight critical avionics is cooled by a standard air cycle bootstrap system.
- The secondary heat exchanger of the air-cycle system is cooled by aft liquid cooling loop.
- The aft loop also cools additional electronic heat loads and the heat pumped by a VCS system from the forward liquid cooling loop.
- The forward liquid cooling loop maintains the temperature of heavier cooling loads of mission critical system.
- The aft liquid cooling loop transfers the heat to a combined fuel flow along with hydraulic and engine oil heat loads. Major portion of this fuel flow is sent to engine where it is consumed, and the return fuel flow is cooled using ram air. The liquid used here is specially developed polyalphaolifie oil J. Ferentinos et. al. [29].
3 Methodology

The methodology used and its implementation is presented in the following section. The shape of the methodology is the result of the studies presented in the previous chapters along with assumptions used in to fill the gap in knowledge. The steps listed here can also serve as a way of evaluation of the tools identified.

3.1 Approach

The main concepts behind the steps in the methodology are presented in Figure 30, along with the motivation for each of them in the context of this project.

Figure 30: A graphical representation of the steps involved on the methodology
1. Benchmarking of cooling technologies
The primary step refers to a theoretical comparison between the investigated cooling technologies. The comparison of cooling technologies performed through benchmarking is used to eliminate the least feasible technologies for the given application. Therefore, the purpose of this step is to identify and focus on the relevant technologies to be further modeled and simulated.

2. Modelling and simulation
Modelling and simulation of the systems is identified as the method of studying the system as it makes the visualization of sensitivities of the different parameters on the system performance easier, compared to direct handbook calculations. The models are created in Dymola with a set of mathematical expressions. This step is represented as the step-1 in Figure 30, the mathematical expressions involving the input variables such as size and state variables such as pressure are then solved to find the out the output variables such as cooling power. A detailed description of the same is presented in section 3.2.2.

3. Optimization of individual technologies
The comparison of technologies is more reliable when corresponding optimum properties and performances are used for the study as it is possible to assess their capabilities using the optima. The dynamic models created are used to search the design space of the systems by carrying out multiple simulations. The main parameters at a subsystem level are the cooling power obtained and the power consumed by the system. The tool used here is an optimization framework made in modeFRONTIER as discussed in 3.2.3. As a result of this process an optimum size of the components and the specific ratios of different parameters for a particular technology can be identified. The aim of this process is to form a fair ground for the technologies to be compared in terms of optimum performance. This step is indicated as step-2 in Figure 30.

4. Method of comparison-Fuel penalty
The selection of a particular technology is influenced by the three main limiting factors of the aircraft concept which are power consumption, weight and size. The use of a particular technology may reflect the changes in these parameters in both increasing or decreasing manner. Therefore the concept of fuel penalty is used to represent the combined effect of all three factors. The fuel penalty is calculated by converting the change in any of these factors into the amount of additional fuel consumed because of the system, using the expressions relating them to the power consumed and the SFC of engine which are presented in detail in section 3.2.3.2. The concept can be represented in a simplified form as given below,

\[ \text{Total fuel penalty} = \text{Fuel penalty due to (System weight + Power-off take + Bleed air off take} + \text{drag from Ram air intake + drag from system size)} \]

5. Application in ECS design-Functional analysis
In order to determine the use of technologies in ECS systems, it is vital to understand the basic functional needs of the system. Functional analysis procedure is used to identify the functional tree of ECS systems. The implementation of which is discussed in 3.2.4. Lowermost functions in the functional tree are considered as basic functions and concept ECS architectures are formulated in such a way to include components which together satisfy all of these functions. The comparison data of the previous step is used here to aid prioritizing the technology to be used while forming the architecture. This process is indicated as step-3 in the Figure 30.

6. Architecture Optimization
A number of concepts can be formulated using combinations of the different cooling technologies and media considered based on the functional analysis. For the purpose of validation of the process, a few of the combination are to be created and compared. Using the same approach as above, the formed architectures are to be optimized using a modeFRONTIER framework through simulation in step-4. Fuel penalty for the complete architectures are considered as the factor of comparison. Finally, a most favourable architecture is selected based on the fuel penalty figures an part of step-5 in Figure 30.
3.2 Implementation

The implementation section aims to present a detailed description of each step represented in the methodology section.

3.2.1 Benchmarking of cooling technologies

At first, a scoring table is used to rate different technologies used, against factors such as Weight/kW, COP, maintenance requirement, compactness, complexity, technology maturity and compatibility with application. These factors are designated using letters from A to G and the weights for the scoring is determined by comparing the relative importance between different factors as given in Table 3. The relative importance is assessed by the authors based on their relevance in the ACD and the knowledge available. In each round of comparison, one factor is compared against all the remaining factors column wise and the important factor is written in the corresponding row. After finishing the comparison with equal number of rows formed as the number of factors, the score for each factor is added up in another column. The weight for each factor is the score of the corresponding factor represented as a fraction of the total score.

<table>
<thead>
<tr>
<th>Factors</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>Sum</th>
<th>Zero correction</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>G</td>
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<tr>
<td>B</td>
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<td>D</td>
<td>B</td>
<td>F</td>
<td>G</td>
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<td>D</td>
<td>G</td>
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<td>4</td>
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<td>F</td>
<td>G</td>
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<td></td>
<td></td>
<td>0</td>
<td>1</td>
<td>0.036</td>
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<td>F</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>5</td>
<td>6</td>
<td>0.214</td>
</tr>
</tbody>
</table>

| sum     | 28 |   |   |   |   |   |   |     | 1              |        |

Table 3: Relative comparison table for finding Weights

The scoring matrix is used to rate different technologies considering the sole function to be producing cooling power in an objective manner. A separate subjective comparison is made between different coolant media which can be used to transport heat in the system.

Furthermore, different cooling technologies have been compared to a reference technology. The function considered for this comparison is purely to produce cooling power. Air cycle Bootstrap system has been chosen as the reference here as it is the most used technology for aircraft ECS today. Each technology is rated 1 to 5 with 5 as most favourable against every factors considered.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Factors or Technology</th>
<th>Weights</th>
<th>BS</th>
<th>RBS</th>
<th>VCS</th>
<th>MC</th>
<th>EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Weight/kW</td>
<td>0.214</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>COP of Carnot</td>
<td>0.071</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>Maintenance</td>
<td>0.107</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>Compactness</td>
<td>0.179</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>Complexity</td>
<td>0.036</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>F</td>
<td>Technology Maturity</td>
<td>0.179</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>G</td>
<td>Compatibility with Application</td>
<td>0.214</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

| Weighted score | 4.72 | 3.61 | 3.48 | 1.44 | 3   |

Table 4: Scoring table for comparison of cooling technologies

The weights for the scoring are determined by comparing the relative importance between different factors as given in Table 3. The resultant weighted score influences the choice of technologies considered for further studies.

Likewise, the temperature control is achieved by the use of cooling technologies together with a heat sink/absorbing medium. The different absorbing media considered here are air, Fuel and PAO oil. A separate comparison is made for these as the factors concerned are different form the analysis above.
<table>
<thead>
<tr>
<th>Item</th>
<th>Air</th>
<th>Fuel</th>
<th>PAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Expendable media, cooling pressurization</td>
<td>Partially expendable, Higher heat capacity, energy recovery</td>
<td>High heat capacity, Wide thermal operating range, direct contact with avionics</td>
</tr>
<tr>
<td></td>
<td>integration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Extremely low heat capacity, low density</td>
<td>Thermal Limits, volume limit</td>
<td>Not expendable, maintenance, separate system</td>
</tr>
</tbody>
</table>

Table 5: Subjective comparison on absorbing media

Since these factors cannot be analyzed in an objective manner theoretically, the comparison process will be completed after carrying out simulations of various cooling architectures with these factors having influence in the outcome. The suitability of each technology will be ascertained by comparing the objective function values.

3.2.2 Modeling

Within the following section the modeling procedure and philosophy used will be presented along with the verification and validation of the components. It is important to keep in mind that due to the aforementioned limitations (see section 1.7), one should seek to have results in the same range as the references taken and not exact values, as accuracy of the results is not the purpose of the conceptual design stage.

3.2.2.1 Connectors

Connecting the models is essential if one strives to have a working system, thus a communication interface is specified in the form of a connector. In Dymola there are numerous connectors created for all applications that can be simulated dynamically, however within the library created here new connectors are needed additionally to the already existing ones, due to the incompatibility of exchanging information between models with the existing connectors. Furthermore, the selected properties to be shared between components are: pressure, temperature, mass flow rate and density. In addition to the models created by E. Safavi for CAVE, the density was added due to its variation as a result of different fidelity of the models, aiming to enhance communication between models.

3.2.2.2 Mission profile

The mission profile is represented through a model denoted as “Input air” and has the purpose to deliver the air properties depending on the atmospheric conditions to the inlets of jet engine and ram air intake. The mission is defined as a surveillance mission, therefore a “high-low-high” profile is considered, as seen in Figure 31.

Figure 31: Representation of the mission profile "high-low-high"
In addition to Figure 31, one can gain a better understanding of how the flight profile was inputted by observing Table 6, where the mission profile is represented against time. In the first row the aircraft is at ground moving very slow (1.2348 [km/h]), moreover, both altitude and speed increase with time until the a/c has reached the desired altitude and Mach number. The mission starts after 50 [min] (i.e. 3000 [s]) and it lasts for approximately 22 [min](i.e. 1280 [s]).

Table 6: Mission profile input data

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Altitude[m]</th>
<th>Mach no.[-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0.001</td>
</tr>
<tr>
<td>480</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>660</td>
<td>3048</td>
<td>0.35</td>
</tr>
<tr>
<td>780</td>
<td>9144</td>
<td>0.9</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>3000</td>
<td>3048</td>
<td>0.45</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>4500</td>
<td>9144</td>
<td>0.9</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6240</td>
<td>9144</td>
<td>0.45</td>
</tr>
<tr>
<td>6300</td>
<td>3048</td>
<td>0.35</td>
</tr>
<tr>
<td>6360</td>
<td>1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

From a modeling perspective, two different tables for altitude and Mach number were created in Dymola using the function CombiTimeTable. This function generates an output signal using linear interpolation by storing the time points and desired value (e.g. altitude) in a matrix table of the form [i,j], where i represents the time point and j the value at that time [60]. Furthermore, the ground conditions, i.e. pressure \(P_0\), temperature \(T_0\), gravity \(g\) are required for computing the ambient conditions depending on altitude and mach number variation. The ground conditions are the following: \(T_0 = 288.15[K]\), \(P_0 = 101[kPa]\), \(g = 9.81[m/s^2]\). Other inputted parameters are: adiabatic lapse rate\(^{12}\) \((C = 0.0065K/m)\), specific gas constant for dry air \((R_a = 287.058[J/kg.K])\) and specific heat ratio\(^{13}\) \((\gamma = C_p/C_v = 1.4)\). The procedure for computing atmospheric conditions and the ram air properties can be found in Appendix A.

As mentioned in section 2.2.1, the newly created model should be flexible. The flexibility for "Input air" is represented through the possibility of connecting it with at least two different models (e.g. engine and heat exchanger). However, in order to obtain this flexibility a partially representation of the mass flow rate\(^{14}\) is sent to the following component as seen in equation (2) due to different geometrical characteristics.

\[
\dot{m} = TAS \times \rho_{ram}
\]  \hspace{1cm} (2)

In order to verify and validate the model, the density of ambient air calculation will be compared with U.S. Standard Atmosphere Air Properties from [18]. Density is selected because its outcome depends on change in both pressure and temperature. By analyzing Table 7 it can be observed that the error\(^{15}\) is negligible, and taking into consideration that the selected values for the altitude in Dymola are not the same as the ones in the standard, this part of the model is accurate.

---

\(^{12}\)i.e. the change in temperature with height.

\(^{13}\)i.e. the ratio between the heat capacity at constant pressure \((C_p)\) to heat capacity at constant volume \((C_v)\)

\(^{14}\)The mass flow rate formula according to the conservation of mass is \(\dot{m} = \rho \times \text{Velocity}_{fluid} \times \text{Area}\).

\(^{15}\)Error \(= 100 \times \frac{\text{Density}_{standard} - \text{Density}_{model}}{\text{Density}_{standard}}\)
Table 7: Density comparison between standard data from [18] and Dymola models

<table>
<thead>
<tr>
<th>Altitude model [m]</th>
<th>Altitude standard [m]</th>
<th>Density standard $[kg/m^3]$</th>
<th>Density model $[kg/m^3]$</th>
<th>Accuracy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.225</td>
<td>1.2248</td>
<td>1</td>
<td>99.9886</td>
</tr>
<tr>
<td>1000</td>
<td>1.112</td>
<td>1.1090</td>
<td>1023.1</td>
<td>99.738</td>
</tr>
<tr>
<td>2000</td>
<td>1.007</td>
<td>0.9925</td>
<td>2138.64</td>
<td>98.563</td>
</tr>
<tr>
<td>3000</td>
<td>0.9093</td>
<td>0.9062</td>
<td>3031.07</td>
<td>99.665</td>
</tr>
<tr>
<td>4000</td>
<td>0.8194</td>
<td>0.7905</td>
<td>4336.29</td>
<td>96.485</td>
</tr>
<tr>
<td>5000</td>
<td>0.7364</td>
<td>0.7358</td>
<td>5005.83</td>
<td>99.926</td>
</tr>
<tr>
<td>6000</td>
<td>0.6601</td>
<td>0.6351</td>
<td>6344.92</td>
<td>96.218</td>
</tr>
<tr>
<td>7000</td>
<td>0.59</td>
<td>0.5889</td>
<td>7014.46</td>
<td>99.819</td>
</tr>
<tr>
<td>8000</td>
<td>0.5258</td>
<td>0.5042</td>
<td>8353.55</td>
<td>95.91</td>
</tr>
<tr>
<td>9000</td>
<td>0.4671</td>
<td>0.4656</td>
<td>9023.1</td>
<td>99.689</td>
</tr>
</tbody>
</table>

3.2.2.3 Jet-engine

As mentioned in section 2.3, a model is a simplification of a real component, thus an adapted procedure from [17] was followed to represent the engine. Moving on to the procedure used, first the model computes the mass flow rate at inlet based on its diameter (see equation (3)) and the BPR\textsuperscript{16}. Moreover, the changes in flow properties are computed depending on the section of the engine represented through the T-s diagram from Figure 32. Detailed description of assumptions, simplifications and calculation procedure can be found in Appendix B.

\[ \dot{m} = BPR \times \dot{m}_{\text{inlet}} \times \left( \frac{D_{\text{in}}}{2} \right)^2 \]  

\textsuperscript{16} i.e. ratio between bypass and core airflow rates

Validation and verification of the engine model was performed first by verifying the assumptions made and secondly by verifying the models outcome, where the jet engine Volvo RM 12 from [61] is used as reference. Therefore, the thrust and SFC are using equations (4) from [62] and (5) i.e. a reversed formula from [63] respectively. Furthermore, in Table 8 one can observe that for the same thrust generated, the error between the SFC computed and the one from [61] is less than 4% which is considered to be acceptable.

Figure 32: Temperature-entropy diagram of the jet-engine, adapted from [17]
Thrust = \dot{m}_{\text{exhaust}} \times V_{\text{exhaust}} - \dot{m}_{\text{inlet}} \times V_{ac} + (P_{\text{exhaust}} - P_{\text{inlet}}) \times Area_{\text{exhaust}} \quad (4)

SFC = \frac{V_{\text{aircraft}}}{g} \times \frac{1}{\text{RANGE}} \times \frac{\text{Lift}}{\text{Drag}} \times \ln \frac{W_{ac}}{W_{ac} - W_{fuel}} \quad (5)

Table 8: SFC comparison between the engine VOLVO RM 12 and Dymola model

<table>
<thead>
<tr>
<th>Thrust [kN]</th>
<th>SFC RM12 [mg/N × s]</th>
<th>SFC model [mg/N × s]</th>
<th>Accuracy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.20</td>
<td>12.624</td>
<td>12.127</td>
<td>96.06</td>
</tr>
</tbody>
</table>

Taking into consideration that for an ECS the bleed air properties are the most important properties coming from the engine it will be further investigated. The bleed air is directed to the ECS using a **low pressure valve** from one of the beginning stages of the engine-compressor or if a higher pressure is required the bleed air is extracted from a higher stage using a **high pressure valve** as presented by J. Parrilla [26]. According to the data received from SAAB AB the maximum bleed air temperature should be approximately 773.15 [K], in addition I.Moir states in [11] that bleed air pressure should be \approx 650 [kPa].

The output of simulations performed in Dymola is presented in Figure 33. One can observe the bleed air temperature depending on the compressor stage chosen, thus if the ECS requires the maximum bleed air temperature then it should extract the air from the final stage, i.e. the 15th stage where the maximum temperature is \approx 778[K] and the maximum pressure 219 [kPa]. The difference between the reference and the computed temperature (i.e. \approx 5 [K]) is considered to be relatively small, however the computed bleed air pressure, is \approx 3 times smaller. The difference in pressure is considered acceptable taking into consideration the fact that the a/c proposed does not yield a similar maximum thrust as the one from [61].

![Bleed air temperature variation along the flight profile](image)

**Figure 33:** Bleed air temperature variation along the flight profile
3.2.2.4 Air cycle machine

Air cycle machine used for Bootstrap system utilizes a compressor to raise the pressure of the bleed air and a turbine connected with the same shaft to expand the cooled air. The type of machines considered here for modelling is centrifugal air compressor and radial inflow turbine. Due to the high level of complexity and computational effort involved in developing a theoretical model of turbo-machinery, many projects such as the vehicle level simulation models in R. A. Roberts [64] utilizes a performance map based on experimental data to model compressor and turbine. Furthermore, due to the limited data availability to form a complete performance map of the compressor, a simplified model is made using the experimental data provided in Z. Zhou [65] as basis. The affinity laws applicable for centrifugal compressors derived from R. N. Brown [66] are used for scaling of the model as needed for optimum performance of the system.

Pressure differential:

\[ P_{ACM_{mod}} = P_{ref} \frac{N_2^2 D_2^2}{N_1^2 D_1^2} \]  \hspace{1cm} (6)

Volumetric flow:

\[ Q_{ACM_{mod}} = Q_{ref} \frac{N_2^3 D_2^3}{N_1^3 D_1^3} \]  \hspace{1cm} (7)

The density at exit is calculated using the universal gas law as given below

\[ \rho_{out} = \frac{P_{out}}{RT_{out}} \]  \hspace{1cm} (8)

using the computed density, mass flow rate is determined by multiplying it with the volume flow rate calculated using 7

\[ \dot{m} = Q_{ACM_{mod}} \rho_{out} \]  \hspace{1cm} (9)

The Temperature difference is calculated by the assumption of isentropic compression and expansion in compressor and turbine respectively.

\[ T_{out} = T_{in} \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma - 1}{\gamma}} \]  \hspace{1cm} (10)
Subsequently, thermodynamic work done is calculated using the expressions given below[67]

\[
P_T = -\eta_T \dot{m}_T c_p T_{in} \left[1 - \left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma - 1}{\gamma}}\right]
\] (11)

\[
P_c = \frac{\dot{m}_c c_p T_{in}}{\eta_c} \left[1 - \left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma - 1}{\gamma}}\right]
\] (12)

The losses occurring in the mechanical power transmission from turbine to compressor is considered in the form of another efficiency factor as given below

\[
P_{actual} = \frac{P_c}{\eta_m}
\] (13)

Figure 35: Increase in pressure performed by the compressor

Figure 36: Pressure variation at inlet and outlet of the turbine
As a verification procedure, the models are tested for ensuring correct thermodynamic process. The simulations performed in Dymola are depicted in Figures 35 and 36 presenting the pressure states of inlet and outlet flow for compressor and turbine respectively. These are used as a sample result to verify compressor and turbine behavior. The plots are generated when the ACM model is used in the Boostrap cooling system with inputs dependent on flight profile.

### 3.2.2.5 Liquid Pump

The liquid cooling systems utilizes pumps to transport the liquid media, for both fuel and PAO. Centrifugal pump is considered for modelling for this application. Performance data of Weinman pump model 1P at 1450 rpm represented as pressure differential against volume flow rate is used as a sample data. The recommended operating point for the particular model is used as reference values and pump affinity laws as in J. C. Shieh [68] are used to scale the pump designs

\[
Q_{\text{Pump,od}} = Q_{\text{ref}} \frac{N_2 D_2^3}{N_1 D_1^3}
\]

The massflow rate is calculated using the computed volume flow rate and fluid density

\[
\dot{m} = Q_{\text{Pump,od}} \rho
\]

The power consumption and the temperature rise is calculated using the expressions given below [19]

\[
P_{\text{Pump}} = \dot{m} \frac{P_{\text{out}} - P_{\text{in}}}{\rho}
\]

\[
T_{\text{out}} = \frac{P_{\text{Pump}}}{\dot{m} c_p} \left( \frac{1}{\eta} - 1 \right) + T_{\text{in}}
\]

### 3.2.2.6 Vapour compressor

The vapour cycle system utilizes a compressor to raise the pressure of vapour while transferring from evaporator to condenser. Reciprocating compressor is considered for modelling the VCS compressor. As it is easier to use related theory directly compared to the above models, the theoretical expression given below is used to compute the required quantities such as mass flow, pressure and temperature.

Volume flow rate is calculated form the rpm and the displacement of the pump [69]

\[
Q_{\text{vc}} = N L \pi D^2 / 4
\]

mass flow rate is calculated using inlet density and and volume flow rate

\[
\dot{m} = Q_{\text{vc}} \rho_{\text{in}}
\]

The outlet temperature is calculated by

\[
T_{\text{out}} = T_{\text{in}} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \left( \frac{\gamma - 1}{\gamma} \right)
\]

The compression ratio is assumed to be fixed for simplification

\[
r_p = \frac{P_{\text{out}}}{P_{\text{in}}} = 2
\]

And the refrigerant gas is assumed as to have same value for \( \gamma = 1.13 \).
Figure 37 illustrate the temperature states of Vapour at inlet and outlet of the VCS compressor when used in the system with inputs dependant on flight profile.

3.2.2.7 Heat exchanger

When developing models for an ECS architecture P. Jordan and G. Semitz state in [70] that careful attention must be given to the heat exchanger development as it represents the root of the cooling power therefore, a higher fidelity model was created. The fidelity of the models refers to the details provided in terms of mathematical equations that will result in a better approximation of the behavior of the actual physical component.

The structure of the model is based on the NTU-method relevant sizing of geometrical characteristics\textsuperscript{17}, correlated with empirical calculation from heat transfer theory, F. Incropera et. al. [50] and mathematical correlations designed for developing a HEX as in J. Dewatwal [71]. The heat exchanger assumptions, simplifications and calculation procedure can be found in Appendix C. From a modeling perspective, three different types of heat exchangers were created based on the media used, i.e. air or liquid (e.g. fuel or oil). Moreover, the HEX is dependent on the previous component used to send the cold fluid, thus the HEX that requires connection with the ”Input air” model (see Appendix A) should find its mass flow rate at inlet, by multiplying $\dot{m}$ received with the inlet area of the ram air duct. Another important characteristic of the HEX is the calculation of air properties (e.g kinematic viscosity, Prandtl number) at each time step based on the inlet temperature change.

Moving on to the verification and validation (see Appendix C.1), the effectiveness\textsuperscript{18} of the HEX is dependent on the heat transfer properties that further generate temperature and pressure drop. In Figure 65, the effectiveness (denoted with $\epsilon$) is represented against time in order to verify how the behavior of the HEX is influenced by each phase flight. Therefore, taking into consideration the cruise phases and the loiter, $\epsilon$ fluctuates between 52.5% and 48.5 %, this results as seen in Figure 64 in a temperature decrease of the bleed air of $\approx 115[K]$ and a temperature drop of $\approx 4500[Pa]$. The effectiveness is strictly related to the heat transfer process, thus according to [50] the overall heat transfer coefficient (U) for a air-to-air HEX should be between 10 and 40 W/m$^2 \times K$. When verified, the U returned by the HEX aforementioned is between 15 and 13 W/m$^2 \times K$, resulting in a favorable heat transfer process.

\textsuperscript{17}E.g. calculation of width of the fin based on the changes in volume of the total HEX

\textsuperscript{18}Referring to the capabilities of the heat exchanger to cool the fluid
3.2.2.8 Evaporator and condenser

As mentioned in section 2.5.3.1, the evaporator and the condenser are two different types of heat exchangers using a different type of fluid, i.e. refrigerant R134a M. O. McLinden et. al. [72]. The modeling procedure is similar, the difference being that the evaporator fluid absorbs heat and it then cools it in the condenser using the ram air as coolant. The difference between the evaporator and the HEX is that the hot side transports the heat to the cold side, which is used further in the system.

3.2.2.9 Evaporator Fan

A fan model is required to generate the forced convection in the evaporator, thus a similar approach as in the compressor was used. The properties of the air from the heat source are used as inputs for the fan that generates a flow to be further cooled by the evaporator. In order to create a parametric model in Dymola, the reference fan from [73] was used.

The results of the model are similar to the reference ones, the difference coming from the different properties of the air used.

3.2.3 Optimization procedure

The implementation in this section refers to the problem formulation created and to the selection of setup. It is highly important to understand the bigger picture that this section returns, where optimization is the method chosen for comparison purposes but also for gaining a better understanding of the capabilities of the systems. Even though in conceptual design more knowledge restricts the development process, it is essential to know what one should expect when performing combinations of different systems.

3.2.3.1 Problem formulation

A generic problem formulation is developed in order to compare the cooling technologies and the resulted ECS architectures. The objectives are to maximize power of cooling represented in equation (22) and to minimize a simplified version of the fuel penalty, i.e. equation 34, described in section (4). Moreover, a constraint is needed in order to determine the cooling capabilities of the technologies, therefore the equation (22) is reformulated as a constraint (see equation 35) that fulfills the need. Last the design vector is represented by the variables regarding the size of the components, i.e. length, width and height, and there rpm.

\[
\text{Maximize } f_1(x) = \dot{m}_{\text{out}} \times C_p \times (T_{\text{ref}} - T_{\text{prod}}) \tag{22}
\]

\[
\text{Minimize } f_2(x) = FP(W_{\text{syst}}) + FP(P) + FP(\dot{m}_{\text{bleed}}) + FP(\dot{m}_{\text{ram}}) + FP(V) \tag{23}
\]

\[
g_1 : f_1(x) > 0 \tag{24}
\]

The terms in equations (22) and (34) are defined as it follows:

- \(\dot{m}_{\text{out}}\) is the mass flow rate of the cooling media.
- \(T_{\text{ref}}\) is the reference temperature that has to be cooled, assumed in this case equal to 340[K].
- \(T_{\text{prod}}\) is the temperature produced by the system to cool the heat load.
- \(W_{\text{syst}}\) represents the mass of the entire system, i.e. sum of the mass of all components.

\(^{19}\text{i.e. a formulation that can be used for the optimization for all cooling technologies. The difference between optimization procedures will reflect only in the design vector due to different parameters needed.}\)
3.2.3.2 Fuel Penalty

A simplified approach is adopted for the calculation of fuel penalty. The amount of additional mass-flow of fuel needed due to each of the influencing factors such as flight path angle $\gamma_v$, SFC and L/D ratio for the flight phase etc is given by Dr. Dieter Scholz in [74] as expressed below,

$$ FP(W_{syst}) = m_{ECS} SFC g \left( \frac{\cos \gamma_v}{L/D} + \sin \gamma_v \right) $$

(25)

$$ FP(P) = P_{ECS} (SFC)_P $$

(26)

where,

$$ (SFC)_P = \frac{k_p SFC m_{A/C} g}{n_{E T/O}} \left( \frac{\cos \gamma_v}{L/D} + \sin \gamma_v \right) $$

(27)

$$ FP(\dot{m}_{bleed}) = k_B \dot{m}_{bleed} $$

(28)

$$ FP(\dot{m}_{ram}) = SFC \rho \dot{Q} v $$

(29)

$$ FP(V) = SFC \times D $$

(30)

where, Drag

$$ D = \frac{1}{2} \rho V v^2 $$

(31)

For simplification, only level flight phase is considered and thus it is assumed that $\gamma_v = 0$ and a set of assumed values are considered for other aircraft operating and design dependant parameters.

3.2.3.3 Functional transformation

The algorithm chosen for carrying out the optimization process of individual technologies as described in section I. is Simplex algorithm. The motivation behind this choice is faster convergence and and also simplicity of results as described in section 2.4.3.

As the Simplex algorithm is a single objective algorithm, the multiple objectives in the present problem formulation which includes both maximization and minimization has to be put together to form a resultant objective function, as shown in Equation 32.

$$ F(x) = [F_1(x), F_2(x), ..F_k(x)] $$

(32)

In order to ensure that the resultant objective is not affected by the scale of different sub-objectives, transformation of objective function is carried out as shown by Equation 32 as indicated in R.T.Marler et.al [75]

$$ F_i^{Trans} = \frac{F_i(x)}{F_i^{Max}} $$

(33)

Where $F_i^{Max} = max F_i(x^*_j), i < j < k$ and $x^*_j$ is the design which minimizes jth objective function. Due to the complexity of the problem presented here, the $x^*_j$ for all sub functions is set as the design corresponding to the maximum of main objective function, that is the cooling power. Thus the normalization is carried out by first maximizing cooling power and subsequently using all sub-function values $F_i(x^*_j)$ corresponding to the obtained maximum $x^*_j$ as $F_i^{Max}$.

3.2.3.4 Optimization framework

The optimization framework refers to the flow that the optimization software performs in order to reach the established objectives, thus a detail explanation of the procedure is presented. Additionally, because of the considerable difference of complexity between the required procedure for optimizing a cooling technology and optimizing an ECS architecture, two slightly different approaches are adopted and presented as it follows.
1. Cooling technologies

The optimization framework for Bootstrap system is represented in the form of a schematic depicted in Figure 38. First the sampling method, i.e. ULH creates the design space based on the bounds given in Table 9, further, the optimization algorithm sends combinations of the samples into the Excel interface. The Visual Basic code from Excel creates a new script file in C language and runs it in Dymola. The selected outputs are sent back to Excel as an array where they are interpreted, hence if for example the maximum value of the array is needed the script returns the desired value. The evaluated output values are sent in the first calculator to compute the volume and mass of the system, whereas the second calculator is used for normalization and combination of the objectives.

![Figure 38: Schematic of the Bootstrap optimization framework used in modeFRONTIER](image)

Table 9: Selected upper and lower bounds for design variables

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary HEX Length [m]</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Primary HEX Width [m]</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Primary HEX wall thickness [m]</td>
<td>$3 \times 10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td>Primary HEX no. of stacks</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Secondary HEX Length [m]</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Secondary HEX Width [m]</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Secondary HEX wall thickness [m]</td>
<td>$3 \times 10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td>Secondary HEX no. of stacks</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Turbine diameter [m]</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Turbine RPM</td>
<td>5000</td>
<td>15000</td>
</tr>
<tr>
<td>Compressor diameter [m]</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
II. ECS architectures

The framework for the second architecture developed is depicted in Figure 39. The flow starts similarly to the one for the cooling technologies, however with considerably more design variables due to the use of multiple cooling technologies. The combination of multiple technologies and their complex interaction requires an increase in the number of objectives due to the normalization complications discussed in section 3.2.3.3. Contrariwise, to the optimization framework for the cooling technologies, the last calculator has the purpose to calculate the main objectives, mentioned in the problem formulation.

Figure 39: Schematic of the second ECS architecture optimization framework used in modeFRONTIER

3.2.3.5 Case study-Fixed cooling power

In order to have a closer look at the application of the methodology developed, a case study with prescribed heat loads and minimum fuel penalty is investigated. For this, the optimization problem formulation is modified to the form as shown below.

Objective function

\[
\text{Minimize } f_2(x) = FP(W_{syst}) + FP(P) + FP(\dot{m}_{bleed}) + FP(\dot{m}_{ram}) + FP(V)
\]  

Constraint

\[
h_1 : f_1(x) = C
\]

where, C is a specific set of heat loads needs to be cooled and the rest of the constraints remain the same.

Thus both the architectures are subjected to the same equality constraints, which are fixed heat loads for each system. In the current problem the heat loads are assumed and chosen form one of the feasible points from architecture optimization results. In order to ensure a smoother optimization process, a 10% tolerance is given for the aforementioned constraint.
3.2.3.6 Setup selection

Furthermore, due to the fact selecting the optimization algorithm is problem dependent, a comparison between SIMPLEX and MOGA-II is required. The comparison between the two algorithms is performed on the Bootstrap cooling technology and the comparison factors are the computational cost, system performances and the objective function defined in equation \(20\) (36). Moreover, the value given in front of \(P_{\text{Cnormalized}}\) is a weight that informs the optimization algorithm which objective is more important. This procedure was selected in order to observe the response of the optimization algorithm to a more complex objective than the one required.

\[
f(x) = F_{P_{\text{normalized}}} - 10 \times P_{\text{Cnormalized}}
\]  

Table 10: Comparison of numerical optimization methods\(^{21}\) used

<table>
<thead>
<tr>
<th>Optimization method</th>
<th>Time to converge [min]</th>
<th>No. of design evaluations</th>
<th>f(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMPLEX</td>
<td>131</td>
<td>488</td>
<td>-0.169</td>
</tr>
<tr>
<td>Genetic Algorithm</td>
<td>953.92</td>
<td>3520</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

In Table 10 the converged solution from SIMPLEX is presented along with the midway solution from the Pareto front calculated by MOGA-II. The midway solution is considered due to its high power of cooling and low fuel penalty obtained. Likewise, it is important to note that the sign of the function \(f(x)\) is related to the added weight, thus one can understand that both algorithms will decrease \(F_P\) value and increase the \(P_C\). Moreover, one should envisage that this is only one design from the Pareto front, however many other feasible designs have better \(f(x)\) than the converged solution from SIMPLEX.

Moving on, from Table 10 it is clear that MOGA-II reaches much better performances than SIMPLEX, however the computational cost is also \(\approx 7\) times greater. This results due to better capabilities for finding the global optimum and also due to the better handling of multiple objectives by MOGA-II. However, even though it is clear that better performances are obtained with MOGA-II, the SIMPLEX algorithm will be further utilized to asses the cooling technologies due to the considerable smaller computational cost that is considered to be highly important in the conceptual design stage.

Contrarily, the developed architectures are optimized using MOGA-II as it is considered important to explore the concept capabilities within the design space. Moreover, the use of the genetic algorithm enhances the understanding of the trade-offs that are executed by the optimizer between components or between the interdependent objectives. Another important reason is to avoid using the functional transformation discussed previously, due to the increase in the number of heat loads resulting in an increase in the number of objectives. Although one might think that using MOGA-II it is contradictory to the purpose of the conceptual stage, by following the previous approach four simulations would have been required\(^{22}\) resulting in a longer time process. However, through by using the MOGA-II approach, the software is run a single time for a longer period.

3.2.3.7 Additional constraints and assumptions

Taking into consideration the amount of components modeled and their different fidelity, several constraints arise in order to ensure that the optimization formulation and the Dymola models will perform well together. Therefore, the problem formulation described in section 3.2.3.1 is completed by the following constraints and assumptions.

- The diameter and the rpm of the turbine are equal to the compressor. This assumption is used due to a need of interrelation between the two components, where as described in the section 2.5.3.1 the turbine is the component that rotates the blades of the compressor.
- The average values of output values (e.g. temperature, mass flow rate) are taken for further evaluation in order to cover the entire behavior depending on the flight profile.

\(^{20}\) The created function is compulsory for using multiple objectives in SIMPLEX

\(^{22}\) i.e. a simulation for each of the three heat loads and then one last simulation for the combined objectives
• The weight of the system is considered to be equal to the sum of the components used. Equations (37) and (38) are used for computing the weight of the HEX and the compressor. The factors describing the equations are defined as follows: \( V \) is volume of HEX, \( N_y \) is number of gaps on width side; \( L_y \) is width; \( b \) is the gap width and the indices refer to the ram or bleed air side; \( \rho_{Al} \) is the density of aluminum.

\[
Weight_{HEX} = (V - (N_y \times L_y \times b_{bleed}^2 + N_x \times L_x \times b_{ram}^2)) \times \rho_{Al} \tag{37}
\]

\[
Weight_{compressor} = \pi \times \frac{Diameter^2}{4} \times \text{Length} \times \rho_{Al} \text{ where the length of the compressor} = 0.02 \tag{38}
\]

• Another important factor that provides a boundary for the optimization process is the creation of a constraint for time. This constrain checks if all time steps have been performed by Dymola, otherwise the design will be considered unfeasible.

• Other constraints and assumptions: the upper boundaries of the components are decreased for the final architecture optimization in order to achieve a sizing closer to the real components; the exit temperature of the Evaporator in the VCS should be lower than 343[K] as specified in section 2.5.3.4.

3.2.4 Architecture formulation

The architecture formulation starts with the functional analysis phase, presented in Appendix D. Based on the study on existing ECS architecture such as F22 TMS, the functional blocks of an ECS are identified such as cooling of cockpit, air cooled avionics, Liquid cooled avionics, Weapon systems etc. Using the information from this step, top level functions are split into sub-functions in a hierarchical manner to obtain the functional tree (see Appendix D.1) for the ECS as discussed in section 2.2.2. The lowest level of functions are identified as the basic functions and they are formed on the basis of detailed analysis of the physical process that the function requires.

The basic functions obtained here are used to from component-function matrix where in components are added as rows and basic functions as columns in such a way that all the basic functions are satisfied. Different architecture concepts are defined by using a combinations of different technologies or methods to satisfy the the basic functions. The component-function matrix for the first concept architecture named as BS-Liquid system is presented in Appendix D.2.

Subsequently, the necessary interactions between different components are studied by building a connection matrix. The components of the concepts are listed at one end of a triangular matrix and the interaction of each component with all remaining components are analyses and marked. This step demands a deeper understating of the function of the concept, certain assumptions are made to compensate for the practical knowledge on the working of the system so as to simplify the analysis.
4 Results

The main result of the thesis is the proposed methodology which is presented further. The steps of the methodology are presented along with the corresponding implementation results.

4.1 Proposed methodology

The proposed methodology for ECS concept development is a simulation-based optimization procedure, focused on higher fidelity models. Likewise, the steps are presented and exemplified as it follows:

Figure 40: Steps for developing an environmental control system concept

4.1.1 Step I: Benchmarking

The benchmarking of state of the art cooling technologies is to be made using the pre-determined factors based on the existing knowledge and present demands. Thus, one should clearly state the important factors that influence the selection of a cooling technology such as weight, costs, risk of failure, etc.

Table 4 clearly highlights the suitability of Bootstrap system for cooling power production on-board aircraft. Therefore, the resulted ranking presented in Table 11 shows that the magnetic cooling and thermo-electric cooling technologies are less suitable for ECS applications.

<table>
<thead>
<tr>
<th>Item</th>
<th>BS</th>
<th>RBS</th>
<th>VCS</th>
<th>EC</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted score</td>
<td>4.72</td>
<td>3.61</td>
<td>3.48</td>
<td>3</td>
<td>1.44</td>
</tr>
<tr>
<td>Ranking</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 11: Ranking of state of the art cooling technologies

A subjective comparison was made between the investigate cooling technologies, as presented in Table 12. This depicts a clear image on the trade-offs of the investigated cooling technologies, based on the pre-study performed.

<table>
<thead>
<tr>
<th>Item</th>
<th>BS</th>
<th>RBS</th>
<th>VCS</th>
<th>MC</th>
<th>EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Pressurization; Air conditioning integration</td>
<td>Ram powered compact; Self-driven</td>
<td>High efficiency; Compactness</td>
<td>Can reach low temperatures</td>
<td>Close temperature tolerance; Compact; Lightweight</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Low COP, Large size</td>
<td>Depressed ambient nature; No cooling on ground</td>
<td>50% heavier than conventional ACM, Refrigerant is toxic.</td>
<td>Slow process, Low pressure system</td>
<td>Small transport distance , very small operating window.</td>
</tr>
</tbody>
</table>

Table 12: Subjective comparison of cooling technologies
4.1.2 **Step II: Modeling, simulation and optimization of individual technologies**

This step is concerned with the development of mathematical models of defined cooling technologies. The development of the models is made based on the chosen fidelity, which is further influenced by other factors such as available resources, time and accuracy needed. The models are to be optimized in order to obtain optimum design parameters which are used as a basis of comparison between the cooling technologies. Furthermore, the fuel penalty is to be calculated based on the mass, size and power consumed etc, and the ratio of power of cooling over fuel penalty is to be used as a factor of comparison between individual technologies.

In addition, this section intends to present the Dymola framework and the optimized results achieved in modeFRONTIER.

### 4.1.2.1 Bootstrap system

First of all, the configuration created in Dymola can be observed in Figure 41, where one can observe that the "Input air" model is the one that dictates where the ram air is sent, first to the engine in order to transform it into bleed air and into the "Secondary HEX ram" used as coolant. The bleed air extracted from the engines compressor is decreased in the "Primary HEX", using the waste ram air from the other HEX, followed by the compressor where the pressure is increased, rising the flow temperature as well. The fluid with this properties is further cooled to an acceptable temperature in the "Secondary HEX ram" and lastly expanded by the turbine.

![Figure 41: Schematic representation of Bootstrap technology in Dymola](image)

### 4.1.2.1.1 Bootstrap system specifications

In addition, the optimized specifications for BS by SIMPLEX method are presented in Table 15. The resulted variables are important to have a clear image on the size of the components, but also in order to give a better description of the output values presented in Table 16.
Table 13: Sizing of the Bootstrap system

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Lower bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary HEX Length [m]</td>
<td>0.79</td>
</tr>
<tr>
<td>Primary HEX Width [m]</td>
<td>0.75</td>
</tr>
<tr>
<td>Primary HEX Height [m]</td>
<td>0.069</td>
</tr>
<tr>
<td>Primary HEX wall thickness [m]</td>
<td>0.000434</td>
</tr>
<tr>
<td>Primary HEX no. of stacks</td>
<td>10</td>
</tr>
<tr>
<td>Secondary HEX Length [m]</td>
<td>0.79</td>
</tr>
<tr>
<td>Secondary HEX Width [m]</td>
<td>0.29</td>
</tr>
<tr>
<td>Secondary HEX Height [m]</td>
<td>0.4</td>
</tr>
<tr>
<td>Secondary HEX wall thickness [m]</td>
<td>0.00031</td>
</tr>
<tr>
<td>Secondary HEX no. of stacks</td>
<td>61</td>
</tr>
<tr>
<td>Turbine/compressor diameter [m]</td>
<td>0.49</td>
</tr>
<tr>
<td>Turbine/compressor RPM</td>
<td>6793</td>
</tr>
</tbody>
</table>

In order to observe specific properties of the cooling technology, Table 16 presents the component used to create the cooling effect and its main characteristics. For Bootstrap technology, the turbine is the component that provides cold flow to the heat load.

Table 14: System characteristics based on the component

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass flow rate [kg/s]</th>
<th>Temperature[K]</th>
<th>Pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>0.146</td>
<td>320</td>
<td>679</td>
</tr>
</tbody>
</table>

Figure 42: Temperature variation of the bleed air in the Bootstrap system
4.1.2.2 Reverse-Bootstrap system

The configuration of Reverse-Bootstrap is represented in Figure 43. As mentioned in section 2.5.3.3, the process starts the same as the Bootstrap system until it reaches the regenerative HEX. The RHE is composed of the same type of HEX used previously, however its temperature storing capabilities are established by using the waste air from the "Radar (heat load)". Moreover, the air is expanded across the turbine after it passes through the regenerative HEX to cool the heat load. The waste air coming from the heat load being discharged by the compressor into the atmosphere.

![Figure 43: Schematic representation of Reverse-Bootstrap technology in Dymola](image)

4.1.2.2.1 Reverse-Bootstrap system specifications

Furthermore, the optimized specifications achieved by the optimization method are presented in Table 15. The resulted variables are important to have a clear image on the size of the components, but also in order to give a better description of the output values presented in Table 16.
Table 15: Sizing of the Bootstrap system

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary HEX Length $[m]$</td>
<td>0.79</td>
</tr>
<tr>
<td>Primary HEX Width $[m]$</td>
<td>0.77</td>
</tr>
<tr>
<td>Primary HEX Height $[m]$</td>
<td>0.073</td>
</tr>
<tr>
<td>Primary HEX wall thickness $[m]$</td>
<td>0.000341</td>
</tr>
<tr>
<td>Primary HEX no. of stacks</td>
<td>11</td>
</tr>
<tr>
<td>Secondary HEX Length $[m]$</td>
<td>0.57</td>
</tr>
<tr>
<td>Secondary HEX Width $[m]$</td>
<td>0.3</td>
</tr>
<tr>
<td>Secondary HEX Height $[m]$</td>
<td>0.067</td>
</tr>
<tr>
<td>Secondary HEX wall thickness $[m]$</td>
<td>0.000356</td>
</tr>
<tr>
<td>Secondary HEX no. of stacks</td>
<td>10</td>
</tr>
<tr>
<td>Turbine/compressor diameter $[m]$</td>
<td>0.49</td>
</tr>
<tr>
<td>Turbine/compressor RPM</td>
<td>11921</td>
</tr>
</tbody>
</table>

Similarly to the Bootstrap cooling technology, the turbine is the component that creates the cooling effect. The characteristics of the turbine are presented further in Table 16.

Table 16: System characteristics based on the component that produces cooling

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass flow rate $[kg/s]$</th>
<th>Temperature $[K]$</th>
<th>Pressure $[kPa]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>0.127</td>
<td>291</td>
<td>292</td>
</tr>
</tbody>
</table>

Figure 44: Temperature variation of the bleed air in the Bootstrap system
4.1.2.3 Vapour cycle system

The created model of vapour cycle system is represented in Figure 45. Contrariwise, to Bootstrap and Reverse-Bootstrap, VCS is a more complex system due to the use of two different media\textsuperscript{23}, phase change of the refrigerant from liquid to gas but also because it is a closed loop system. Taking into consideration the complexity of the technology but also because of the stage of the design process, i.e. conceptual design stage, the phase change is represented through the use of the specifications of the vapor properties of the refrigerant in the compressor and liquid properties in the condenser, capillary tube and evaporator.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure45.png}
\caption{Schematic representation of Reverse-Bootstrap technology in Dymola}
\end{figure}

4.1.2.3.1 Vapour Cycle System specifications

The specifications of the optimized vapour cycle system are presented further. Table 17 presents the sizing of the components used in the VCS and the necessary inputs required by the compressor and fan to fulfill the objective. Moreover, as presented for the previous technologies, the specifications of the component that produces the cooling effect are presented in Table 18.

\textsuperscript{23}\textit{i.e.} refrigerant R134a [72] and air on the hot side of the evaporator.
Table 17: Sizing of the vapour cycle system

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser Length [m]</td>
<td>0.149</td>
</tr>
<tr>
<td>Condenser Width [m]</td>
<td>0.75</td>
</tr>
<tr>
<td>Condenser Height [m]</td>
<td>0.000436</td>
</tr>
<tr>
<td>Condenser no. of stacks</td>
<td>11</td>
</tr>
<tr>
<td>Evaporator Length [m]</td>
<td>0.227</td>
</tr>
<tr>
<td>Evaporator Width [m]</td>
<td>0.533</td>
</tr>
<tr>
<td>Evaporator Height [m]</td>
<td>0.000328</td>
</tr>
<tr>
<td>Evaporator no. of stacks</td>
<td>11</td>
</tr>
<tr>
<td>Expansion Valve Diameter [m]</td>
<td>0.0049</td>
</tr>
<tr>
<td>Expansion Valve Length [m]</td>
<td>0.564</td>
</tr>
<tr>
<td>Fan Diameter [m]r</td>
<td>0.087</td>
</tr>
<tr>
<td>Fan RPM</td>
<td>11745</td>
</tr>
<tr>
<td>Reciprocating Compressor Diameter [m]</td>
<td>0.055</td>
</tr>
<tr>
<td>Reciprocating Compressor RPM</td>
<td>100</td>
</tr>
<tr>
<td>Compressor Length [m]</td>
<td>0.355</td>
</tr>
</tbody>
</table>

Table 18: System characteristics based on the component

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass flow rate [kg/s]</th>
<th>Temperature[K]</th>
<th>Pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator hot side</td>
<td>0.215</td>
<td>276</td>
<td>107</td>
</tr>
<tr>
<td>Evaporator cold side</td>
<td>0.114</td>
<td>328</td>
<td>980</td>
</tr>
</tbody>
</table>

Figure 46: Temperature variation of the refrigerant in the Vapour Cycle System
4.1.2.4 Quantitative and qualitative comparison

This sub-chapter presents important quantities for selecting a cooling technology for further use in an architecture, such as weight and volume of the whole system and the power consumption. Moreover, the figures representing the dependency of important components on the characteristics of the flight profile are presented.

The qualitative comparison is made in Table 19 by using the ratio of the two objectives, hence one can determine which technology affects the aircraft performances the most.

Table 19: System characteristics based on the component that produces cooling

<table>
<thead>
<tr>
<th>Cooling technology</th>
<th>Weight [kg]</th>
<th>Volume [m$^3$]</th>
<th>Power of cooling [kW]</th>
<th>Power consumption [kW]</th>
<th>$\frac{\text{Power of cooling}}{\text{Fuel penalty}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bootstrap</td>
<td>241</td>
<td>0.089</td>
<td>2.93</td>
<td>0.685</td>
<td>53.6</td>
</tr>
<tr>
<td>Reverse-Bootstrap</td>
<td>200</td>
<td>0.073</td>
<td>6.15</td>
<td>2.767</td>
<td>133.29</td>
</tr>
<tr>
<td>Vapour Cycle System</td>
<td>13.3</td>
<td>0.0049</td>
<td>7.34</td>
<td>4.44</td>
<td>1563.6</td>
</tr>
</tbody>
</table>

In addition, in Figure 47 density of the cooled air is chosen for comparison between Bootstrap and Reverse-Bootstrap. The reason is that the density calculation involves both temperature and pressure of the air thereby representing the cooling capacity for a given volume flow rate, as seen in equation (39)

$$\rho = \frac{\text{Pressure}}{R_a \times \text{Temperature}} \text{ where } R_a \text{ is the gas constant for dry air} \tag{39}$$

Figure 47: Bootstrap versus Reverse-Bootstrap density changes at turbine exhaust within the flight profile
4.1.3 **Step III: Functional analysis and architecture formulation**

The third step is the core of the proposed methodology, where the knowledge gained previously is used to identify the main functions of the environmental control system. The process leads to a thorough analysis of the functional tree resulting in a clear decomposition into basic functions. The concept architecture is developed by using the functions-component matrix and subsequently connection matrix.

The steps presented in section 3.2.4 results in two different architectures by using the functional analysis presented in presented in Appendix D.

4.1.4 **Step IV: Modeling, simulation and optimization of ECS architectures**

The fourth step is a similar approach as step II, where the formulated architectures are integrated in Dymola and then optimized in modeFRONTIER. The integration is done by ensuring the compatibility of basic components, based on the media used. The optimum parameters are to be used to calculate the ratio of power of cooling to the fuel penalty for the purpose of comparison between different architectures.

4.1.4.1 **Concept architecture I**

The first architecture generated is a combination of conventional Bootstrap system, liquid cooling system and the fuel system. The schematic of the first ECS architecture generated by the proposed methodology is depicted in Figure 63, having the purpose to give a straightforward process based on the conventional air-cycle machine as the principle means of cooling the heat loads.

![Figure 48: Architecture 1: "BS-Liquid System"](image-url)
4.1.4.2 Optimization outcome for architecture I

As mentioned in section 2.4.2, when multiple-objectives are used the optimum point is represented through a trade-off between objectives. Thus, Figure 49 presents the Pareto optimal points between the two main objectives. Moreover, one can observe the Pareto frontier representing the points that have no superior for the given objectives, and three possible solutions for final proposals of the ECS architecture chosen on their capacity of meeting both objectives.

![Pareto Frontier based on the last 500 designs for architecture I, after 8000 evaluations](image)

A major trait of the developed ECS architectures is to provide sufficient power of cooling to the heat loads, for this reason the Parallel Coordinate chart is used for further investigation. According to *modeFRONTIER User Manual*, the chart is used for displaying the multivariate data in order to assess designs in a particular range. Figure 50 illustrates the requirements that the influencing components have to achieve in order to obtain high cooling power for the cockpit heat load. The chart shows the importance of the width of both secondary and primary heat exchangers, along with the high work that has to be performed by the air cycle machine.

![Parallel coordinate chart of architecture I for cooling the cockpit heat load, where the cooling power is represented in Watts and the sizing in meters](image)

Figure 50: Parallel coordinate chart of architecture I for cooling the cockpit heat load, where the cooling power is represented in Watts and the sizing in meters
A similar approach is taken for investigating the remaining heat loads, however only one chart is used in order to show the interaction of the fuel and PAO cooling systems. In Figure 51 it can be observed that the two heat loads are inverse proportional, additionally one can observe that the length of the heat PAO and liquid heat exchangers is having a higher impact on the cooling capabilities of the heat loads.

As shown previously, the heat exchangers have a major influence on the cooling capabilities, therefore the sensitivity of the objectives to the sizing of the heat exchangers is analyzed. The method for assessing the sensitivity analysis depicted in Figure 52, is by using the Pearson correlation matrix described in the modeFRONTIER User Manual as "a measure of linear dependence between two variables". The negative values represent the opposite influence that a variable has on the objective, whereas the positive value shows a direct correlation between the objective and the variable. Thus, one can observe that when the size of the secondary HEX increases the cooling of the cockpit increases along with the fuel penalty. Contrariwise, when the Fuel-PAO HEX sizing increases, the cooling of the fuel decreases and similarly when the Fuel-Air HEX sizing increases the cooling of the PAO heat load decreases but the fuel heat load increases.

As shown previously, the heat exchangers have a major influence on the cooling capabilities, therefore the sensitivity of the objectives to the sizing of the heat exchangers is analyzed. The method for assessing the sensitivity analysis depicted in Figure 52, is by using the Pearson correlation matrix described in the modeFRONTIER User Manual as “a measure of linear dependence between two variables”. The negative values represent the opposite influence that a variable has on the objective, whereas the positive value shows a direct correlation between the objective and the variable. Thus, one can observe that when the size of the secondary HEX increases the cooling of the cockpit increases along with the fuel penalty. Contrariwise, when the Fuel-PAO HEX sizing increases, the cooling of the fuel decreases and similarly when the Fuel-Air HEX sizing increases the cooling of the PAO heat load decreases but the fuel heat load increases.

Figure 51: Parallel coordinate chart for cooling the PAO heat load, where the cooling power is represented in Watts and the sizing in meters

Figure 52: Sensitivity analysis of the heat loads to the mass of the heat exchangers
4.1.4.3 Concept architecture II

The proposed methodology is used to generate a second architecture, having as an overall objective to lower the bleed air consumption. The resulted architecture is a substantially more complex system, based on the heat transfer capabilities of liquid systems connected through the vapour cycle system. The complexity arises from the use of the VCS which aims to cool the PAO heat load by discharging the accumulated heat into the jet-fuel.

![Architectural diagram](image)

Figure 53: Architecture II: "BS-VCS-Liquid System"

4.1.4.4 Optimization outcome for architecture II

The Pareto frontier for the second architecture is presented in Figure 54. Similarly to the first ECS architecture three solutions that have no superior can be used for further investigations of the ECS architecture specifications.

![Pareto Frontier chart](chart)

Figure 54: Pareto frontier based on the last 500 designs for architecture II, after 8000 evaluations
In order to observe the designs with the "best" cooling power, the Parallel Coordinate chart from Figure 55 is used for displaying the multivariate data. Based on the filtering made, i.e. the transparent green area, the graph provides useful information on how the components of the Bootstrap system should be sized in order to achieve the highest power of cooling for the cockpit heat load.

Figure 55: Parallel Coordinate chart of architecture I for assessment of the cockpit heat load, where the cooling power is represented in Watts and the sizing in meters

Likewise, the graph presented in Figure 56 displays the dependencies of the VCS components in order to maximize the power of cooling capacity for the PAO. The graph also shows the interconnection between the power of cooling of the fuel system and the PAO system.

Figure 56: Parallel Coordinate chart of architecture II for assessment of the interaction between cooling the PAO and fuel heat loads, where the cooling power is represented in Watts and the sizing in meters
Furthermore, the sensitivity of the objectives to changes in the size of heat exchangers, condenser and evaporator is made by interpreting the correlation matrix. Therefore, by exploring Figure 57 one can observe that when the secondary HEX mass increases, the power of cooling for the cockpit increases as substantially. On the other hand, when the condenser mass increases the cooling of the fuel load decreases, as more heat will be transferred to the fuel.

**Figure 57: Sensitivity analysis of the objectives based on the mass of the condenser, evaporator, primary HEX, secondary HEX and liquid Air-Fuel HEX**

### 4.1.4.5 Architectures comparison

The last step of the proposed methodology is to compare the concept architectures generated. In order to have a thorough comparison, at least three design points from the resulted Pareto frontier should be selected.

In Figure 54 and Figure 49 three solutions are chosen based on the designs capability for fulfilling the objectives. Therefore, "Solution 1" and "Solution 3" are the designs that represent the most favorable solution for one objective but also the least favorable for the opposite objective. A trade-off is done when selecting "Solution 2", i.e. the optimum design point that has minimum negative impact on both objectives.

In order to understand the distinction between the two generated ECS architectures, the graph depicted in Figure 58 is proposed. Here the designation of the points represented contains design number followe by architecture number, for example D2A1 means the second design of architecture 1. The data is represented in the following way: the X and Y axis represent the fuel penalty and power of cooling, the colour refers to the power consumption and the diameter of the bubbles represent the ratio between the power of cooling and fuel penalty.

**Figure 58: Comparison of the selected Pareto designs for both ECS architectures**
4.2 Additional findings

This section intends to present the most relevant findings by following the thesis methodology.

4.2.1 Case study

The result of the case study optimization returns designs with the minimum fuel penalty for a common heat load when applied in each of the architectures. This enables a direct comparison between architectures for a specific requirement. In table 20 the design with the lowest fuel penalty for each architecture is presented.

Table 20: System characteristics based on the heat loads

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture I</td>
<td></td>
<td>1880</td>
<td>715.999</td>
<td>33735.1</td>
<td>47.77</td>
</tr>
<tr>
<td>Architecture II</td>
<td></td>
<td>1880.05</td>
<td>716.004</td>
<td>33735</td>
<td>32.92</td>
</tr>
</tbody>
</table>

4.2.2 Flight profile dependency

The flight profile, i.e. the "Input air" model has proven to be highly important for the cooling technologies behavior. In order to assess its importance, the power consumption it is depicted represented in Figure 59 in order to show its fluctuating behavior based on the stage within the flight profile.

Figure 59: Power consumption performance based on the main cooling technologies for the given flight profile
4.2.3 Complexity of cooling technologies

The complexity of the cooling technology refers to the amount of time needed for the CPU to integrate, but also to the amount of iterations performed by the optimization software to find the converged solution.

Table 21: Complexity of the technology from the solver and optimizer perspective

<table>
<thead>
<tr>
<th>Cooling technology</th>
<th>Bootstrap</th>
<th>Reverse-Bootstrap</th>
<th>Vapour Cycle system</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU time [s]</td>
<td>0.019</td>
<td>0.004</td>
<td>0.01</td>
</tr>
<tr>
<td>No. of iterations</td>
<td>233</td>
<td>688</td>
<td>952</td>
</tr>
</tbody>
</table>
5 Discussion

The main goal of the thesis is to propose a methodology for the aircraft conceptual design stage and to further implement it. Therefore, an objective assessment of the proposed methodology is performed along with its implementation and the obtained results. The chapter ends by answering the research questions.

5.1 Overview of the proposed methodology

The methodology adopted is a typical top-down approach, focused on developing an ECS architecture in conceptual design stage based on state of the art techniques, such as modeling and simulation followed by design optimization. Moreover, the basic principle of the method refers to the development of a mix of lower and higher fidelity models that can be further used to form new architectures. This approach has already been discussed by G. Schmitz and P. Jordan in [70] where different levels of complexity are presented, or by E. Safavi in [2] where it is acknowledged the need for more detailed models in conceptual design. On the other hand, even though the multidisciplinary design optimization was implemented by E. Safavi (see [2]), the purpose of the optimization was purely to evaluate the tools capabilities and not to make use of it in the design process.

Henceforward, the thesis strives to involve one more discipline, i.e. design optimization into the conceptual design process. At first, this approach seems to be an expensive process, but the knowledge gained through the optimization process and its results, enhances the understanding of the created models, their capabilities and their relevance in a system. When implemented in the industry the knowledge development process as pre-study, simulation and optimization of individual cooling technologies can be avoided, as the existing knowledge can be used instead. Knowing this, one can use steps 3 and 4 respectively, to develop and asses the ECS-concept architectures.

5.2 Results of proposed methodology

Benchmarking of cooling technologies indicate that the Bootstrap system is the most suitable technology for application in environmental control systems. The benchmarking acts as a foundation for the remaining steps in the proposed methodology, as its outcome was analyzed further. The results show that the compatibility of the technologies already used in the aviation sector are far better than the new technologies investigated. The reasoning is that the new investigated technologies are not studied extensively for such applications, resulting in a lack of favorable characteristics. As the problem of comparison is highly complex, the objective scoring method alone cannot assess the suitability of a technology in a holistic manner. The subjective comparison sheds light into the complex interaction of different factors such as media properties, pressure requirement, heat transfer rate etc. These arguments suggest that a more qualitative and quantitative investigation is a mandatory process in order to characterize each technology.

Modeling and simulation of the cooling technologies shows a clear distinction between the Vapour Cycle System, the Bootstrap and Reverse-Bootstrap respectively. The reason behind this discrepancy is due to the higher heat transfer capabilities of the refrigerant in comparison to the ram air. Moreover, it is worth mentioning that even though the weight of the refrigerant was not considered in the estimation of the fuel penalty, the resultant cooling capabilities are considered to be remarkably for such a small-scale system.

Moving on to the comparison of the air-cycle technologies, it is noticed that the ratio of the two objectives\(^{24}\) is considerably larger for the RBS, referring to a better suitability for further use in the application. The reason behind this result is the use of the compressor at the end of the system to discharge the waste air instead of increasing the pressure inside the system, hence rising the temperature as in the case of the BS. Nevertheless, the result is considered to be more delusive than realistic due to the considerably lower pressure generated in the RBS, which cannot be used for applications such as cockpit pressurization. This result confirms the description made in section 2.5.3.3 by L. De Francesco, concluding that the RBS is a technology more appropriate for cooling lower pressure regions of the aircraft, such as avionics.

From a different perspective, the optimization results show that optimum configuration of Bootstrap system indicates a clear trend as higher size of the secondary heat exchanger over the primary heat exchanger.
exchanger. On the contrary, the RBS does not return such a behavior the reason being related to the use of the waste air coming from the heat load as coolant for the secondary HEX.

The resultant functional analysis was carried out based on the knowledge gained after the optimization process performed for the individual cooling technologies. The developed architectures share certain characteristics, meaning that both architectures use Bootstrap as main cooling technology based on functional requirement. The particularity of the second architecture is based on the reduction of bleed air consumption. Thus, the second architecture turned out to be similar to the ECS architecture described by S. Brown and R. Ashford in [16]. The process followed ensured for both formulated architectures the fulfillment of all the functional requirements of an environmental control system. The overall picture remaining to be completed by the use of design optimization methods, in order to size and evaluate the concepts capabilities.

Furthermore, the optimization results of the first architecture show a good equilibrium of the cooling capabilities requirements for the considered heat loads. This permits the optimizer to find high cooling powers while it minimizes the size of the influencing components. In this respect, one can observe by following the parallel coordinate charts that components of each active and passive cooling technologies are scaled in accordance to the needs. Hence, in order to maximize the cooling of the cockpit, the length and height are decreased, whereas the width is expanded to the topmost boundary. Furthermore, the sensitivity analysis encloses the required knowledge needed for this stage in order to understand what objectives are affected by which component. The most influential heat exchanger used in the system is the secondary HEX, which affects in a negative way the fuel penalty, but it improves both cooling of the PAO and cockpit heat loads.

In contrast to the results achieved by the first architecture, the second architecture presents a substantial trade-off between the cooling technologies used. The trade-off arises while coupling the two liquid systems by means of the VCS, resulting in an increase in complexity and thus a tougher problem to be optimized. The complexity is seen in the Parallel coordinate chart from Figure 56, where one can observe that in order to maximize the cooling performed by the PAO liquid system, the fuel liquid system has to decrease its performances. This is explained by the use of the VCS to cool the PAO liquid system, while discharging the gained heat into the fuel that is to be used for the cooling of the auxiliary heat source. The sensitivity analysis confirms the inter-connection between the liquid cooling systems, by displaying the negative influence of the condenser on the liquid fuel system while improving the the cooling done by the PAO.

The last step before proposing a suitable ECS architecture to be investigated in the preliminary design stage, is the comparison between the generated concept architectures. This is performed here by analyzing two extreme designs and one optimum design in order ensure the correctness of the evaluation. Furthermore, by comparing the extremes and optimum designs between each architecture as it follows: D1A1 with D1A2, D2A1 with D2A2 and D3A1 with D3A2, it results that the first architecture is considerably better than the second architecture. Moreover, one can observe that the design with the least power of cooling capabilities of the first architecture, i.e. D1A1, is in the same range as the one with the highest power of cooling capacity of architecture II, i.e. D3A2. Initially, it may seem that by adding one more cooling technology should result in a higher power of cooling, however by using the design optimization procedure the overall picture is revealed. The comparison of the optimum points, i.e. D2A1 and D2A2, shows that both architectures have the capability of achieving low fuel penalties, however the capacity of providing adequate cooling power is considerably less for the second architecture. The reasoning behind this is related to the negative correlation of the mass flow of the fuel and PAO. Hence, the flow inside the VCS lines gives in less heat to the fuel resulting in lower cooling of the avionics bay, i.e. the heat load cooled by the PAO cooling system.

5.3 Additional findings

Along the thesis work-flow, several leanings have been acquired and their importance is discussed within this section.

The results from Architecture optimization as presented in section 4.2.1 clearly shows that the Architecture 1 (A1) has a better optimal design than the Architecture 2(A2) in terms of power of cooling over
fuel penalty. However, due to the highly complex nature of the system this result cannot be generalized to the entire design space yet. The case study with a fixed cooling power better resembles an actual ACD scenario. It is evident from the results of case study that for the specific heat loads used, the second architecture has better designs than the first architecture contrary to the above findings. The perceived reason for the better performance of architecture two was observed in the lower amount of bleed air consumed. This can be observed in Figure 58 when comparing a design with a high power consumption and low fuel penalty (e.g. D2A1) with a design having a low power consumption but a high fuel penalty (e.g. D3A1).

The behaviour of the system in response to changes in system parameters in different flight phases is depicted in section 4.2.2. The variation in the ram air flow which acts as heat sink for different heat exchangers is one of the main reasons for the changes in behavior. Other factors such as engine power state, bleed air temperature also affect the system performance. The sharp corners in the flight profile is observed to be the cause of errors during simulations because of the difficulty it presents to the navigation of the iterative solver used in Dymola.

The complexity of a particular cooling technology directly correlates to the cost of simulation. Table 21 presents the comparison between BS, RBS and VCS in terms of time required for execution of models and number of iterations required for convergence. In Table 21 one can see that Bootstrap system is considerably slower than Reverse-Bootstrap system and Vapour Cycle System. On the other hand, the optimum value is achieved faster than in the other cooling technologies for the BS. The result shows the complexity of the VCS in comparison to the air cycle technologies, and it strives to show how did the complexity of the architecture has increased for the second architecture only by considering the VCS.

5.4 Assessment of implementation

The implementation suggests a clear idea considered from start, i.e. the use of higher fidelity models for assessment in the conceptual design stage. Additionally, the increase in fidelity has been performed for certain components selected based on their function and overall influence in the investigated cooling system. However, during the course of the project, it was observed that the extent of details which can be incorporated in the Dymola models are limited for the time and resources available. This fact has influenced the extent of fidelity of the models even after a focused effort towards the matter was made. This resulted in systems with intermediate level of fidelity, that further translated into a slightly better performance. On the other hand, the increase levels of details has resulted into a more complex, elaborated and rigid process.

The second major phase of the implementation is the design optimization process, which as mentioned previously has as main purpose the increase in knowledge in an early stage. Consequently, the capability of each cooling technology was assessed in a straightforward process with a robust result. However, the choice of optimization has its down side, meaning that additional time and computational cost arises. This can be accompanied by human-errors, which will considerably delay the process. From a different perspective, the time consumed within the delay it becomes negligible when compared with the knowledge and understanding gained through the optimum ratios of different parameters, such as the importance of the sizing of secondary heat exchanger in the Bootstrap system.

The limitations mentioned in section 1.7 have been highly influential along the thesis process. First of all, the most influential limitation consists in the lack of existing knowledge in the literature for the development of mathematical models specifically for the aircraft industry. This is reflected in large number of assumptions. Another limitation that slowed the process was the lack of data for validation of the developed models, which also resulted in a continuous inclination for the improvement in the accuracy of the models.
5.5 Answers to research questions

This section provides answers to the research questions specified in section 1.4.

**RQ1: To what extent does the fidelity of the models affect the conceptual design process?**

Based on the learning from this project, it can be stated that the fidelity of models influences the ACD in both positive and negative manner. The relevance of simulation based ACD is directly correlated to the fidelity of models used. In other words, higher fidelity models help predict the behavior of the systems more accurately thus, results in an early identification of optimum designs. During the execution of optimization, it was observed that the assumptions and simplifications affect the results to a great extent, this can be attributed to the highly complex design space of the ECS system. But higher fidelity models demand higher effort in handling changes and results in increased risks of errors and possible cost overruns. The use of higher fidelity models demanded extensive maintenance in terms of inter-compatibility between systems and change management.

**RQ2: Is the selection of tools adequate regarding their availability compatibility and fidelity?**

Modeling platform Dymola is suitable for complex system simulation with the acausal modeling capability. However, the lack of standard components for ECS system led to additional modeling work and reduced accuracy. The optimization tool modeFRONTIER is found to be highly useful in handling the complex interactions between the system parameters and performance by providing aids for execution, visualization and post processing of optimization tasks. The fidelity of the tools is found to be sufficient for use in conceptual design, being adequate for later stages as preliminary or detailed design.

**RQ3: To what extent CAVE capabilities can be improved?**

By introducing the concept of functional analysis and optimization, the current project extends the usefulness of simulation based conceptual design process envisioned in CAVE. One of the most important findings is that the inter-dependency between components and subs-systems. This finding could be an important addition to CAVE, in order to increase applicability with respect to environmental control system.
Conclusions and further work

Conclusions

The main objective of the project was to propose a methodology for forming concepts of environmental control system in the aircraft conceptual design stage. The proposed simulation-based optimization method, showed satisfactory results in terms of possibilities to generate complex ECS architectures. Additionally, more in-depth knowledge of the interdependence of the system parameters was also gained.

The concept of fuel penalty is a very useful tool. It can be seen that without considering fuel penalty, it is hard to understand the merit of one technology over another as the main output parameters namely weight, volume and power consumption do not vary in a similar manner. By using the ratio of power of cooling to fuel penalty as the basis of comparison, the cooling technologies or architectures can be compared in an objective manner, with a focus on the relevant characteristics of the system.

As discussed in section 5.3, on the analysis of the case-study, the mutually opposing results of the architecture comparison leads to the inference that the better capabilities of a particular architecture in comparison to the other architectures are applicable only in the region of design space closer to its own optimal point. This demands a design specific investigation while selecting an architecture, meaning that one should carry out an optimization process for a specific combination of heat loads in order to obtain a valid result, i.e. the optimum ECS architecture.

To sum up, a simulation-based optimization method that allows inclusion of ECS system in aircraft conceptual design phase was developed. The study demonstrated the complexity of the conceptual design stage with a focus on ECS architectures, which in turn, influences the later design stages of the combat aircraft.

Further work

The first proposal for future work refers to the validation of the proposed methodology in the industry. Furthermore, one can compare CAVE’s methodology with the proposed simulation-based optimization method.

Additionally, the methodology can be improved by making use of the Dymola’s acausal working principles. This refers to a similar procedure taken by E. Safavi in [2], where certain outputs, such as the heat loads, are transformed into inputs followed by computing the new outputs which can be the former inputs.

One interesting proposal is related to the change of the software’s used to assess the importance of the tools. Here, one can verify the factors aforementioned, but can also strive to achieve similar or better results with less effort.

The fourth and last further work proposed is related to the implementation of even higher fidelity models with assumptions replaced with application related data used with the proposed methodology. The outcome of this proposal is considered to be a one time job per aircraft type, resulting in a clear description of the interaction between components of the cooling technologies. The interpretation of the results will be extremely helpful when functional analysis will be used to generate new concepts.
References


[25] Rolando Vega Diaz. Analysis of an electric environmental control system to reduce the energy consumption of fixed-wing and rotary-wing aircraft. Cranfield University, 2011.


Appendix A

Input air

Figure 60: Input air diagram

The first calculation performed is to find other important constants that change with time, hence the gravity is computed with respect to the change in altitude, see equation (43). Moreover, the ambient temperature and pressure are computed depending on altitude changes, see equations (44, 45 and 46), where equation (46) is applied \iff the altitude exceeds $11 \text{ km}$.

\[
a = \sqrt{\gamma \times R_a \times T_a} \quad \text{where speed of sound varies with ambient temperature} \quad (40)
\]

\[
TAS = Mach \times a \times \sqrt{\frac{1.225}{\rho_{ram}}} \quad \text{where TAS is the true air speed}^{25}. \quad (41)
\]

\[
\dot{m} = TAS \times \rho_{ram} \quad (42)
\]

\[
g_2 = g \times \frac{6400}{6400 + \frac{\text{Altitude}}{1000}} \quad \text{where 6400 is the earth radius at equator} \quad [76] \quad (43)
\]

\[
T_a = T_0 - C \times \text{Altitude} \quad (44)
\]

\[
P_a = P_0 \times \left( \frac{T_0 - C \times \text{Altitude}}{T_0} \right)^{\frac{g_2}{\gamma \times R_a}} \quad (45)
\]

\[
P_a = P_0 \times \left( \frac{T_0 - C \times \text{Altitude}}{T_0} \right)^{\frac{g_2}{\gamma \times R_a}} \times e^{\frac{-g_2}{\gamma \times R_a}} \times (\text{Altitude} - 11000) \quad (46)
\]

Moving on to the outlet of the “Input air” model, the temperature and pressure represent the ram air properties thus according to I.Moir in [11] kinetic heating\textsuperscript{26} should be taken into consideration.

Therefore, the ram air properties calculations is performed using equations (47), (48) and (49).

\[
T_{ram} = T_a \times (1 + \frac{\gamma - 1}{\gamma} \times Mach^2) \quad (47)
\]

\[
P_{ram} = P_a \times (1 + \frac{\gamma - 1}{\gamma} \times Mach^2 \frac{\gamma + 1}{2}) \quad (48)
\]

\[
P_{ram} = \frac{P_{ram}}{T_{ram} \times R_a} \quad (49)
\]

\textsuperscript{25}I.e. speed of the aircraft relative to the atmospheric conditions

\textsuperscript{26}“Kinetic heating occurs when the aircraft skin heats up due to friction between itself and air molecules”
Appendix B

Jet engine assumptions, simplifications and calculation procedure

Figure 61: Jet-engine diagram

The following assumptions and simplifications have been done:

- Neglect all losses and impossibilities. All processes are isentropic.\(^{27}\)
- Neglect all kinetic energy components except at the inlet and the nozzle.
- Air and fuel mixture behaves as an ideal gas and has the same thermal properties as the air.
- All shaft works produced by the turbine are used to drive the compressor.
- Air (mixture) has a constant \(C_p = 1.005\, [kJ/kgK]\), and \(\gamma = 1.4\).
- Speed of sound is constant \(a = 343\, [m/s]\), due to the fact the ambient air temperature does not correspond to the actual air temperature coming from the input air model so calculating it using 40 it is impossible.
- Multistage compressor number of stages = 5; efficiency per stage = 0.75; pressure is multiplied along each stage by a factor = 1.8 \(^{77}\).
- Assumptions for air exiting the nozzle: temperature \(T_6 = 1600\, [K]\); mass flow rate is 20% larger than inlet \(\dot{m}_{exhaust} = 1.2 \times \dot{m}_{inlet}\); air velocity is 5 times larger than inlet velocity; pressure is equal to the inlet pressure.\(^{28}\)
- Other inputs and assumptions are made based on the engine VOLVO RM 12 specifications \(^{61}\) and from SAAB AB\(^{29}\): engine diameter \(D_{in} = 0.9\, [m]\); nozzle diameter \(D_{ex} = 0.5\, [m]\); bypass ratio\(^{30}\) \(BPR = 0.31\); a/c weight \(W_{ac} = 7000\, [kg]\); useful load (e.g., radar, ammunition, etc.) \(W_{load} = 5000\, [kg]\); fuel weight \(W_{fuel} = 2000\, [kg]\); range of the a/c \(RANGE = 2000\, [km]\)

Taking into consideration the aforementioned assumptions, the following steps were performed in order to create the jet engine model.

- Within the engine model, a similar table to the ones in section 3.2.2.2 is created for Lift/Drag ratio based on the given phase of the mission. The table is represented through the graph in Figure 62 and its importance is in computing the SFC\(^{31}\). It is worth to notice that the ratio decreases when maneuvers are made and it increases when speed decreases as see in the loiter phase.

\(^{27}\)having equal entropy
\(^{28}\)The nozzle of a turbine engine is usually designed to make the exit pressure equal to free stream \(^{62}\)
\(^{29}\)The data from SAAB AB are weight and range of the a/c.
\(^{30}\)ratio of the mass flow rate of the bypass stream to the mass flow rate entering the core
\(^{31}\)i.e. a quantity used to describe the fuel efficiency of an engine
• Within section 1-2 the flow is slowed down while pressure and temperature increase. The relation $h_1 + \frac{V_2^2}{2} = h_2$, where $h$ is the enthalpy, is used in order to compute the temperature and pressure compressors inlet (see equations 50 and 51)

$$ T_2 = T_1 + \frac{V_2^2}{2 \times C_p} $$

$$ P_2 = P_1 \times \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} $$

• Inside the multi-stage compressor, i.e. section 2-3, the pressure increases depending on the number of stages, efficiency ($\epsilon_{\text{stage}}$) per stage and by a predetermined factor. Additionally, the equations representing the outlet of the compressor are presented below.

$$ P_3 = N_{\text{of stages}} \times \text{factor} \times \epsilon_{\text{stage}} \times P_2 $$

$$ T_3 = T_2 \times \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} $$

• In order to compute the change in flow within section 4-5, i.e. between combustion chamber and turbine, the work of the shaft is computed using equation (54) and because the work of the compressor is equal to the one produced by the turbine, one can compute the temperature drop as seen in equation (55).

$$ W_{\text{compressor}} = \dot{m}_{\text{inlet}} \times C_p \times (T_3 - T_2) $$

By computing the temperature turbines outlet (see equation (56)) using the assumptions aforementioned, the temperature and pressure exiting the combustion chamber can be finally found as seen in equations (56) and (57)

$$ \Delta T = \frac{W_{\text{turbine}}}{\dot{m}_{\text{exhaust}} \times C_p} $$

$$ T_5 = T_6 \times \frac{\frac{V_2^2}{2 \times C_p}}{1000} $$

73
\[ T_4 = T_5 + \Delta T \] \hspace{1cm} (57)

\[ P_4 = P_3 \times \left( \frac{T_4}{T_3} \right)^{(\frac{\gamma}{\gamma - 1})} \] \hspace{1cm} (58)

\[ P_5 = P_4 \times \left( \frac{T_5}{T_4} \right)^{(\frac{\gamma}{\gamma - 1})} \] \hspace{1cm} (59)
Appendix C  Assumptions, simplifications and calculation procedure of a plate-fin heat exchanger

Figure 63: Heat exchanger diagram

As mentioned in section 3.2.2.7 the model requires inputs regarding its volume, thus the length \((L_x)\), width \((L_y)\) and the number of layers \((z)\) are user-defined. Other physical parameters are: fin thickness \((t_w)\), aluminium properties \((\rho_{Al} = 2712[kg/m^3] \) and \(k_{Al} = 240[W/m \times K]\) \) selected from [50] and the area inlet of ram air duct selected from [78].

Furthermore, the following assumptions and simplifications are considered:

- A cross-flow HEX is considered, thus different number of fins will be allocated for ram and bleed air sides. Moreover, the fin on the cold side, i.e. the ram air side, is considered two times larger in order to enhance the heat transfer.

- In order to simplify the geometrical calculations a square cross-section was considered for fin geometry, thus Fin height is equal to fin width.

- Computing fin width, denoted with “b” is based on a reference width \(b_{initial} = 0.002[m]\)

The following steps are performed by the software to compute the size of the HEX:

1. The fin geometry is calculated at first based on the inputted dimensions. Due to the fact the cold side is larger than the bleed air side, the number of gaps is computed independently as seen in equations (60) and (61). Likewise, computing fin width is done by using equation (62), followed by computing the height of the HEX (see equation (63)).

\[
N_x = \frac{L_x + 2 \times b_{initial}}{2 \times b_{initial} + t_w} \text{ where } N_x \text{ value is taken as an integer.} \quad (60)
\]

\[
N_y = \frac{L_y + b_{initial}}{b_{initial} + t_w} \text{ where } N_y \text{ value is taken as an integer.} \quad (61)
\]

\[
b = \frac{L_y - N_y \times t_w}{N_y - 1} \quad (62)
\]

\[
L_z = z \times (2 \times t_w + b + b_r) \text{ where } b_r \text{ is } 2 \times b. \quad (63)
\]

2. The air properties are computed at every time step based on the effect on the inlet temperature according to the equations in [79].

3. All steps presented above will conclude with the computation of the overall heat transfer coefficient as seen in equation (64), according to [50].

\[
U = \frac{1}{h_h} + \frac{b}{k} + \frac{1}{h_c}; \quad (64)
\]
4. Due to the fact this is a method based on effectiveness, a criteria (see equation 65) is established from which the value of the effectiveness is defined as seen in equations from 66.

\[
C_r = \frac{\min(m_{\text{hot or cold}} \times C_{\text{phot or cold}}, m_{\text{hot or cold}} \times C_{\text{phot or cold}})}{\max(m_{\text{hot or cold}} \times C_{\text{phot or cold}}, m_{\text{hot or cold}} \times C_{\text{phot or cold}})}
\]  

(65)

\[
\text{if } C_r = 1 \quad \text{then } e = \frac{NTU}{1 + NTU} \\
\text{if } C_r = 0 \quad \text{then } e = 1 - \exp(-NTU) \\
\text{Otherwise } e = \frac{(1 - \exp(-NTU \times (1 - Cr)))}{(1 - Cr \times \exp(-NTU \times (1 - Cr)))}
\]

(66)

5. The output temperatures based on the heat transfer process, thus the temperature is computed based on the heat transfer rate described in equation (67), using the equations (68) from [50].

\[
Q = e \times \min(m_{\text{hot or cold}} \times C_{\text{phot or cold}}, m_{\text{hot or cold}} \times C_{\text{phot or cold}} \times (T_{\text{inlet hot}} - T_{\text{inlet cold}}))
\]

(67)

\[
T_{\text{outlet cold}} = \frac{Q}{m_{\text{cold}} \times C_{\text{pcold}}} + T_{\text{inlet cold}}, T_{\text{outlet hot}} = \frac{-Q}{m_{\text{hot}} \times C_{\text{phot}}} + T_{\text{inlet hot}}
\]

(68)

6. The output pressure is estimated based on the pressure drop inside the HEX according to the procedure from [80], where the friction factor is computed based on the Reynolds number that determines if the flow is laminar or turbulent.

7. Last steps done by the HEX code, is to compute the outlet density based on the new temperature and pressure, followed by a computation of the mass flow rate (see equation (69) from [50]) depending on the free flow area, velocity of the fluid based for each side and the new densities

\[
\dot{m} = V \times A_f \times \rho
\]

(69)
C.1 Heat exchanger validation and verification

(a) Pressure drop on the bleed air side of the HEX

(b) Temperature drop on both the ram and bleed air side

Figure 64: The heat transfer process inside the plate fin HEX
Figure 65: Effectiveness of a HEX with the following dimensions $0.3[m] \times 0.3[m] \times 0.7[m]$.
Appendix D  Functional Analysis

The functional schematics and matrices are presented in this section.

D.1  Functional tree

Figure 66: The Top level function tree
Figure 67: The sub function tree for "Maintain Temperature"
Figure 68: The sub function tree for "Maintain Pressure"

Figure 69: The sub function tree for "Maintain % Fresh Air"
### D.2 Functions/components matrix

<table>
<thead>
<tr>
<th>Functions/Components Matrix</th>
<th>Architecture 1 BS Liquid system</th>
<th>Components</th>
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<td>Maintenance of Temperature of Recompressing fluid</td>
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Figure 70: Functions-components matrix for Architecture 1:Bootstrap-Liquid concept
### D.3 Functions/components matrix 2

| Functions-Components Matrix for Architecture 2: Bootstrap-VCS-Liquid concept |

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Figure 71: Functions-components matrix for Architecture 2: Bootstrap-VCS-Liquid concept
Figure 72: Connection matrix for Architecture 1: Bootstrap-Liquid system concept
Figure 73: Connection matrix for Architecture 2: Bootstrap-VCS-Liquid system concept.