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DESIGN SYSTEM INTEGRATION FOR MULTI-OBJECTIVE OPTIMIZATION OF AERO ENGINE COMBUSTORS

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To my sister Elena

"When you're down and out
When you're on the street
When evening falls so hard
I will comfort you
I'll take your part
Oh, when darkness comes
And pain is all around
Like a bridge over troubled water
I will lay me down"

Bridge over Troubled Water,
Simon & Garfunkel - 1970

"The best thing for disturbances of the spirit is to learn. That is the only thing that never fails. You may grow old and trembling in your anatomies, you may lie awake at night listening to the disorder of your veins, you may miss your only love and lose your moneys to a monster, you may see the world about you devastated by evil lunatics, or know your honor trampled in the sewers of baser minds. There is only one thing for it then – to learn. Learn why the world wags and what wags it. That is the only thing which the poor mind can never exhaust, never alienate, never be tortured by, never fear or distrust, and never dream of regretting."

"The Sword in the Stone" by T.H. White (Collins, 1938)

Acknowledgements

I still remember the day when Antonio, now Professor Andreini, proposed me to be part of this project. Maybe it was because I was young (well, not that young) and full of energy (probably overloaded), but I could never have imagined how tough the challenge I accepted to face would turn out to be. Some four years have passed since that time, in which I believe I have pushed his patience beyond the limit more than once. It is precisely for this reason that I feel the need to thank him at the opening, even though I know that I will never be grateful enough for the precious experience he has given me. And this certainly would not have been possible without Prof. Bruno Facchini, whose memory I cherish of all things is the hug we exchanged not too long ago, before I embarked on a new and exciting adventure. When I reflect on how much I have changed since the first time I walked into his office, how many years he has put up with me... I am almost embarrassed! I often think about how complicated the duty of raising people, caring for them and preparing them for the World can be. In this mission of his, I only hope that I have been able to return him with the satisfaction that I myself feel in reaching the end of this journey. A path that I must admit has not always been easy, that has penetrated my deepest inner self to the point of inexorably merging with it. A trail, this one, made up more of climbs than descents and which would not have had the same meaning without the people found along the way: it is not to me, in fact, that I owe this achievement, but to you. I owe you a lot, if not everything, because if anything good has come out of this long and exciting work, it is mainly thanks to you for having managed to bring out the best in me.

So it is with some trepidation that I thank the entire HTC group: from the seniors to the newbies, be they in the Santa Marta offices or in the THT lab... And now scattered all over the place outside the University. I don't think I will ever stop feeling part of this community because, granting me a bit of poetic license, “you can take a man out of the HTC Group, but you can never take the HTC Group out of a man”. My best wishes go to my colleagues from the XXXIV cycle: Tommaso, Pier Carlo and Leonardo L. . With the latter I also had the chance to share the magnificent experience that was Visionary, alongside our CEO Davide. Thanks to Lorenzo P. and Simone P. for the help that on a human and technical level you always managed to provide in a timely and surgical precision manner. A couple of stronger hugs are reserved for Matteo, friend and partner in crime, and Sabrina, for the perfect understanding that never needed many words.

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Because “lo zingaro quando gli gira... Gira!”, and so I can't wait to leave for the next “Zingarata”, together with Leonardo G., Stefano and Lorenzo C. (for the sake of the holy women who put up with us). I want to celebrate here the affection and sincere friendship that we have managed to build over all these years, equal only to that which binds me to Matteo M., my 'Soul Mate'. It would really be a shame not to thank at this very point two people who mean a lot to me: Lorenzo Mazzei and Massimo Giovanni Giambra. I want to thank them for having been and continuing to be a guide for me, not only a beacon but also a compass in this sea of... Life! Serena and Emanuela, you are truly lucky, but I feel the same way about knowing you are together on this earth.

And I can do nothing but feel blessed to have met the person with whom I share my life. Marta, in the chaos of this existence my greatest fears vanish in the face of the enthusiasm of growing our projects, and the deepest voids are filled with the joy of the future we imagine together.

My last thought goes to my family: to the sweetness of my mother Emanuela, the determination of my sister Elena and the charm of Antonio, the affection of my aunt and uncle, and the joy of my niece Diletta. I have never seen a year go by as fast as the one that has just ended. Coping with it was not easy and, as we unfortunately had to learn, one cannot always keep control. Many things that we considered as certainties have instead shown themselves to us in their true essence as fragile balances. In trying to hold the pieces of what remains together, we have revealed our frailties, and helplessly perhaps found a way to accept and appreciate ourselves for who we are. I think there is no sorrow or injustice that can deprive us of the joy of this new consciousness. Dad, for my part I think I have learnt more from you in this year than I have in the last 30... Maybe it is because I have decided to listen to you, even though I can no longer hug you. And whatever new steps I take, so far from those I imagined, I will take them to be happy and continue to make you proud. From the bottom of my heart, from the folds of my soul, my greatest thanks go to you.

Abstract

The transformation towards a climate-neutral civil aviation is providing significant business opportunities to the aero engine market players. To meet this target and keep competitiveness, however, groundbreaking solutions must be introduced at the product's level in the shortest possible time. Industry leaders are increasingly embracing lean and digital approaches for this purpose, by applying these concepts at all company's levels. Considerable room for improvements can be identified in the development of complex components as, for instance, the combustor. Due to the complexity of phenomena taking place and interacting into it, there are conflicting functional requirements defined over different physical domains. This leads to a design approach that must be both multidisciplinary and multi-objective, in which the need for supporting know-how and product expertise arises with extensive and structured studies of the design space arises. Nowadays, simulation-based methodologies represent a standard in evaluating multiple configurations of the system, although it may lead to heterogeneous models interacting with each other, sharing miscellaneous information within the process. In this context, taking advantage of integrated design systems has been proven to be beneficial in standardizing the simulation processes while embedding design's best practices.

The subject matter of this work is the Combustor Design System Integration (DSI), an integrated methodology aimed at easing and streamlining the preliminary design phase of aero engine combustors. Its concept will be described in the first part, where the automation of low value-added tasks will be introduced together with four custom integrated tools. It is composed of a CAD generation system, a RANS-based CFD suite for reactive flow calculations, a boundary-conditions processor for 3D thermal FEA and a FE structural environment for stress and displacement estimation. Particular importance is given to the definition of cooling and quenching systems on combustor's liners, since their prominent impact on aero-thermal and durability performance. Therefore, specific features for a detailed topological management of holes are presented in this work, providing advance patterning and arrangement capabilities which are not addressed in other design systems. Finally, it will be possible to prove the reduction of lead time for analysis, as well as the enhancement of the overall process robustness. The NEWAC combustor, a lean-burn concept developed in the context of the homonymous European research project, will be exploited as a case allowing, moreover, an assessment of the DSI modelling approach. In the second part will be presented a dedicated framework for multi-objective design optimization, comprising the DSI tools for CAD generation and CFD analysis. A fully automated and water-tight process is here implemented in order to address the combustor's problem of dilution mixing, aimed at optimizing the temperature profiles and the emission levels at its outlet. This approach will leverage on advanced neural network algorithms for improving the overall design workflow, so to ensure that the optimal combustor configuration is defined as a function of the product's Critical-To-Quality. The results of the optimization will be shown for a rich-quench-lean combustor concept intentionally designed to support this activity, referred as to LEM-RQL.

The general intention of this work, in the end, is to demonstrate how integrated design systems embedded in optimization frameworks could represent both a strategic asset for industry players and a relevant topic for academics. Given the pervasive integration-and-automation of the process, the generality in processing multiple design layouts and the possibility to accommodate increasingly advanced and sophisticated optimization algorithms, the DSI procedure configure itself as an ideal platform within the technology maturation process, thus enabling not only the improvement of in-service components but also the development of next-generation combustor products.

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Nomenclature

c	*Progress variable*	*[-]*
D	*Diameter*	*[mm]*
J	*Momentum flux ratio*	*[-]*
i	*Scalar quantity, counter*	*[-]*
j	*Scalar quantity, counter*	*[-]*
k	*Scalar quantity, counter*	*[-]*
M	*Molar mass*	*[kg/mol]*
$\dot{m}$	*Mass-flow rate*	*[kg/s]*
P	*Pitch*	*[mm]*
p	*Pressure*	*[Pa]*
r	*Pearson's product-moment correlation coefficient*	*[-]*
T	*Temperature*	*[K]*
V	*Velocity*	*[m/s]*
u	*Weighting scalar*	*[-]*
w	*Mass fraction*	*[-]*
S	*Curvilinear abscissa coordinate*	*[mm]*
Y	*Jet penetration*	*[m]*
Z	*Mixture fraction*	*[-]*

Greeks

α	*Fuel/air ratio*	*[-]*
Δ	*Variation of quantity*	*[-]*
ϕ	*Equivalence ratio*	*[-]*
ρ	*Fluid density*	*[kg/m^3]*
θ	*Angular coordinate*	*[°]*

Subscripts

0	*Baseline*
1	*Lower limit*
2	*Upper limit*
30	*Referred to combustor inlet station*
40	*Referred to combustor outlet station*
ad	*adiabatic*
ave	*Average*
ax	*Axial direction*
dil	*Dilution*
eff	*Effusion*
gas	*Gas*
inn	*Inner*
jet	*Jet*
lin	*liner*
max	*Maximum*
mean	*Mean*
min	*Minimum*
out	*Outer*
ref	*Reference*
tg	*Tangential direction*
wall	*Near to wall quantity*

Acronymous

ACT	*Advanced Customization Toolkit*
ANN	*Artificial Neural Network*
CAD	*Computer-Aided Design*
CAEP	*Committee of Aviation Environmental Protection*
CFD	*Computational Fluid Dynamics*
CO	*Carbon Monoxide*
COS	*Combustor Optimization Suite*
CPU	*Central Process Unit*

CTQ	*Critical To Quality*	
DIEF	*Department of Industrial Engineering of the University of Florence*	
DSI	*Design System Integration*	
DOE	*Design Of Experiments*	
EA	*Evolutionary Algorithm*	
EI	*Emission Index*	*[-]*
EU	*European Union*	
FEA	*Finite Element Analysis*	
FNS	*Flow Network Solver*	
GE	*General Electric*	
GUI	*Graphic User Interface*	
HTC	*Heat Transfer Coefficient*	*[W/m^{2}K]*
ICAO	*International Civil Aviation Organization*	
LDI	*Lean Direct Injection*	
LEMCOTEC	*Low EMissions COre-engine TEChnologies*	
LEM-RQL	*LEMCOTEC Rich-Quench-Lean*	
MBPM	*Metric Based Process Mapping*	
NEWAC	*NEW Aero engine Core concepts*	
NN	*Neural Network*	
NOx	*Nitrogen Oxides*	
OF	*Optimization Factors*	
OPR	*Overall Pressure Ratio*	
PERM	*Partial Evaporation and Rapid Mixing*	
PM	*Particulate Matter*	
RANS	*Reynold Averaged Navier-Stokes*	
RSM	*Response Surface Method*	
SAF	*Sustainable Fuel Aviation*	
TET	*Turbine Exhaust Temperature*	*[K]*
TIT	*Turbine Inlet Temperature*	*[K]*
TBC	*Thermal Barrier Coating*	
UHC	*Unburned HydroCarbons*	

UNIFI	*University of Florence*
VSM	*Value Stream Mapping*
XML	*eXtensible Markup Language*

Introduction

Propulsive systems based on aero gas turbine engines have become the standard in both civil and military field. Although this technology might appear mature and yet established, its evolution among the last 80 years suggests that there are still many aspects to be deepen and further explored [1]. The first jet engine to be conceived was the famed *Whittle Supercharger Type W.1*, which had its maiden flight only in the 1941 powering the *Gloster E.28/39* aircraft. Although Sir Whittle started its development in the latest 1920s, about a decade was necessary to produce a working demonstrator of the system he patented in 1930. It is a known fact that one of the major problem he faced during the prototyping phase was related to the combustion process, which did not allowed to achieve safety requirements due to significant levels of instability [2]. Meanwhile, on the other side of the English Channel, Dr. Hans von Ohain powered the first jet airplane with the Heinkel HeS 1, a system he designed and the winner of the challenge for the first jet engine to take off [3]. From this perspective, it cannot be difficult to understand how the combustion system played a significant role since the beginning of the jet propulsion era.

The line of development for early combustor products focuses on driving such system towards higher performance, higher reliability, and lower fuel consumption. A "cut-and try" method was the baseline approach for combustor design, in which different variants of the system were tested until a suitable arrangement could be found [4]. Despite the empirical correlation and the experimental derivatives retrieved from such techniques have helped designer in accelerating the technology maturation, this resulted in extremely expensive programs with exceptionally long development times. An important change of direction to the driving requirements of aero engine combustors has been introduced in the 1970s, when the International Civil Aviation Organization (ICAO) published the “Control of Aircraft Engine Emission” document [5]. In this regulatory act were addressed the most relevant aspects impacting on environment, in order to define a roadmap to reduce the pollutant and noise emissions in this field: to this end, in 1977 the Committee of Aviation Environmental Protection (CEAP) have published the first standards. From this moment on, the development of modern combustors has followed increasingly restrictive specifications related to the combustion emissions. However, this did not lead to more advanced design approaches which were still relying on intensive experimental campaigns. Anyway, it has been necessary to wait until the 1980s to attend a deep revolution into the development process of combustors. The increase in the accuracy of numerical methods coupled with the rising power of computational techniques has set off the advent of the simulation era [6]. Through these methods it has been possible to demand the most expansive and time demanding tasks (as testing, prototyping, etc.) to computational models’ representative of the product. Despite the last decades were marked by a rising demand in computational resources, increasingly precise and accurate numerical models have led simulation to play an irreplicable role in the design of combustors. Next to this, simulative design systems aimed at making the development stage an effective and efficient process have raised in the last 20 years.

From an industrial point of view, time-to-market has become indeed a crucial aspect also in the field of aviation. If the increasingly high requirements act as a catalyst for the technological maturation, the demand for making advanced solutions available at product level can shorten the whole development phase. This is leading all the actors belonging to an aircraft program to optimize their processes: from designers to manufacturers, from airframes to systems and engines. In such a challenging environment, introducing methodologies and tools devised to save time and resources is strategical. The requirements for a climate neutral aviation are leading the aero engine to undergo a deep revision of its architectures, as well as the implementation of terrific advancements which are inevitably considering the combustion system: Sustainable Fuel Aviation (SAF), pervasive electrification and Hydrogen-based propulsion are the nowadays most promising technologies [7]. Today, the digital revolution is giving further rooms for the improvement of such a complex product and in this context, simulation-based integrated platforms have the potential to help companies in driving innovation frameworks and keep asserting their competitiveness.

Aim of the work

Since the combustor's preliminary design phase consists of an iterative and time-consuming practice, integrated design systems have demonstrated to be beneficial in deriving an optimal design while rationalizing the available resources. The aim of this work, indeed, is the development of the Combustor Design System Integration (DSI), an advanced platform for the aero-thermal and structural design of aero-engine combustors. For this purpose, advanced features aimed at managing the definition of cooling and quenching systems on liners locations have been conceived and implemented within the software tools of which the methodology is composed. The process digitalization has been here taken as a key enabler for the integration of the multiple analysis steps and the automation their tasks, leading to the definition of four Ansys Customized Tools (ACT) extending the capabilities of the Ansys standard software products. The resulting streamlined workflow is then included in a specific framework for design optimization, based on the DSI tools for CAD generation and CFD analysis. Through this last, advanced optimization algorithms have been made available within a water-tight and fully automated process.

In conclusion, the purpose of this research activity is to demonstrate that the adoption of software-based advanced design platforms, made of an optimization framework embedding integrated tools, provides multiple benefits to the combustor's preliminary design phase. From a process perspective, the design workflow is enhanced by an increased robustness, thus reducing the overall time-to-design. Instead, the product is defined as a trade-off between the most relevant design variables, meaning that the optimal design configuration is driven by the requirements of the system.

Thesis Outline

During the research activity, the design process of aero-engine combustors has been addressed in its preliminary phase. Since this last consists of subsequent steps of analysis, the mapping of the value generated across the design workflow represented the initial premise for implementing the Combustor DSI logic. Here, special emphasis has been given to minimizing the adoption of time and computational resources without compromising the representativeness of the simulation models. In order to enhance the overall process, the design tools have been included in a framework to standardize workflow, providing it with a set of advanced algorithms for product optimization. The manuscript will be structured as follows:

- **Chapter 1** – It is dedicated to introducing the state-of-the-art in aero engine combustor development, the requirements existing at the product's level and the phases in which the design process unfolds. By considering the impacts on the most relevant aero-thermal characteristics, the definition of cooling and quenching systems over liners' locations is here addressed. The context of "design systems" will be lastly provided by summarizing the plethora of methodologies specifically developed to standardize such a demanding activity, as well as an overview on the surrogate modelling and optimization techniques.
- **Chapter 2** – Right after reviewing the preliminary design phase through a metric-based process mapping technique, thus evidencing the weak and not

efficient tasks of this process, the Combustor DSI can be introduced as the result of applying principles as process-integration and task-automation to this phase. The description covers the four tools composing the resulting workflow (CAD system, the CFD suite, the FE thermal processor and the FE structural environment) and the framework provided for the design optimization (COS). Here, since the consistency of information and the linking between tools is a mandatory aspect to be achieved, dedicated scripts are implemented to include a detailed cooling and quenching definition, as well as variation logics to drive an optimization process based on these aspects.

- **Chapter 3** – The NEWAC combustor concept, a lean-burn, real test-case, is processed through the present design procedure. The DSI key features will be presented, and the methodology assessed through a test-cell data comparison. For a straight-forward design activity, the saving in time and resources will be quantified by comparing the DSI workflow to a manual and user-dependent process.
- **Chapter 4** – It will be presented a design optimization activity addressing the dilution jets mixing problem. To this end, a dedicated framework integrating the DSI tools for CAD and CFD, as well as a novel rich-quench-lean academic test case, are implemented to carry out the study. Through the definition of an optimal design configuration, which is based on the multi-objective minimization of temperature profiles and emission indexes at combustor's outlet plane, it will be demonstrated that making use of advanced optimization algorithms within a water-tight process is beneficial both in terms of lead-time to design and increasing accountability of design solutions.

In the last chapter, a summary of the main achievements of this research is given, together with conclusions and recommendations for future works.

Chapter 1. Integrated approaches to combustors design

As is well known, the combustor is a critical component of the whole engine. It is by means of the reaction process that the energy contained in the fuel is converted into enthalpy for the working fluid, which can then be extracted to realize the propulsive effect. The combustion, however, is not so easily realized, nor even controlled. In fact, in maximizing the combustion process for performance, the resulting stresses may be challenging for component durability. Therefore, the development of such products is traditionally marked by a trial-and-error approach. Reason for this can be found in the complexity of phenomena taking place in the combustion process, combined with the increasingly demanding requirements on the product [4]. Whilst experimental analysis is still a fundamental component at all Technology Readiness Levels (TRL), in recent decades numerical simulation has become a strategic element in the design of such complex systems. The constantly growing reliability of numerical models, as well as the increasing access to computational resources, have been decisive for industry in reducing products' lead times and costs while increasing value [6,8]. Significant benefits have been brought to the design process, and in particular to the preliminary phases, in which the most promising candidate is defined through an extensive exploration of the design space [9]. It is precisely in this context that integrated approaches for combustor design, as the one presented in this work and named Combustor Design System Integration platform, find room.

1.1 Aero engine combustor fundamentals

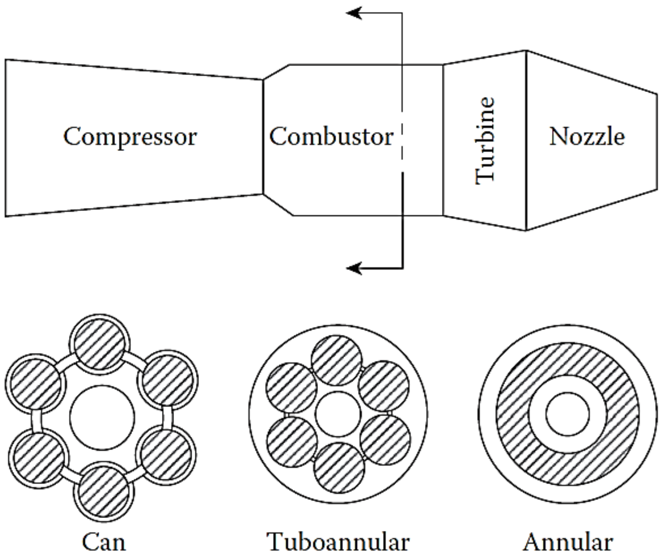


Figure 1.1 – Common arrangements for combustion systems

In order to reduce product's weights and ensure a minimum levels of pressure losses, modern aero engine combustors are usually conceived as annular or tuboannular layouts, depending on the desired performance levels and the field of application: civil or military (Figure 1.1). Between the several requirements that this is called to meet, the operability may represent one of the most important: this means being capable of starting and work successfully in a wide range of temperature (and pressures) environments, as well as to provide a reliable relight in case of flame extinction. Since the conditions encountered during a standard flight are various and high performance are always required, some strategies are employed to ensure the need for engine flexibility [10]:

- Variable geometry systems employ controllable air bleedings for managing the amount of air destined to the flame tube, and hence setting the thermal power produced by the reactive process. In order to achieve low emissions, these devices provide the opportune fuel/air ratio α for keeping the flame temperature ranging the low pollution limits values; drawbacks of this solution stems from the complexity in controlling such mechanisms as well as achieving the desired outlet profile temperature for all operative conditions, which is a crucial point in the design of cooling systems installed on the turbine 1st stage.

- *Staged combustion* solution provides a fuel staging by modulating its injection, depending on the different conditions in which the engine is going to operate. The objective of such “selective fuel feeding” is to raise the equivalence ratio ϕ -which is defined as the ratio between operative and stoichiometric α conditions- and hence controlling the temperature of the localized combustion zones at low-power operation (from $\phi = 0.8$, down to $\phi = 0.6$). Such solution is commonly obtained with a staging of the flame tube, which should be arranged in a “radial” or “axial” configuration as shown in Figure 1.2.

The adoption of these strategies is clearly in agreement with a low-emission concept. Both are in facts based on the control of flame temperature which, as will be seen in the following, represents a significant factor for the pollution problem. The general layout is also determined by engine dimensions since the development

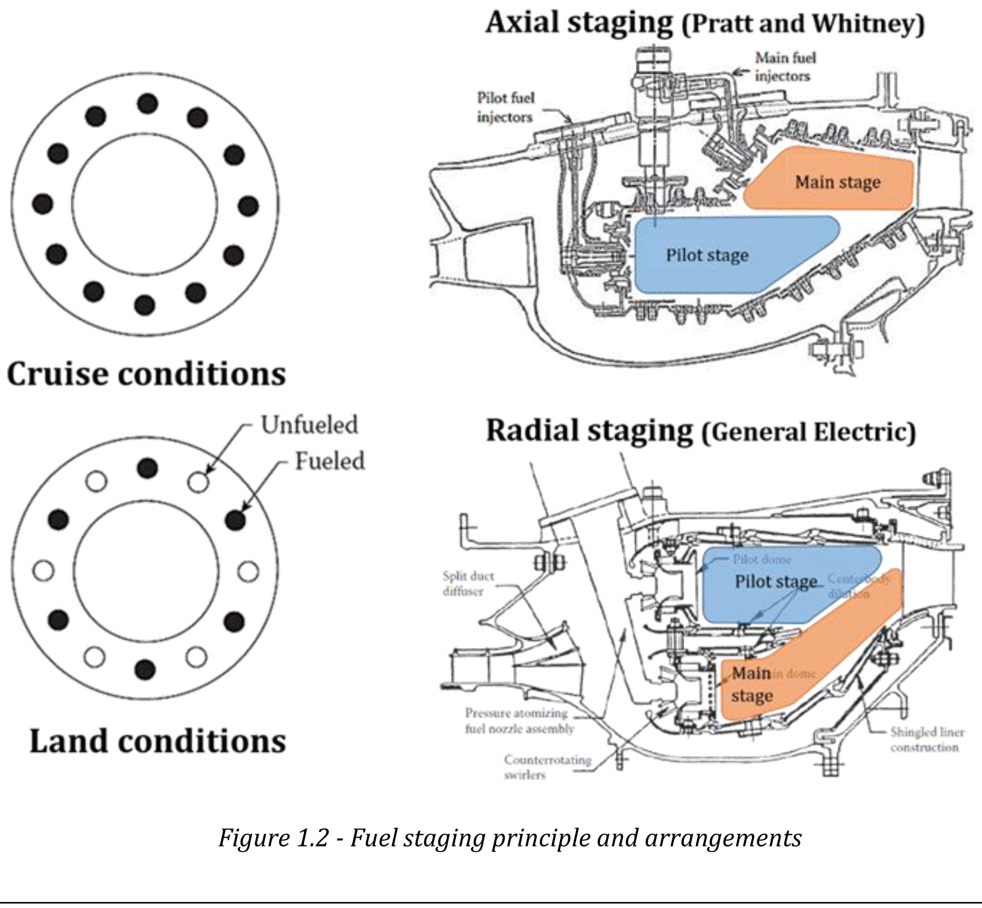


Figure 1.2 - Fuel staging principle and arrangements

of the combustor geometry must consider also to the amount of space available for its placement. Configurations which have been reported until now shows a straight-through arrangement, in which the air flows in a direction parallel to the axis of the gas turbine system. Such solution represents the standard in conventional aero engines; however, for small engines or in application in which the compactness is an important requirement, reverse-flow combustors are generally exploited. For such arrangement, as highlighted in Figure 1.3, the air that flows through holes in the outer liner wall approaches these holes from a direction which is opposite to that followed by the air entering the combustion zone through holes in the inner liner wall. Several are the advantages resulting from the employment of such configuration: i.e., the provision of a radial diffuser at inlet, which deals with reduced pressure losses and a better flow distribution, as well as a bigger volume available for the conducting of the reactive process. These benefits arise mainly from the integration of the final centrifugal stage of compressor, which is the standard for revers-flow arrangements; furthermore, the growth in axial direction of the combustor -on an equal combustion volume- leads to a shorter engine shaft and hence a reduction of the total weight (which means less fuel consumption) [11]. On the other hand, principal concerns are related to ignition, wall cooling and fuel injection.

If aspects considered up to this point allowed an identification of the combustor constructive arrangement, is the reduction in pollution emissions, together with

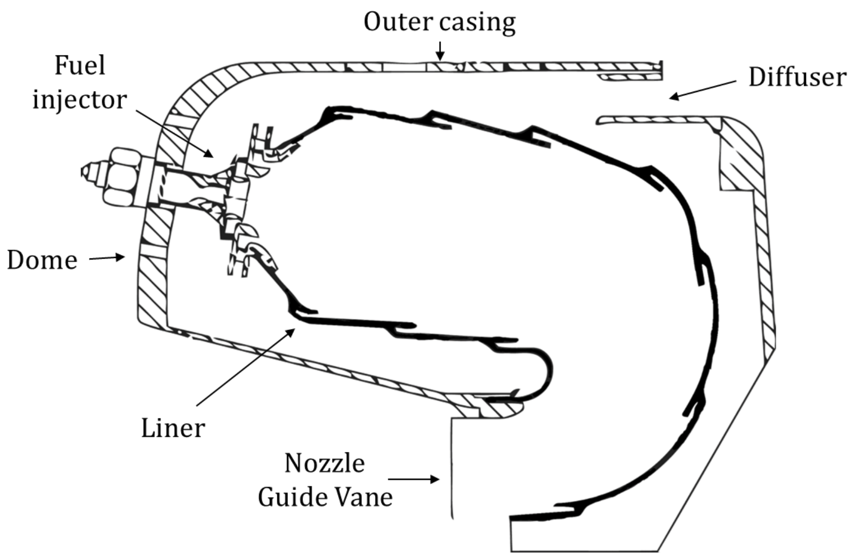


Figure 1.3 - Sketch of a reverse flow annular combustor

the state of the fuel, which represents the driving requirement in the design of combustor concepts. The potential impact on health end environment caused by the increase in civil transportation, hence in fuel consumption, has led to ever more stringent regulations in the last years; for these reasons engine manufacturers developed new and even more efficient ways for realizing the combustion process. The production of pollutant is depending by the engine operative condition as well as the by the performance of the primary zone of the chamber, as reported in Figure 1.4.In order to understand the strategies adopted in the emission reduction, a preamble on pollutants nature and production is required. A more in-deep and detailed description of the argument can be found in [10].

- CO and UHC – Carbon monoxide and Unburned HydroCarbons are toxic substances common to all combustion processes. Their production stems from a partial failure of the chemical reaction, which arises in depletion of oxidizing (rich burning) or when rates of oxidation are too slow (lean burning); inlet temperature and chamber pressure are two of the main influential parameters in emission, other than equivalence ratio. Both CO and UHC are related to low efficiency combustion, a condition which -for gas turbines- occurs in low power regimes. Techniques provided for reducing that kind of pollutant are based on flame temperature control, condition achievable by adopting the previously shown “variable geometry” or “combustion staging system” arrangement.
- Smoke – is a pollutant relevant for liquid fuels since its production starts close up to the fuel spray where the inception of finely divided soot particles -due to the quenching of HC in rich regions of the flame- can take place. Particulate Matter (PM) is responsible for atmosphere soiling and is strongly associated to respiratory diseases. Since the rate of PM formation is governed more by the physical process of atomization then from the combustion process itself, its reduction can be achieved with an improvement in the injection technology.
- NOx – Oxides of Nitrogen are substances common to all the combustion systems which exploit air for oxidizing. Most of the pollution is generated by the

oxidation of atmospheric N_2 in high-temperature regions of the flame (Zeldovich mechanism), hence flame temperature as well as equivalence ratio can be considered the most influencing parameters for NOx. Since high temperatures leads to high power, pollution is present during high-efficient combustion processes. Because of their stability in atmosphere, such toxic substances represent the most worrying one and should be limited as possible. Is in the view of this last consideration that the development of so called "low emission" combustor takes place: here again, temperature control is the technique employed for limiting the pollution which leads -neglecting obsolescent solutions such as water/steam injection- to "Rich-Quench-Lean" and "Lean Direct Injection" concepts.

"Rich-burn/quick-Quench/Lean-burn" combustor represents the state-of-the art in ultralow NO_x emissions for aeronautical applications. This concept provides a reduction in pollution by controlling the flame temperature, by means of the control on local stoichiometry of the combustion process. In Figure 1.5-a, a cross-section of a RQL combustor is reported together with trends of pollution levels with equivalence ratio. In the primary zone, a fuel-rich (R) primary zone is employed to prevent NO_x formation, thanks to the combined effects of the low temperature and oxygen depletion. Downstream, a sharp mixing is obtained with a local introduction of the air (Q) required to complete the combustion and reduce the high temperatures spots which can arise for local stoichiometric zones; in the last zone (L), the reactive

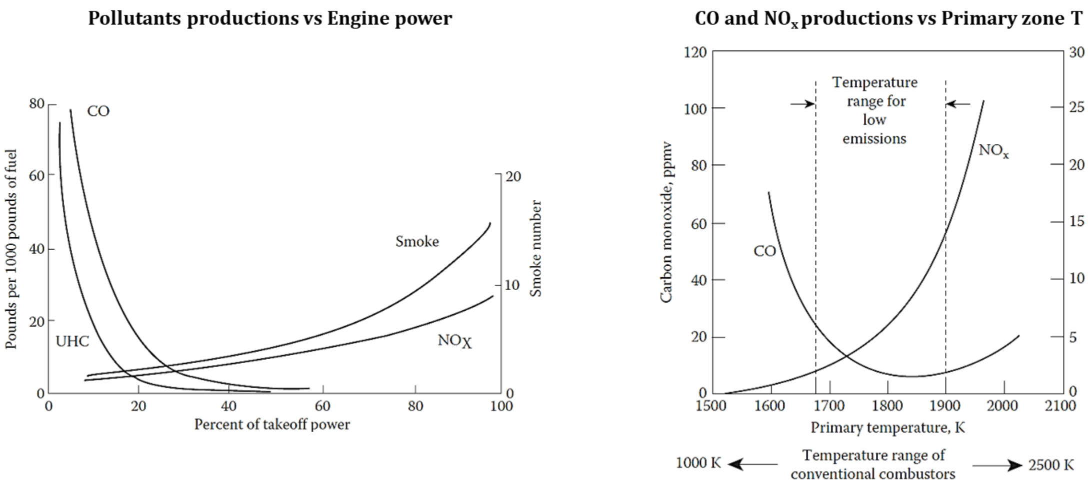


Figure 1.4 - Pollutant's production, depending on engine power and primary zone temperature

process draws to its completion in a lean environment. “Lean Direct Injection” combustor represent a promise for NO_x emissions for aeronautical applications. This concept provides a reduction in pollution by controlling the flame temperature, by means of the control on global stoichiometry of the combustion process. In Figure 1.5-b, a cross-section of a LDI combustor is reported together with trends of pollution levels with equivalence ratio. This concept aims to develop only lean flames, in order to completely avoid the NO_x formation. In zone (1), a diffusive flame characterized by a higher equivalence ratio works as a pilot for the leaner flame developed in (2). Since in the primary zone only about 30% of flow provided by compressor is going to feed the diffusive flame, the remaining air -about 70%- is used to feed the cooling system as well as for controlling the reactive process. For achieving such conditions, the liquid fuel needs to be completely evaporated between the start of the reaction process, so injectors play a crucial role in the functioning of the system. Other drawbacks are related to the stability of the flame, which work in quenching proximity and hence are strongly influenced by functioning instabilities (i.e. thermal-acoustic issues).

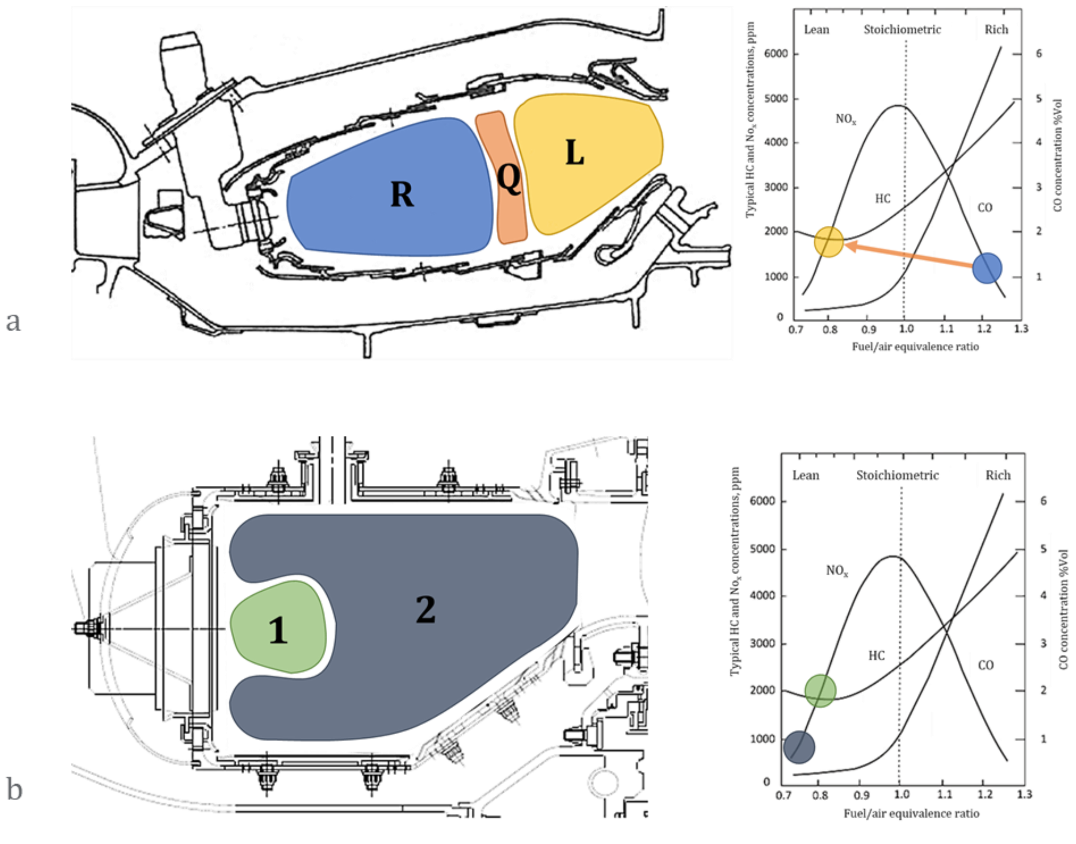


Figure 1.5 - Example of a RQL (a) and LDI (b) combustors, with trend of NO_x vs Equivalence ratio

1.2 Overview of the combustor design process

As a complex industrial product, the requirements that a gas turbine combustor have to fulfil are several [4]. With reference to the aviation field, a set of peculiar characteristics should be guaranteed to ensure the engine system in serving its main purpose, thus producing a propulsive effect by converting the energy stored in the fuel. Due to the wide range of phenomena which are taking place in this system, several are the physical aspects that must be considered during its development. Throughout the reactive process, indeed, complex 3D flow structures are interacting each other, giving rise to high turbulence levels. Its production rate is critical for the stabilization and the development of the flame, where the high-temperature exothermic redox reaction takes place. The resulting hot gasses, as well as the radiation effects, are responsible for thermal loads of considerable entity which may compromise the durability of the combustor parts. The components, which are subject to significant pressure levels, shall be additionally preserved from thermoacoustic fluctuation which could occur during its operability. This determines the design process to be necessarily approached through a multidisciplinary method. Besides that, the presence of different and potentially conflicting requirements, as well as multiple performance conditions to be achieved, implies the combustor candidate in be-

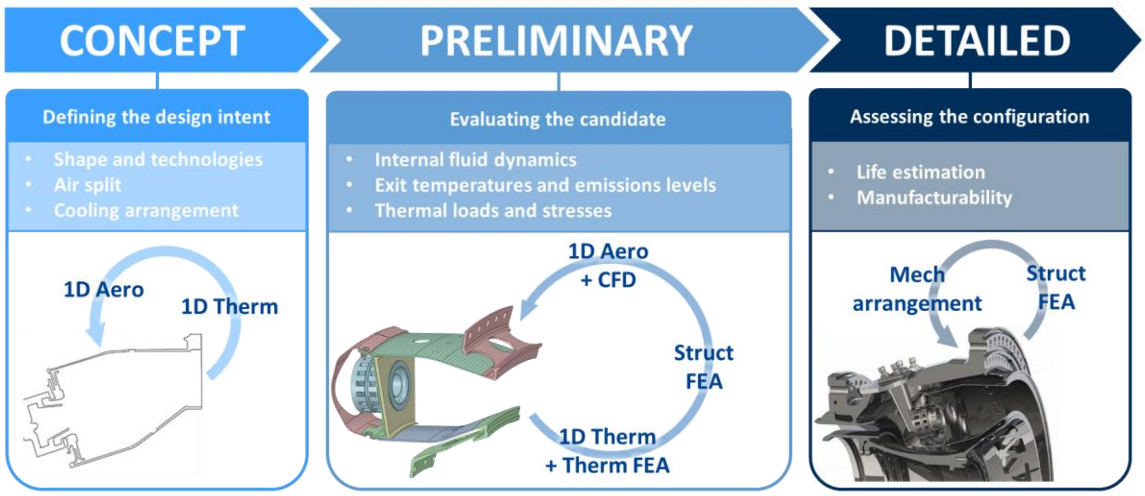


Figure 1.6 – Phases of the combustor design process

ing inevitably a compromise of some kind. Multi-objective criteria must so be comprised in the process to ensure that all the design drivers are carefully considered during the selection activity. A further aspect which might not be overlooked is the multidimensionality of the problem: the design process, in the present case, results in an analytical task which evolves in the direction of detailing the product's functional characteristics. It unfolds from one-dimensional to full 3D evaluations, from steady to transient analyses, to verify the conditions that must be ensured to the system. It is precisely through product's requirements that is possible to carry out the down-selection of technologies to be adopted, as well as the most promising layout, based on the application. Anyway, this is not calling into question the generality of the design process addressed, which shall be considered composed of three main phases. In this chapter an attempt is made in describing the three main phases is which a combustor for aeronautical application can be considered to deploy (Figure 1.6).

The very first step is constituted by the conceptual design phase. In its general purpose, it is devoted to determining a combustor architecture able to meet the basic design targets and the legislative constraint. By means of conceptual design rules and correlative tools, the down-selection of technologies to be employed and the shape assumed by the system can be here defined. The combustor layout is the first characteristic that shall be retrieved from the engine system's definition, since it can be traced on the inside of compressor-exit and turbine-inlet interfaces, by considering the maximum eligible dimensions. This aspect also deals with the chamber's total volume, which is crucial in the deployment of an effective reactive process and in the rapidity/effectiveness of the ignition. The latter depends on the size of the zones in which the chamber is divided, according to correlative criteria based on experimental evidence. If on the one hand the ignition starts the engine, on the other it is relevant for aeronautical applications to have a wide range of operability and the ability to perform the relight – this is crucial for critical engine operability condition that may imply in the blow-off of the combustor. Pressure loss levels have also to be considered at this stage since they are proportional to the square of flow velocity and can be hence related to the air flow and momentum within the chamber.

As it will be deepened in the next Paragraph, they are driving the design of dilution and cooling features, which are determining for the overall performances of the system. It is by leveraging on 1D flow, kinetic and thermal network solvers that is possible to give a definition to combustor's main components (i.e. injector, liner's cooling, quenching system, etc.), thus maximizing the efficiency of the reactive process.

The second step consists of the preliminary phase, aimed at evaluating the different configurations which may be embodied from the design intent. The main purpose is here to elect a candidate suitable for being assessed in the upstream detailed design. The 0-1D level information resulting from the conceptual phase represent the standard input for generating a 3D preliminary CAD, on which a first feasibility check can be performed. Geometrical guidelines, derived from structural or manufacturability evaluations, are at this level adopted to find an ideal arrangement for specific features (i.e. cooling or dilution holes). This resulting configuration becomes the reference model, on which more detailed analysis can be performed. CFD simulation are generally exploited to assess the internal aerodynamics and the development of the reactive processes. The main intent here is to evaluate the response of the system in terms of the main aero-thermal functional parameters: gas temperature and its distribution at the exit station, as well as the level of emissions produced by the simulated reaction kinetics and boundary conditions for the thermal assessment and emissions. The first aspect deals with the requirements of turbine first stages, to which a uniform radial and circumferential temperature distribution allows to enhance it functioning both in terms of system efficiency and durability (peak gas temperature that could affect the cooling of the first nozzle). The second aspect must be minimized, according to regulations provided for the civil aviation [12]. Both aspects are depending on how the main physical characteristics are evolving in the chamber, which is strongly influenced by the mutual interaction between fluid structures, in particular swirled flows for injectors and jet structures from dilution ports in case of a RQL technology. In case of LDI technology, the fluctuations of thermoacoustic phenomena are considered at this stage. Lastly, a FE analysis can be also foreseen to assess the hardware's temperature level considering heat loads of different nature, as well as the resulting stresses coming from functioning conditions.

In the last step, namely the detailed design phase, are addressed the hardware's manufacturing and operability aspects. The 3D geometry inclusive of the architectural details and holing features is verified for the constructive feasibility. In order to freeze the design configuration and release then the components' drawings, the combustor structure is optimized to match with the principal manufacturing technologies. Here, aspects as admissible tolerances and productive costs are taken into account to provide the productive configuration. Several, high detailed FE studies for fatigue are carried out at this point to predicts the reliability and durability of the different components – crack propagation is of primary importance, since on liners the presence of multiple holes acts as a structural weakening.

1.2.1 Liner's cooling and quenching design

The functions of the liners are to contain and assist the combustion by facilitating the distribution to air at all combustor's zones and features. Given the pressure and temperature levels at which this system is conceived to operate, these components must ensure a relevant structural strength and an outstanding resistance to the high thermal loads. To ensure a durability comparable with the product's requirements, temperature level must be limited below certain acceptable values: these could be arbitrary or congruent with the evolution in metallurgy and surface treatment techniques. In any case, cooling systems are necessary to ensure this condition. Forced convection is not suitable for the high temperature within the combustor flame tube, leading different approaches to be studied with the purpose of increasing the heat transfer at liners surfaces. The promotion of turbulence through ribs, usually employed for blade cooling, allows an increase in heat transfer coefficients of 2-3 times with respect to smooth surfaces. Studies on the application of different cooling arrangements are available in literature, such as impingement cooling or alternative configurations obtained combining different techniques. Nowadays, film cooling result as the most widely used technique to control the liner temperature. Cooling air flows through small, multiple orifices holes arranged onto the liners, generate a layer (film) of cool air able to protect the liner from the combustion temperatures. The implementation of this cooling technique must be carefully performed in order to do not interact directly with the flame structure. A general approach to evaluate the thermal loads to which liner are subject, thus properly define the technology and the geometrical/functional aspects to be adopted in the specific application, is proposed by Lefebvre [4] and it is based on the assumption of 1D heat conduction across the liner and the widespread use of correlations for the estimation of convective and radiative thermal loads, could have been considered to be sufficiently accurate due to the one-dimensional characteristics of the flow field, on both cold and hot sides of the liners, mainly ascribable to the significant axial extension of old generation, tubular combustors.

The flow through a liner hole, whether it shall be an effusion orifice or a dilution port, depends not only on its size and pressure drop applied, but also on the duct geometry and flow conditions in the proximity of the hole. The influence that such aspects may imply on its effective area can be expressed by the discharge coefficient, a non-dimensional parameter assuming values between 0 and 1, which can be defined as the ratio of effective and theoretical (isentropic) mass-flow rates.

$$C_D = {}^{\dot{m}}/_{\dot{m}_{is}} < 1 \qquad \text{Equation 1.1}$$

$$A_{eff} = C_D \cdot A_{geom} \qquad \text{Equation 1.2}$$

in which the basic equation to describe the flow across a liner's hole can be retrieved through a local application of Bernoulli:

$$\dot{m}_{is} = C_D \, A_{eff} \left[2\rho \left(p_{in} - p_{out_{stat}}\right)\right] \qquad \text{Equation 1.3}$$

where ρ is the flow density and the pressure difference is calculated between total upstream and static downstream values. In general, to describe the pressure drop across combustor features, we will refer to the following equation:

$$\frac{dp_i}{p} = \frac{p_i - p}{p_i} \cdot 100 \qquad \text{Equation 1.4}$$

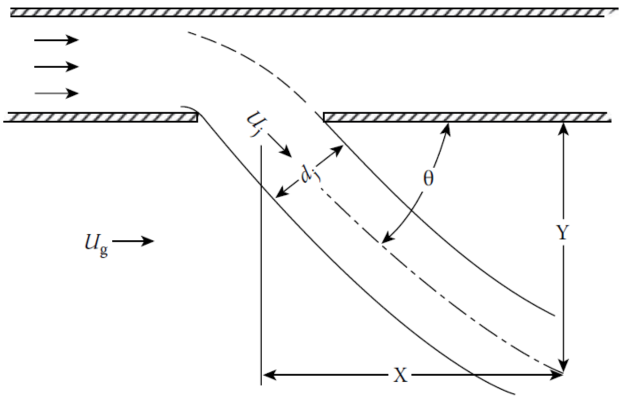


Figure 1.7 - Depiction of a jet flowing though the liner

Many studies have been carried out on the influence of hole shape on the exhaust coefficient and the influence of hole type and pressure loss to obtain correlations for the C_D coefficient [13,14]. However, whenever parameters such as the length-to-diameter ratio change, the correlations lose their validity and consequently change. All the parameters introduced above can estimate the mass flow through the hole rows but does not indicate the effective number of holes that are necessary to have a correct wall cooling and/or flows mixing. To this end it can be considered the jet penetration coefficient Y which is graphically shown in Figure 1.7, which indicated how the flows are mutually mixing and the effect on the main flow field. As demonstrated in the context of different works [15,16], it is related to the momentum flux ratio J, defined as the ratio between the jet momentum and the mainstream flow gas momentum:

$$J = \frac{\rho_{jet}\, {V_{jet}}^2}{\rho_{gas}\, {V_{gas}}^2} \qquad \text{Equation 1.5}$$

For multiple jets, as in the case of effusion cooling arrangement or dilution jets patterns, Norstar [17] proposes a correlation for estimating the maximum jet penetration for multiple cylindrical holes by taking into consideration the ratio of mass-flow between jets and chamber:

$$\frac{Y_{max}}{D_{jet}} = 1.25\, J^{0.5}\, \frac{\dot{m}_{gas}}{\dot{m}_{gas} + \dot{m}_{jet}} \qquad \text{Equation 1.6}$$

from which it is possible to evaluate the optimum holes number, also based on the criterion of maximum penetration for annular combustors D_{lin}.

$$Y_{max} = 0.4\, D_{lin} \qquad \text{Equation 1.7}$$

The mass-flow introduced in the chamber is responsible for both local and global effect on the reactive process development, based exactly on its penetration and mutual interaction with the overall flow field. In RQL applications, a portion of available air is used to dilute the chamber's hot gasses for reducing the temperatures and the local fuel-air ratios. The quenching is the final part of the combustor, also referred as dilution zone and characterized by a set of dilution holes that will affect the temperature profile at the exit of the combustor. The most difficult problem and challenging thing in the design of gas turbine combustion chamber is to achieve a satisfactory and consistent distribution of temperature at the exit of the combustor of the efflux gases discharging into the turbine. The most important temperature to be consider is the turbine inlet temperature, TIT or T4, which is the mass-flow-weighted mean of all the exit temperatures recorded. Thus, the parameter of most relevance to the design of nozzle guide vanes is the Pattern Factor PF, describing the overall temperature distribution at combustor's outlet by highlighting the maximum location's temperature. It is normally defined as

$$PF = \frac{T_{max} - T_{40}}{T_{30} - T_{40}} \qquad \text{Equation 1.8}$$

where max stands for the maximum recorded temperatures, while 3 and 4 subscripts are related to the mean inlet and exit temperature, respectively. This parameter indicates in dimensional terms the maximum temperature irregularity that can occur on the output section in the tangential direction. It indicates the number by which the nozzle cooling system should be oversized. The other important parameter is the Profile Factor that represents the temperatures of most significance to the turbine blades which consist of the average radial temperature profile T_{mr}. These are obtained by adding together the temperature measurements around each radius of the liner and then dividing by the number of locations at each radius, i.e., by calculating the arithmetic mean at each radius.

$$PrF = \frac{T_{mr} - T_{40}}{T_{30} - T_{40}} \qquad \text{Equation 1.9}$$

In Figure 1.8 is illustrated the radial profile seen by the rotor, in which the continuous line is deemed ideal for turbine entry, while the dashed is the measured one. The average radial distribution of temperature at the combustor exit plane usually has a profile that peaks above the mean-line of the blade. In fact, the target to achieve might be to have a temperature peak placed at the highest possible radial height but this would lead to excessive stress on the tip of the blade as well cannot be too low otherwise the hub blade could be damage as it is the most mechanically stressed part. The principal dilution-zone design variables are the number and size of the air-admission holes and the zone length. To ensure a satisfactory temperature profile at the chamber outlet, there must be adequate penetration of the dilution air jets, coupled with the correct number of jets to reach sufficient localized mixing regions. If the total dilution-hole area is spread over a substantial number, of small holes, penetration will be inadequate, and a hot core will persist through the dilution zone. On the other hand, the use of a small number of large holes will lead to an overpenetration and so to an unsatisfactory mixing. Thus, the first step in the design

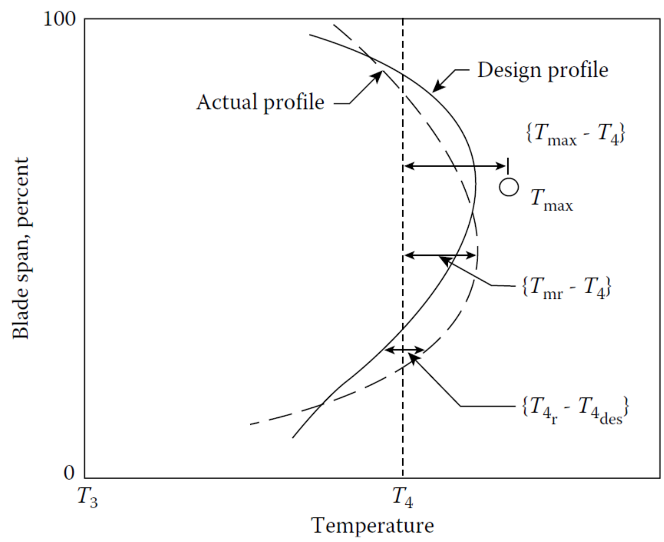


Figure 1.8 – Example of exit temperature profiles

process is to determine the optimal number and size of the dilution holes. Lefebvre and Norster's work on the aerodynamics of tubular combustors shows that, for any given value of the ratio of dilution air to approach gas-stream mass $\dot{m}_{jet}/\dot{m}_{gas}$, the best pattern factor is obtained for a specific value of the group $D_{lin}/n\,D_{jet}$. The length of the dilution zone should be around 1.5 D_{lin}. Shorter lengths lead to inadequate mixing, while longer lengths would not improve the pattern factor significantly, since the additional wall-cooling air required would reduce the amount of air available for dilution. Two parameters of crucial importance to pattern factor are the liner length, which controls the time and distance that are available for mixing, and the pressure drop across the liner, which governs the penetration of the dilution jets and their rate of mixing with the products of combustion. From the analysis of experimental data on tubular, tuboannular, and annular combustors,

$$\frac{T_{max} - T_4}{T_3 - T_4} = 1 - \exp\left(-0.050\,\frac{L_{lin}}{D_{lin}}\frac{\Delta P_{lin}}{q_{ref}}\right)^{-1} \qquad \text{Equation 1.10}$$

By managing these quantities, it can be possible to explicit the liner length L_{lin} which is crucial for the conceptual phase of design.

With reference to the discussion of Section 1.1, it should be also clear that these conditions can directly influence the production of pollutants. A measure of the emissions related of the i species can be provided with the index below reported

$$EI(i) = \frac{w_{s,mean}}{Z_{mean}} \cdot \frac{M_{fuel}}{M_i} \qquad \text{Equation 1.11}$$

1.3 Integrated design systems

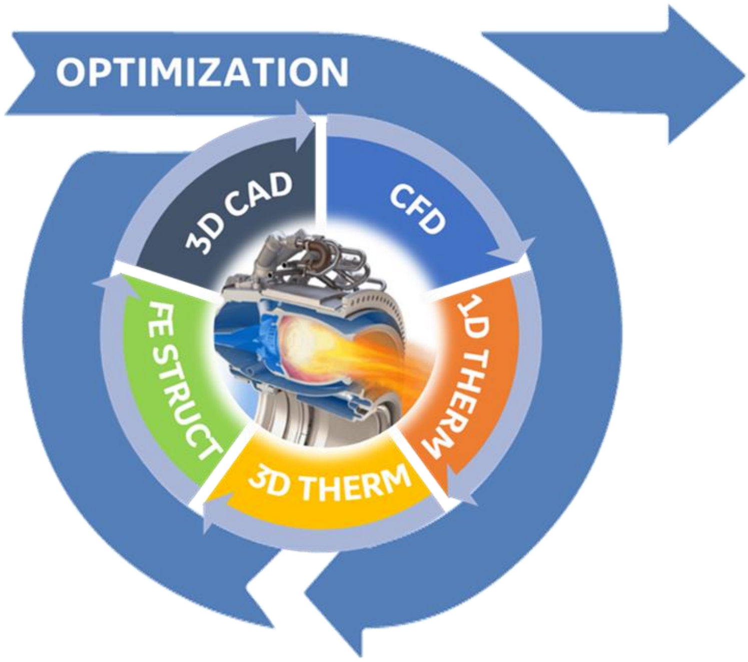


Figure 1.9 - The aero engine combustor design: a multidisciplinary and multi-objective process

Whilst experimental analysis is still a fundamental component at all Technology Readiness Levels (TRL), in recent decades numerical simulation has become a strategic element in the design of such complex systems. As it has been mentioned already, it is thanks to the constantly growing reliability of numerical models and to the increasing access to computational resources that simulative approaches have configured themselves as one of the most suitable means in reducing products' lead times and costs while increasing value [6,8]. Significant benefits have been brought to the design process, and in particular to the preliminary phases: in which the most promising candidate is defined through an extensive exploration of the design space, and therefore involves a large number of candidates to be analyzed [9].

In this context, CAD-based approaches have been the first methodologies in use that proved an effective impact to the simulative design process. Here, the configuration of the product is reproduced through a master geometrical model which can be modified according to the changes intended to be applied to a baseline design. This editable reference could be then used as a geometrical source for the downstream analysis steps, making possible to assess the performance of multiple configurations by simply simulating the different cases in which the desired modifications are implemented iteratively. A first fundamental example has been given by the parametric design approach presented by Tangiarala et al. and developed in General Electric (GE) [18]. To analyze the aerodynamic performance of a combustor concept, a parameterized CAD model has been exploited for generating the set of configurations to be analyzed through CFD simulations. This work has demonstrated not only a more robust approach to analysis but also a reduction of the overall design time, an aspect further exploited by dedicated strategies designed to make the CAD-to-results process leaner [19].

The idea of a more robust and leaner approach has led to subsequent design procedures being characterized by an increasing CFD-based connotation. A first comprehensive and industry-relevant case has been showcased by Pratt & Whitney in the context of the PW6000 combustor development. This procedure focuses on the evaluation of exit temperature distribution, which is here evaluated and optimized by leveraging on a standardized CFD calculation methodology conducted on the entire combustor domain. In a first part of the work, the elements constituting the methodology are presented: the chain of tools is composed by an integrated CAD-to-grid generation system, linked to a core CFD solver embedding the models for combustion and fuel spray. A validation based on test-cell data comparison is also provided in order to assess the accuracy in predicting the exit temperatures profiles [20]. In a second part it is presented the application of such calculation methodology for the previously mentioned combustor test case, with the objective of evaluating the predictive capabilities of the system and exploiting it for a design optimization problem [22]. The main aspects concerning the efficiency and the usability of a design system have been later deepened by Honeywell Engines & Systems, which developed a comparable CAD/CFD integrated toolkit aimed at streamlining the aero-thermal design of combustors: the so-called Advanced Combustion Tool. This is representative of the first fully simulation-driven design optimization of a combustor, considering a domain ranging from the compressor deswirl to the turbine stator inlet. [22]. The analysis cycle time has been reduced by introducing a parametric and modular CAD-to-grid system, while the geometrical model has been made easier through the elimination of inter-features (i.e. wall cooling configuration, swirlers details, splash plate edges, etc.). The ease of use, which reduces the setup time and the possibilities of errors, has been provided via an highly customizable interface and the efficiency of the CFD solution has been guaranteed by the 60 combustor flow-field on a 30 degree sector model compared to experimentally measured results [23]. A further, crucial step in the evolution of such methodologies has been represented by PRECODES (Preliminary Combustor Design System), which integrated a Knowledge-Based Engineering (KBE) platform in the design process. Through this, Rolls-Royce has been able to build a design framework comprehensive of a system to include and manage design rules and practices [24,25], and for the first time improved cooling models have been integrated in the analysis [26]. This automated design tool has been further implemented by Gessel et al. [27], equipping it with optimization design capabilities suitable for the development of low-NOx combustion systems. A more systematic but general approach is instead represented by the PROMETHEUS design system, where pre-and-post processing activities for the analyzed combustor configuration are streamlined by a feature recognition-based method [28,29]. Since all of these methodologies are based on Steady-State Reynold Averaged Navier-Stokes (RANS), most recent works are focusing on taking into account highly-resolved CFD simulation in the optimization process [30].

For all of these works, as well as other examples coming from the Academic field [31–35], it is possible to notice how the so-called "dynamic workflow generation" retains a central role in defining the efficiency and the functionality of design systems [36]. It is through its definition that design changes will be implemented within the process in a versatile and robust way: from the CAD model to the generation of the associated grid, ending up to the simulation activities downstream in the process. Furthermore, to provide the workflow with elements to guide the design according to user-defined rules and best practices has the potential to include the designer choices and constraints in the loop, by adopting the already mentioned KBE approach [9].

In the plethora of design systems presented, the Combustor Design System Integration can be considered as an enhanced approach to the aero-thermal and structural preliminary phase. This CAD-based procedure facilitates the geometry creation step, with particular emphasis on liners' cooling design. All sorts of legacy information are embedded in each tool, ensuring that companies' design rules and practices are considered both in the modelling and in the analysis step. Moreover, a pervasive feature recognition approach allows the mesh-to-solution workflow to be accelerated. As a result, the application of the DSI to a real-case combustor concept demonstrated high potentialities in reducing the total amount of temporal resources needed to drive a design loop, with a resource saving up to 70% of the overall time [37,38].

1.4 Advanced optimization algorithms

Nowadays in engineering design, optimization has been established as a widespread practice in defining the best configuration for a product. Several methodologies have been developed to this aim, based on a mathematical formulation of the optimization problem itself. These are particularly useful when, as is it often the case, there are multiple design objectives and so a closed-form solution is difficult to achieve because no unique solution exists [39]. Indeed, design candidates result in a space of solutions where the optimum should be evaluated as a trade-off amongst the different objectives considered. Statistical methodologies based on Response Surface (RS) represent a robust approach in this context and have been demonstrated to be effective in the optimization of combustors as well [40]. The relationship between explanatory and response variables of the system is here approximated using specific metamodels, representative of the system itself and hence valid for deriving an optimal design configuration. The implementation of RSM, however, requires a sequence of different product configurations to be defined and simulated, following the theory of Design of Experiments (DoE) [41]. The specific optimization problem, however, must be specified both in terms of explanatory and response variables. The first of these, also referred to as input design parameters, are represented by the set of independent variables of a system that are intended to be modified, with respect to a precondition. The second, named output design factors, represent the quantities on which the impact of such variations should be evaluated.

Across the research works in the field of aeronautical engines, the RSM approaches exploit in the design optimization of gas turbine's combustor is mainly driven by the branch of the evolutionary algorithms (EAs), although the artificial neural networks (ANNs) are emerging in the last few years. In the combustor design applications, many studies shall select the genetic algorithms, among the EAs, because of their successful application in various multi-objective engineering design problems. The work of Torkzadeh et al. [42] aims to investigate the effects of swirl velocity of inlet air on important objectives in the design process (combustion efficiency, pollutant emission and pattern factor) and determine the optimal Swirl number to satisfy all targets, by means of the genetic algorithms. Saboohi et al. [43] present an optimization approach, based on the genetic algorithms, with the purpose of achieving an optimal conceptual design of the combustor. In presenting the results, the emission index for NOx and CO were defined as the main objectives of the optimization problem. One of the few studies available in the literature that uses the ANN as optimization algorithm is showed by Park et al. [44] inside their toolkit aimed at assessing the combustor's performance. The goal of their work is to predict the combustor operation characteristics such as fuel mass flow, turbine inlet temperature (TIT), fuel distribution of each nozzle, NOx, operating pressure through measured turbine exhaust temperature (TET) selected as input parameter. As highlighted in the above-mentioned research activities, both the algorithms were the most appropriate candidates for the design optimization of a gas turbine combustor on the basis of the following reasons. The preliminary design of the combustor is generally classified as a multidimensional (large number of inputs, objectives, design variables) and constrained problem, as well as the equations defining the relation between the input variables to the objectives are non-linear, non-smooth and non-differentiable [31]. Based on the high-level comparison between the genetic algorithms and ANN reported afterwards, the adoption of the ANN as metamodeling strategy in this work is justified. The genetic algorithms take an initial population as input and choose a fitness function to generate an optimal or near-optimal solution. By means of operations as selection, crossover and mutation, the population continues and evolves until it satisfies the optimization constraints. On the other hand, the neural networks are defined as a computing system made up of several simple, highly interconnected processing elements, so called neurons, with linear or non-linear transfer functions.

The ANNs are able to derive the correlation between the input and output parameters, obtained by optimized weight and bias of each node and layer [45]. It consists of an adaptive system made of groups of information mutually interconnected by artificial neurons, allowing the structure to change according to the information provided for its training. With reference to Figure 1.10, such a non-linear structure is organized into layers. The input nodes receive the statistical information to be processed, creating preferential connections with the neurons of layers which follows. In this region, the hidden layer, each neuron elaborates the input stimulus into output reactions by means of specific activation functions. Through the output nodes, lastly, is possible to take advantage of the resulting network to simulate the response of the system. In contrast to the capabilities of the genetic algorithms, ANN represent a mathematical model that can solve and model complex data patterns and prediction problems. Genetic algorithms usually perform well on discrete data,

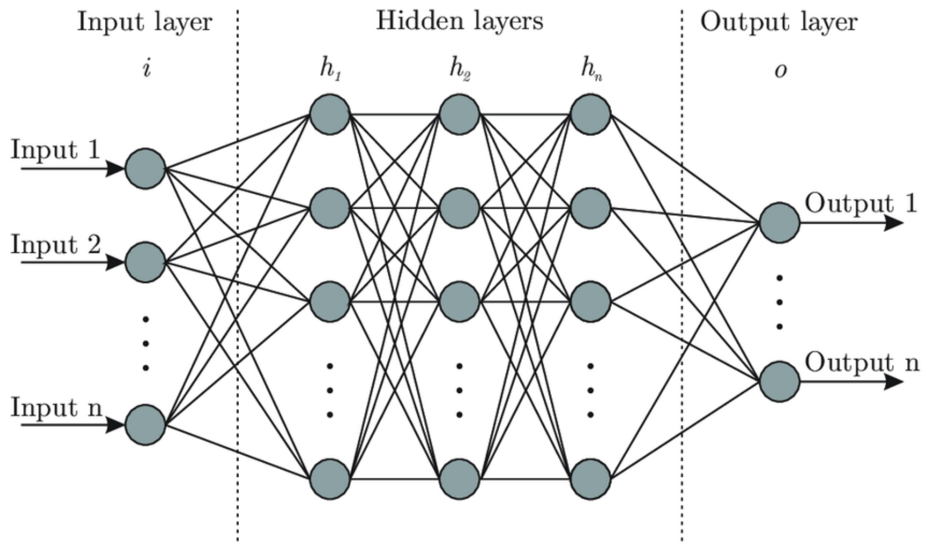


Figure 1.10 - Structure of a generic Artificial Neural Network

whereas ANN operate efficiently on continuous data (infinite number of possible values within a selected range), exactly like the degrees of freedom (DOF) of this design optimization activity. Genetic algorithms calculate the fitness function repeatedly to get an accurate solution, thus it employs plenty of time to compute a reasonable result. Instead, ANN needs less time for the classification of the new inputs. As a matter of principle, ANN appears to be ideal for modelling the behavior of a system, by training with dataset, whereby the choice falls on these algorithms for this work.

Chapter 2. Combustor Design System Integration methodology

Once the phases in which the development of aero engine combustors unfolds are illustrated, with the intent of bearing the most relevant aspects of product's aero-thermal and durability performance, it is possible to introduce the foundations of the design platform object of this work: the Combustor Design System Integration, or DSI. This section is dedicated to present the methodologies that have been developed, adapted, or used in the context of this research. First, it is mandatory to provide a detailed assessment of the process which it is enabling, so that a proper justification for the strategies and the logics adopted to improve the overall design workflow could be given. With reference to the tasks involved in the generation and simulation of numerical models, the application of such measures led to the definition of the DSI toolkit as a set of customized design tools dedicated to the analysis of performance in the different physical domains of interest. In order to ensure the management of the simulative workflow, as well as the collection of functional and performance system characteristics of the system, it is deployed the Combustor Optimization Suite (COS). Such a standardized framework offers the capabilities to define and perform a custom design optimization process, based on a surrogate modelling and multi-objective investigation approach. The parts of which it is composed of will be first presented, to discuss then the set of tailor scripts developed to ensure a full-integrated and water-tight design process based on the DSI and COS procedures.

2.1 Combustor's preliminary design phase

As it is often the case in the development of complex industrial products, the preliminary phase represents a critical aspect also for aero engine combustors. The requirements that exist at this stage, which should now result clear given the discussed of the previous Chapter, brings the designer to assess a wide and mutual-interacting spectrum of physical phenomena, thus leading to a process dominated by multidisciplinarity. In this context, the variety of design systems proposed in the last decades have demonstrated that simulation-based approaches are effective in managing this sort of tasks. Its potential goes in fact well beyond being a cost-effective solution if compared to experimental studies – an aspect, this latter, still of primary relevance in the industrial field and indispensable for engine manufacturers. By means of computational methods, both the local conditions and the whole fields of physical quantities can be indeed evaluated across the global domain assumed to model the system. Not least, the range of variations to be considered in the study might be boundless, since this technique is relying on a numerical modelling of the design problem. Anyway, multiple numerical approaches characterized by different accuracy levels and computational costs can be adopted to this specific end.

Conjugate methodologies are framed in the way of considering the different physical aspect as coupled, proposing a joint approach to analyze the different contributions to product's performance. One example is the so called "UTHERM-3D" procedure, a loosely-coupled design framework for combustors' aero-thermal assessment which leverages on unsteady calculations approaches, developed by the Department of Industrial Engineering of the University of Florence (DIEF) [46]. Given the elevated levels of precision, as well as the number of computational resources required to perform the analysis, this kind of tools are more appropriately used in the detailed design phases, where the elected design configuration must be verified thoroughly. Standard approaches, instead, are based on a subsequential analysis in which the variety of design evaluations are performed in cascade: this determines a workflow where results of a simulative step are constituting the input for the downstream evaluations. This results in a more flexible and accessible process, making it more suitable for preliminary design phases. By the way, the adoption of an iterative process is inevitable in order to simultaneously fulfill the multiple requirements existing at product level [47]. Despite the contributions to system's performance are here considered as decoupled, this kind of methodologies offer the opportunity to add or exclude evaluation tools according to the requirements which are intended to be addressed. Both approaches that have been presented here in brief, have been developed and are currently in use at the Heat-Transfer and Combustion research group of DIEF (HTC Group), as it has been presented in the much more comprehensive overview proposed by Andreini et al. [48]. The procedure that is going to be presented in this work will be leveraging on many of the methodologies implemented by the research group during the last decade, with specific focus on the CFD modelling of combustion [49–51] , fuel spray [52] and cooling management [53,54] of aero-engine combustion chambers. Nevertheless, the DSI procedure serves as a collector for such modelling approaches, encompassing them for the first time within a comprehensive and structured framework for the design of combustors.

For the purposes of this work, indeed, the design process adopted in *Avio Aero – a GE Aviation business* to design combustors in the preliminary phase has been taken as reference. Its generic depiction is given in Figure 2.1, in which the main

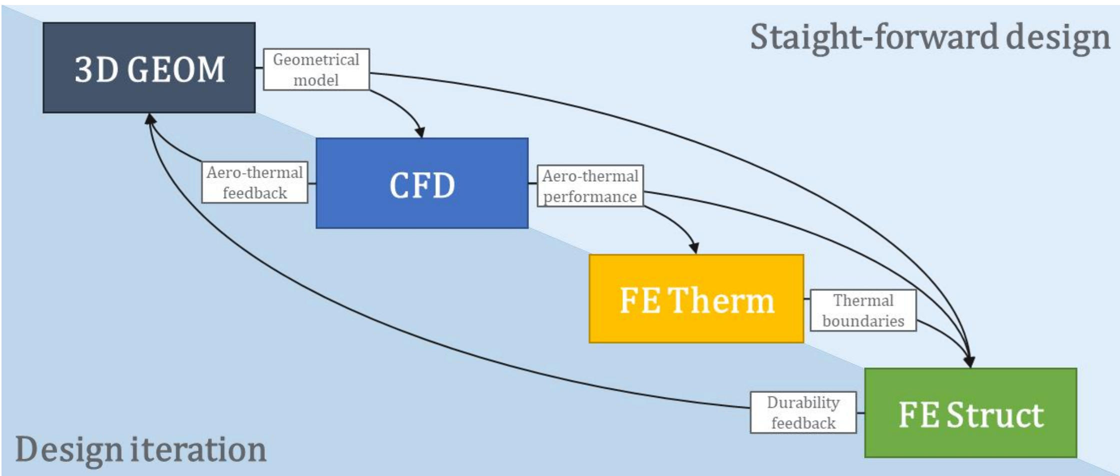


Figure 2.1 - Block diagram of the combustor preliminary design phase of Avio Aero – a GE Aviation business

steps composing the workflow, as well as the links existing among them, are highlighted. It is made of 4 key tools performing evaluation in the physical domains that are deemed relevant in this design stage:

- a CAD system, to generate the combustor geometrical model;
- a CFD process, to assess the configuration's aero-thermal performance;
- a Thermal evaluation, to verify that components are not exceeding thermal thresholds of the constructive materials;
- a Structural analysis, to check components are complying with stress and displacement requirements.

As it is often the case in simulation-driven processes, the information exchanged among the tools results in being miscellaneous, thus requiring the designer in manually processing the data to continue through the design steps. But this brings the execution to be prone to error, as well as being slowed down by redundant and low-value-added operations. It should also be considered that exception made for the sequence of tasks defined in the process itself, there is no framework aimed at driving the process appropriately. This aspect results to be crucial for the overall deployment of the process and it is even more critical when multiple, conflicting objectives are expected to drive the design. It is not difficult to understand that trial-and-error approaches are more likely to be followed in this context, bringing no structured approach leading the design execution and evaluation process which ends to be rely on designer's experience only. This description highlights the underlying complexity in developing combustor products, which is configured not only in its multidisciplinary nature but also in the conflicts that can occur from a multi-objective approach. So, if the first issue mostly deals with the communication between several tools involved in the design flow, the second one implies the iterative nature of the process itself. In such an intricate procedure, we can understand how digitalization may increase the overall value of the process -and hence- the product [55]. Indeed, it is not only important how quickly results are generated but also the reliability of the information that is processed and, not least, the possibility of making such information available globally within process. The Combustor DSI platform has been developed to satisfy these requirements, streamlining the design process while enhancing its robustness.

2.1.1 Process analysis and improvement

In order to understand the impact of the aspects here introduced, as well as the temporal and computational resources required by carrying out a preliminary design evaluation with the discussed below, a Metric-Based Process Mapping has been adopted [56]. The MBPM is a practice developed in the context of lean management that is typically used for analyzing and documenting an existing process, in order to identify areas for improvement and to strategically define actions for its enhancement. Together with mapping the value across a process, this specific method includes information about key times and quality metrics. Such details are necessary to drive changes, therefore MBPM has been chosen instead of the Value-Stream Mapping method [57], despite the latter being more streamlined and therefore easier to implement for the present case.

The first step for implementing MBPM for the combustor design process has been to map the “current state”. Two different schemes have been created:

- “Straight-forward design” activity, in which models are generated “from scratch” and hence phases of building and debugging are included, in addition to simulation times.
- “Design iteration” activity, intended for design loops in which feedback are re-processed through the design workflow, to address the effects of major/minor modification mate to the existing combustor model.

The second step consists in depicting the “future state” which is the result of designing and implementing all the improvements that could be offered for the improvement of the design process. By leveraging on this technique, three main categories have been identified to propose enhancements:

1. **Inter-tool** –A set of operation causing downtimes and a reduction to the overall process’ robustness have been detected within each of the analysis steps.

These tasks are characterized by adding low value to the functioning and for being redundant, since they are usually performed by the user during the models' processing phases. In order to reduce the wastage in temporal resources and process performance, the fundamentals of lean philosophy have found application. By the pervasive automation of such ineffective and prone-to-error activities, it has been possible to achieve a leaner and quicker execution of the simulation steps. This has been promoted among the four tools for analysis, leading to the definition of the DSI toolkit: 4 customized tools developed in Ansys environment in which standard operations are performed in complete autonomy, thanks to the advanced scripting which impact will be described in the next Section.

2. **Intra-tool** – A further major issue has been identified in the information's structure and, particularly, in its management across the process. The "current state" occurs with a disjoint fashion, where the data produced by a simulative tool requires to be elaborated before initializing the steps downstream. As it is common, the information is manually processed and only in rare cases scripts/routines aimed at ease these operations are made available: the problem lies therefore in a non-standard definition of the interfaces between the tools. By relying on the principles of digitalization, the information exchanged between the tools has been rationalized and collected in standard procedural files to be adopted as front-end through the overall process. It will be clear from the following sections that such measure is responsible in the ease of the process and the streamlining of its execution.

3. **Overall process –** By considering its overall execution, it can be noticed that a framework for driving the process during the multiple design steps is not formally defined. This activity is demanded to the design owner, which leads the design team through the product's development. Design's best practices and common rules are often introduced by the knowledge of these last, showing a misleading approach in embedding this kind of information into de process. Furthermore, the activities related to driving the design and selecting the system's configuration to be deepened is not aided by any methodology, bringing the de-

cision-making process to rely only on the experience of the users. The COS optimization suite has been incorporated with the precise purpose of providing a process management system, in which metamodeling and optimization capabilities are made available for supporting the designer in driving the selection stage.

The application of this philosophy to the aero-thermal and structural methodology, with a focus on the tools adopted and developed for the preliminary design phase, will be described in the following. To establish an integrated design platform as a collection of procedures aimed at multiple purposes, it has been necessary to implement a set of custom scripts aimed at enabling the communication at all platform's levels. Finally, the results expressing savings between the "standard" and DSI approaches have been estimated by relying on a direct comparison between the "current" and the "future" states, considering both the schemes identified for the preliminary design phase, as it will be presented in at the end of Chapter 3 and Chapter 4.

2.2 DSI toolkit

The preliminary design process enabled by the Combustor DSI toolkit can be assessed through the block diagram presented in Figure 2.2. It is showing the set of 4 tools which have been implemented with the purpose of addressing the inter and intra tool capabilities discussed in the context of the previous Section. All the applications have been created in Ansys Application Customization Toolkit (ACT), in which pervasive scripting in IronPython allows to customize off-the-shelf Ansys software. Beyond establishing the overall process and the system's standard interface files, the main contribution lies in the definition of logics and strategies dedicated at ensuring the proper tools' functioning. Particular relevance is assumed by the definition of cooling and quenching systems, thus special effort has been made in shaping techniques and methods dedicated to performing an optimized topological arrangement of holes on combustor's liners, by taking into account *Avio Aero* design rules and requirements existing for this topic. Regarding instead the software development part, the extensions have been scripted by Ansys in the context of a specific funded project.

In its most schematic depiction, the DSI procedure allows to perform a preliminary design evaluation, by processing the conceptual design results through an

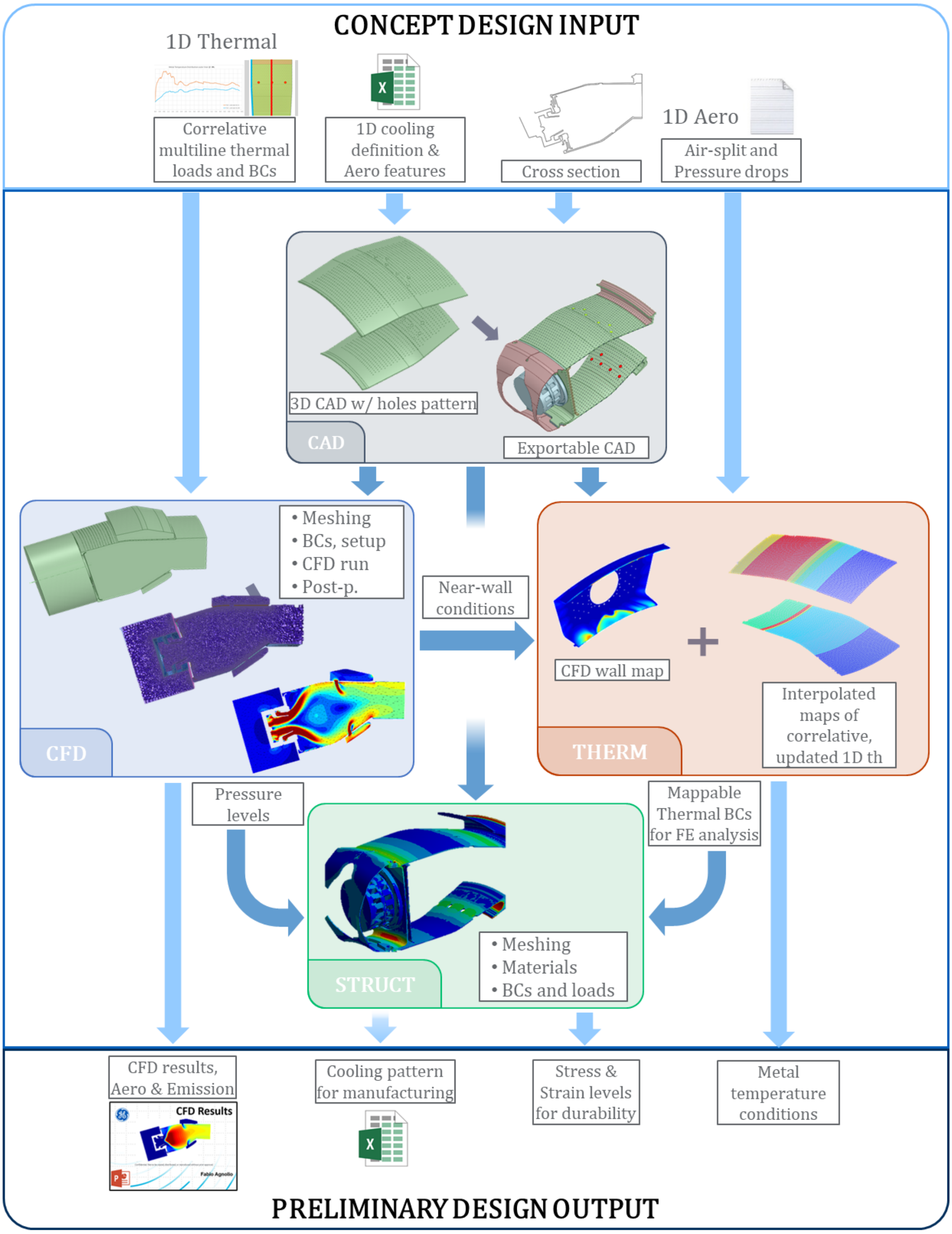


Figure 2.2 - Combustor DSI procedure in the preliminary design phase

aero-thermal and structural analysis process. In Paragraph 2.2.1 will be described the combustor's CAD model generation tools, which plays a key role in the whole design process since all the information related to the product's configuration are here collected to be made available to the rest of the procedure. Then, in Paragraph 2.2.2, the workflow for preparing, executing, and elaborating the CFD analysis of the combustor is detailed. A specific focus will be given on the structure of the tool, designed to collect and rationalize both the design information and the numerical models to be employed in the simulation. In Paragraph 2.2.3, the steps required for creating the set of thermal boundary conditions necessary to perform a 3D thermal FE analysis are reported. These are generated starting from the results of the 1D thermal tool employed for assessing the combustor metal temperature and designing the cooling system on liners. The Structural FE process, in which the information resulting from the upstream analysis steps are collected to address stress and displacements of the configuration, will be finally presented in Paragraph 2.2.4.

2.2.1 CAD process

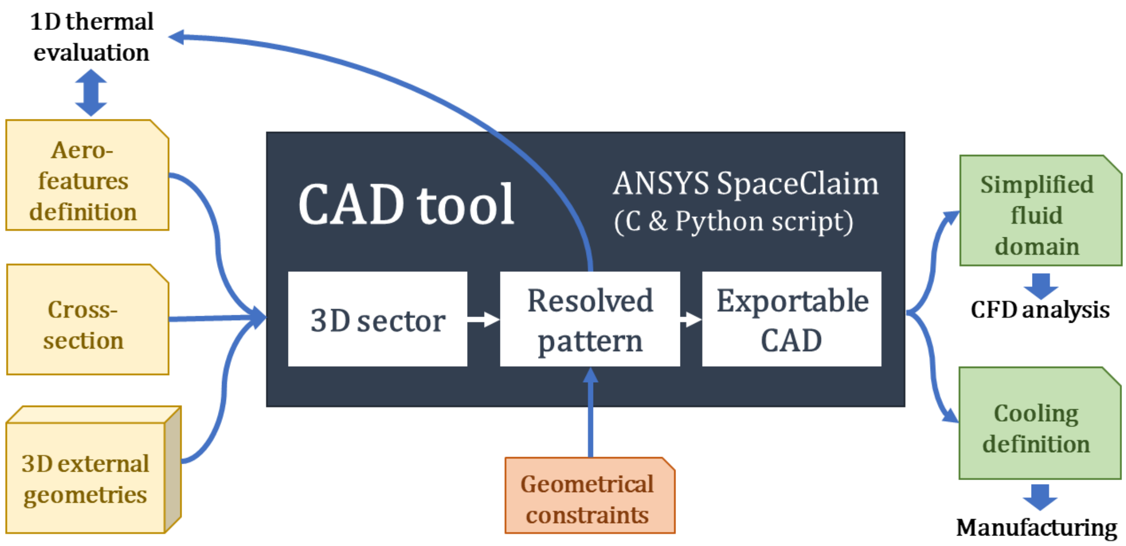


Figure 2.3 – Flowchart of the CAD process

The goal of the customized CAD tool, whose general process is shown in Figure 2.3, is to generate a geometrical model which is representative of the combustor. Within the DSI, such 3D geometry accounts for the most significant element of the methodology: it represents the repository of all the information regarding the product's configuration, and hence is taken as reference for providing all the geometrical input for the downstream process.

The tool has been developed in ANSYS SpaceClaim [58], a fully scriptable program designed to create and adjust CAD geometries. To export the proper information for the different simulation disciplines involved in the design, a set of dedicated routines have been implemented. Up to now, the SpaceClaim script is able to export the parameters necessary to manufacture the cooling system, and a properly defined fluid domain on which a CFD analysis can be performed. Given the topic of this section, this last process will be considered. The starting point for the geometry generation is the output of the 1D design tool, so-called Therm-1D, which allows definition of the most appropriate cooling system and arrangement to adopt, considering the combustor's cross-section definition and the air split for a certain design point; this will be described in depth in the next paragraphs. The main challenge for building the 3D model is to arrange the different hole features, as long as only a few physical constraints can be considered in such a simplified approach. The additional rules, which mostly address solving the collision problem between geometrical bodies, can be grouped as follows:

- Structural constrains
- Fluid dynamic constrains
- General design constrains

The first constraint ensures a minimum distance between neighboring holes and is critical, because in case of violation the design can break. The second one includes the cooling concept itself. Such constraints are that holes in the jacket should not be placed on top of holes inside the liner, or that holes in the liner should be staggered properly for creating a continuously cooling film. The last constraint regards the design process itself, i.e. moved, added, or deleted holes that can affect the functioning of the combustor by modifying the pressure drop and the air-split between the different features. Within the procedure, up to four different types of holes are available for the design:

- dilution holes, to feed the flame tube so the quenching effect can be realized;
- multi-holes, for effusion cooling effect;
- impingement holes, which realize a cooling effect by jets impinging on the cold side of a component, such as liners and/or heat shields;
- nugget holes, to produce a film coverage from a slot geometry.

To complete the model generation, and hence realize an exportable CAD, all the geometrical features that are not addressed by the 1D design tool can be imported from dedicated libraries. Swirlers and heat shields, as well as mounting flanges and casings, can be selected as 3D external parts according to the design purpose.

According to the CAD tool functioning, the first activity performed is a general check over the input coming from the conceptual design phase. This has the dual purpose of rationalizing the information required to define a repeatable combustor

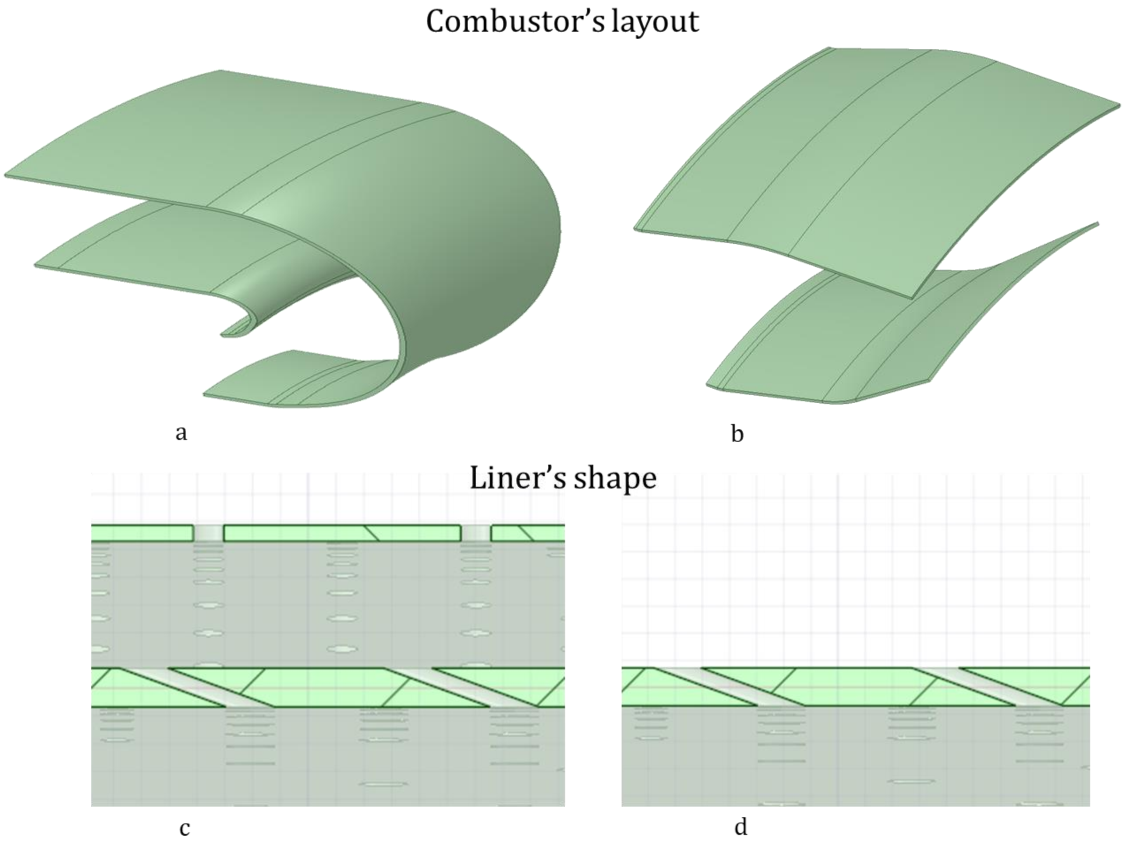


Figure 2.4 – Feasible geometries by the CAD tool

sector, representative of the full annular configuration, and analyzing the consistency of the cooling definition derived from Therm-1D. For the latter case, the number of holes constituting the rows is adjusted to obtain a symmetric and repeatable cooling pattern upon the complete configuration. The reference sector's extension is determined by the number of injectors in the configuration. Once the input passes all the preliminary checks, the combustor shape can be generated. As reported in Figure 2.4, the flame tube layouts enabled by the automatic procedure are both reverse-flow (a) and straight-through (b); the liner shape can come as double (c) or single wall (d) on which thickness, as well as Thermal Barrier Coating (TBC) application, can be fully defined by the designer. The positioning of the different holes can be now addressed at a 3D level for each different liner location. A hierarchical approach between the different types is used to perform this second tool's main task: the dilution holes are placed first, then the effusion holes are arranged around these and, lastly, the impingement holes are placed considering both the previous arrangements. Different strategies have been developed to automatically solve the problem of intersection between these geometrical features, with the purpose of providing the best cooling distribution in regions with limited space. Dealing with minimum distance requirements and optimal arrangement for cooling effects, these rules are based on the relative position between the effusion hole rows and dilution holes. According to different situations, each cooling hole can have an axial or tangential sliding, but even a change in the impact angle can take place. In case of a double wall liner, the collision problem (and hence strategies for solutions) are extended to impingement holes too, that come up in conflict with the effusion cooling arrangement. Nevertheless, the problem can even get more complicated in regions of high curvature of the liners. A strategy to solve all the collisions in a single step has proved to be too complex, so an iterative process has been implemented. During the loops, the distances between neighboring rows is estimated. In case of minimum distance being reached, the holes are moved forward or backward until the minimum distance criterion is satisfied. According to test cases of interest, most of the pattern results as resolved with about three iterations. The designer can also take control of these movements with a manual procedure since an interactive interface has been implemented as well. All those changes are driven by specific commands recorded in dedicated input files, which represent the starting point for a more complex optimization strategy that is currently under development. Once the cooling holes are all set, a post analyzing routine is used before the last major activity: the exporting. Each row position of the resolved pattern is averaged according to the coordinates of the holes that belonging to it. The values are compared once again with the initial input values: if there is a gap that exceeds the accepted range, an update of the 1D design tool needs to be performed for consistency inside the design loop. The export for the CFD analysis represents the final task of the automated CAD process. Via a dedicated routine, a ready-to-mesh fluid domain is created according to the design specifications that are needed. The volume is generated by intersecting the exportable CAD model, as described above, with a standard starting domain on which “static” named selections are defined. The set of “dynamic” named selections is instead retrieved by the specific design, i.e. cooling hole inlets and dedicated planes for post-processing. Since features such as injectors and dilution holes are explicitly resolved, this phase defines and places the proper feeding plenums to be merged to the main domain. The rest of the information required by the downstream process is collected into a python library file.

With the purpose of presenting the strategies conceived and implemented within the tool for the adaption of cooling patterns, a schematic visualization will be used in the following. This representation is intended to make the understanding of such logics simpler and more direct, but also to preserve the confidentiality of the methods that are currently in use by Avio Aero. Indeed, the set of rules and methods implemented in the tool consist of established practices retrieved for legacy combustors design improved with geometrical evaluations, as well as consideration from scientific studies as the one carried out in the research group [51,59,60] and proposed by others in literature [61–63]. To this end, the uniform pattern of effusion holes of Figure 2.5-a is considered, as it is representative for a standard cooling application for combustor liners. A single row of dilution holes is included, so that the situation of interference with the four effusion rows can be reproduced. The region taken into account in the example is representative of a hot-side liner’s section as it is processed by the CAD tool: it corresponds to a single sector of the combustor liner, since aspects as periodicity and symmetry could be more easily considered for the generating the feasible solution of cooling pattern. Indeed, at this stage, a set of preliminary checks are performed to evaluate the compliance of the user's input with

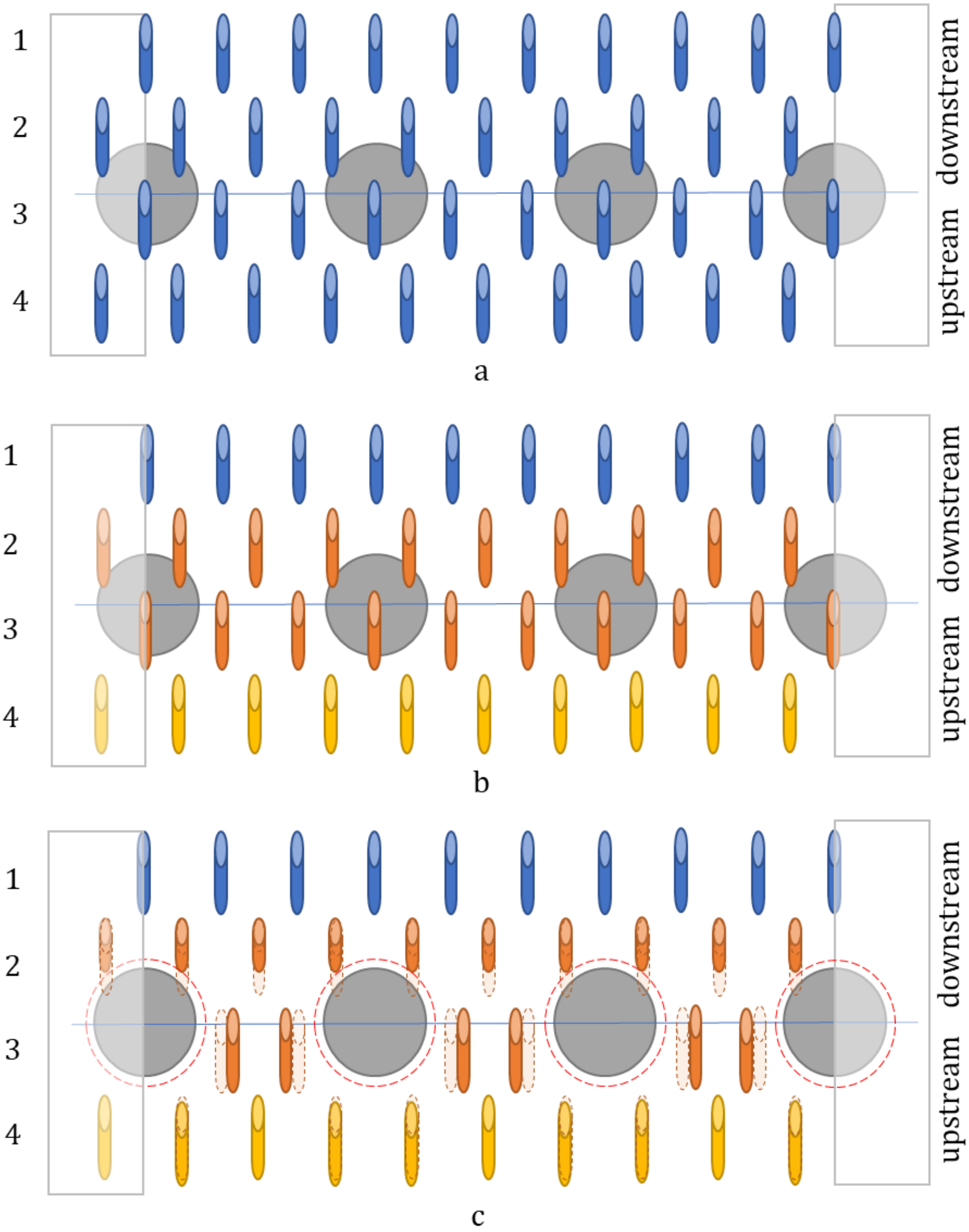


Figure 2.5 - Schematic depiction of the baseline logics for cooling holes pattern correction, implemented in the DSI tool for CAD generation

the requirements of a baseline pattern: to identify the effusion rows impacted by the dilution row, to ensure that the number of effusion holes are a multiple of dilution holes and injectors, to evaluate the minimum distance between holes features. As per Figure 2.5-b, 3 out of the 4 effusion rows are interesting dilution-influence area. No modification is going to be applied to row 1, given its distance from the quenching region, while from row 2 to row 4 modifications will be suggested considering their relative position upstream and downstream the dilution row. The updates to the pattern will be updated with local modifications according to their direct or indirect impact with the dilutions, which are here reported in orange and yellow, respectively. For rows which are indirectly influenced by the dilutions, i.e. the minimum distance between effusion and dilution holes cannot be guaranteed for some cooling features, a translation in axial direction is envisaged to comply with the pattern constraints. This is the case of row 4, in which an axial movement is applied to the effusions in front dilution to respect the keep-out zone imposed for the dilutions. On row 3, two different types of modifications can be seen: the first one concerns the number of effusion holes to be considered, while the second deals with their positioning. These basic modifications must be applied subsequentially to ensure an acceptable result from a user perspective, which is here represented as a row with a reduced hole number and where cooling features are patterned in the gaps between dilution holes, needing a tangential shift to be applied for this case. The type of correction that is proposed for row 2 is instead peculiar for holes placed downstream the dilution position. It consists in the modification of the holes' impact angle, as a measure that allows to keep the axial position of the cooling outlet ports, and hence the uniformity of the cooling pattern on the hot side, while preventing the inlet port from interfering with the dilution holes on the cold side. The set of modifications shown in Figure 2.5-c are representative of the baseline changes that might be applied to a cooling pattern. In facts, measures as the number adaption, the axial and tangential shift and the variation of impact angle could be applied jointly to respond at complex hole arrangement problems more effectively.

2.2.2 CFD simulation

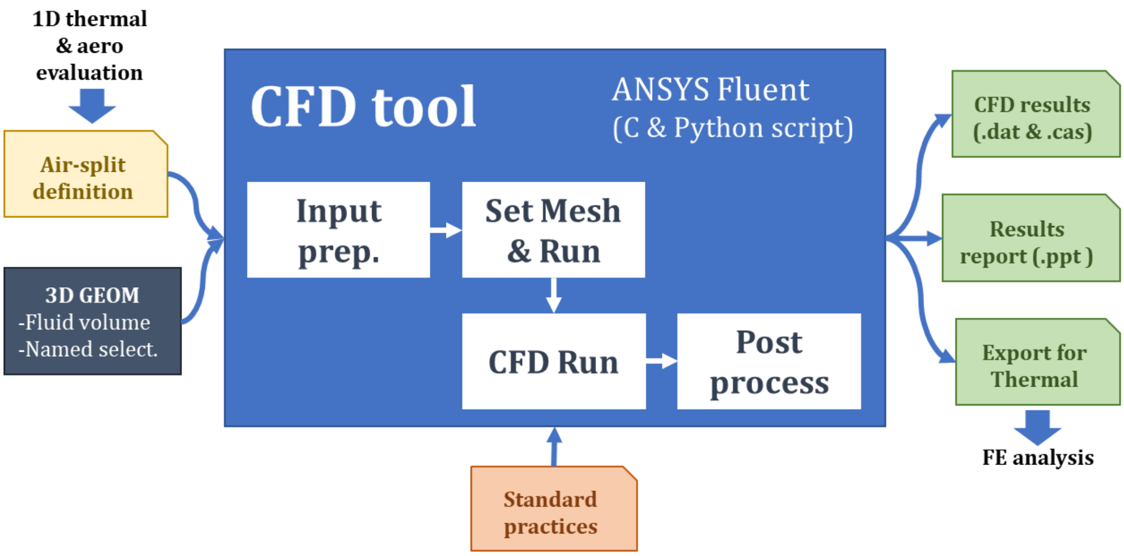


Figure 2.6 – Flowchart of the CFD process

The goal of the customized CFD Tool is to enhance, streamline and automate the whole CFD workflow. The automation of pre/run/post-processing operations enables the reduction of the human and CPU time per analysis loop, the enhancement of the procedure robustness and so its optimization. The CFD system automation is done within the Ansys Workbench environment [64] using ANSYS ACT, a fast and easy way to tailor simulation workflows based on easy-to-learn yet powerful XML and IronPython programming languages. In the DSI framework, an ACT application has been developed to automate and customize the full routine CFD workflow and to integrate data with the ANSYS product line. This application comprises four wizards with different purposes. With reference to Figure 2.6, a summary description of the wizard scopes (white boxes) involved in the CFD process can be given.

A first wizard has been developed to collect the data coming from the upstream processes, to organize and prepare them for the complete workflow. The CFD input data are synthetized in a file: boundary conditions and their characteristics (mass flow, inlet angle, temperature), injection properties, monitor definitions and data for the post-processing. The second wizard has been developed to cover the whole CFD process. It allows users to both automate and customize the whole stream and it is made of the steps reported below:

- CFD Mesh
- CFD Setup
- CFD Calculation
- CFD Post-processing
- CFD Report.

This wizard walks non-expert end users step-by-step through the simulation, each of them asking the user to define the required information. For the CFD Mesh step, the Wizard Guided User Interface (GUI) collects all the main mesh characteristics and the number of cores for parallel meshing the fluid domain generated by the CAD tool. The wizard also offers the flexibility to create tetrahedral, polyhedral or poly-hexacore meshes. The latter two, generated in Ansys Fluent Meshing, provide a comparable accuracy in terms of results whilst minimizing mesh size and maximizing cell quality. The CFD Setup requires some generic Ansys Fluent files (UDF, scheme, pdf table, interpolation files). In this step, if an interpolation file has already been generated it can be used as an initial solution, otherwise a hybrid initialization method is set as default. To save CPU time, a convergence criterion based on outlet temperature monitors can be defined. The iterations number and the Ansys Remote Solver Manager submission parameters are required to define the CFD Calculation step. The latter enables the automatic submission of the calculation job to a remote cluster for the parallel computing. In the CFD post-processing step, a list of post-processing outputs is submitted, such as contours, profiles, probes, tables, etc... This step manages the data export creation required for the downstream processes.

Once all the wizard fields have been filled, the python code performs the complete CFD workflow in a fully automated way without any human intervention: from the creation of the mesh to the filling of a PowerPoint report in which all the exports of interest are summarized so it can be used for checking activities. The wizard offers the flexibility to exit the full automated process at several steps: after the setup definition, after the run calculation or after the post-processing results. Then a third and a fourth wizard are available to cover different scenarios and continue the workflow from the current state to automate the missing steps. One is dedicated to the automatic creation of the post-processing and the PowerPoint report; another one is dedicated to the automatic creation of the PowerPoint report only. Thanks to those two wizards, users can easily bypass the default RSM servers to run on other machines, run further iterations or create additional specific post-processing to be added in the report.

2.2.3 Thermal maps processing

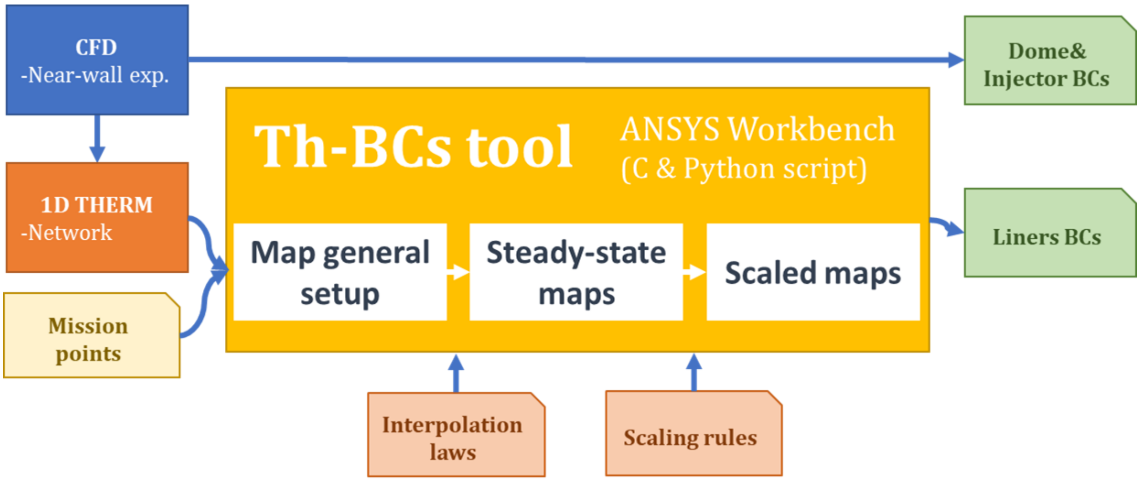


Figure 2.7 - Flowchart of the Thermal BC preparation process

Automation in generating the thermal boundary conditions for a thermal FEA is achieved with a process as depicted in Figure 2.7. This is enabled by an ACT extension developed in ANSYS Workbench environment. The goal of this procedure is to create 3D cloud-points of thermal boundary conditions that can be mapped in a thermal FE model. To do this, the wizard comprises three main steps that can be managed by user interface or in batch mode, to fully automate the following operations. A first, preliminary activity is dedicated to specifying the resolution of the map, as the number of points in the axial and tangential direction, while linking the Therm-1D results to be adopted. The generation phase can so be managed, in which rules to be adopted for interpolating 1D results at the 3D level must be defined for the various locations (outer or inner liner). The result is a set of 3D distributions of quantities of interest, in the specific mission conditions of the 1D model. Furthermore, in the last steps, such maps can be scaled on different mission points by means of correlation and best practices. It provides the input for the transient thermal assessment, giving the desired flight mission. An additional plug-in enables visualization of the maps, which is useful for checking and comparison activities.

In a traditional design workflow, the information to be processed through this tool might be updated with the near-wall quantities resulting from the upstream CFD simulation step. In this way, the thermal distributions to be considered in the thermo-structural process have been demonstrated to be more credible from a physical standpoint, since they are retrieved from a higher order solver instead of being formulated by the user and defined as assumptions. The baseline Therm-1D model is here undergoing a re-run of networks, with a superimposition of quantities as flow velocity and density in order to update the heat transfer and adiabatic wall temperature results. A description of this approach will follow in Paragraph 2.4.1, dedicated to presenting the general functioning of an integrating tool tailored for linking the Therm-1D tool in the DSI application

2.2.4 Structural assessment

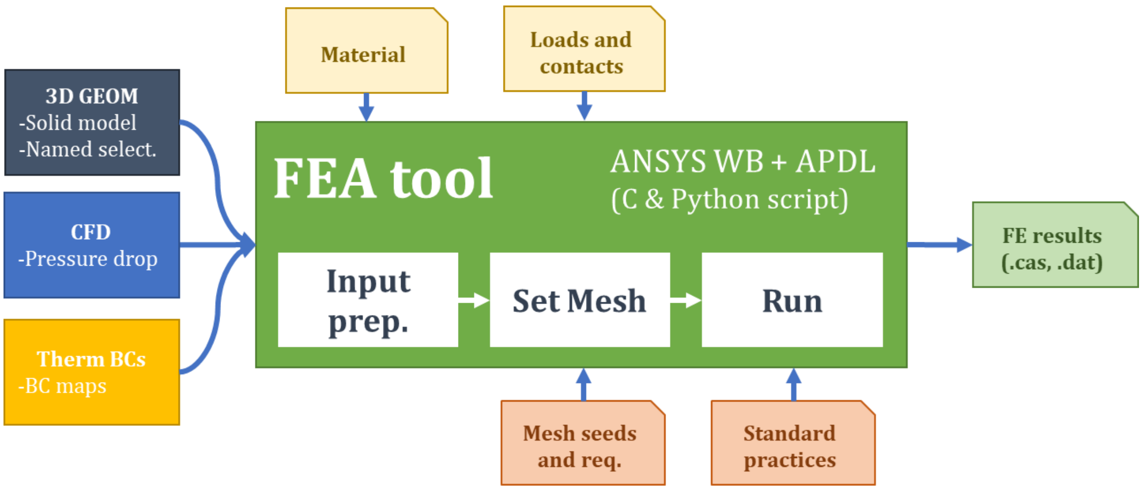


Figure 2.8 - Flowchart of the Structural FE process

The evaluation of the structural conditions to which the combustion system is subject is a fundamental step in product development. At this stage, information of distinctive character that are related to both constructive configuration and operative conditions is taken into account, so that requirements as components' strength and durability of the whole system can be verified. In fact, this step takes place downstream the overall process and is receiving the results coming from the previous configuration analyses. In the same way, the result of this evaluation is capable of providing sufficient elements to evaluate the effect of design modification and suggest changes which might impact positively to the system's performance. In analogy with the CFD analysis tool, the Structural FEA tool is intended to streamline and automate the pre and processing steps of the FEA workflow. Such system is developed as an Ansys ACT in Workbench and it is composed of two Wizards. With reference to Figure 2.8, a summary description of their scopes can be given. The first one is dedicated to collection and process the analysis input data, which can be organized in three main classes:

- Upstream analysis processes – made of the geometrical export of the CAD tool, in which defeaturing and named selection are applied to the model, as well as the pressure and temperature boundary conditions resulting from the CFD and the Thermal FE processes, respectively.
- Current analysis process – collecting all the information relevant from a structural standpoint, such contacts, internal tensions, external loads, and constraint, etc.
- Definition of the model – as the material/properties to be given to the model components,' as well as the mesh properties and seedings. list, mesh seedings

Still relying on the analogy with the CFD process, a standard .xlm repository has been defined to harmonize all of the information mentioned above. The organization into a standard template allows the system to link this input to the second Wizard. The latter is dedicated to the generation of a standard, consolidated workflow for structural analysis. It is made of a default APDL element connected to a geometry component and a thermal \analysis feature. Through a list of instructions embedded in the extension, this Wizard performs all of the pre-processing activities required for a FEA calculation. The first task is the import of the CAD model, to be then meshed taking into account meshing best practices and refinement seedings. It is then possible to define materials, prior to setting up contacts and internal/external loads. Lastly, the aerodynamic and thermal BCs can be mapped onto the domain, in order make the simulation step possible.

2.3 COS procedure

After exploring the details of the Combustor DSI functioning, the discussion can move to the description of the process enabled by the optimization framework. The Combustor Optimization Suite (COS) has been developed by Morfo Design [65], an engineering firm specialized in advanced aerodynamic design and in the development of tools for CAE applications. Its framework is a customization of Morfo Design's baseline optimization software, revised to fit with the application to a combustor product. In order to show the subsequential steps required for driving an optimization activity, in Figure 2.9 is outlined the COS workflow in which each of the five box is intended as a step in performing a specified function in the optimization pipeline.

The first task is aimed at defining the entire optimization problem. Here, the Degrees Of Freedom (DOF) and the Optimization Factors (OF) of the system are specified, in order to describe both input parameters expected to be varied and the multiple objectives deemed relevant for the design study. A specification to the problem's dimension, which is focal in the implementation of a metamodeling-based optimization process, is performed at this stage by the definition of variational range to the DOFs. To complete the design space definition, dedicated sampling methods can be exploited to provide the definition of Design Points (DPs) to be considered in

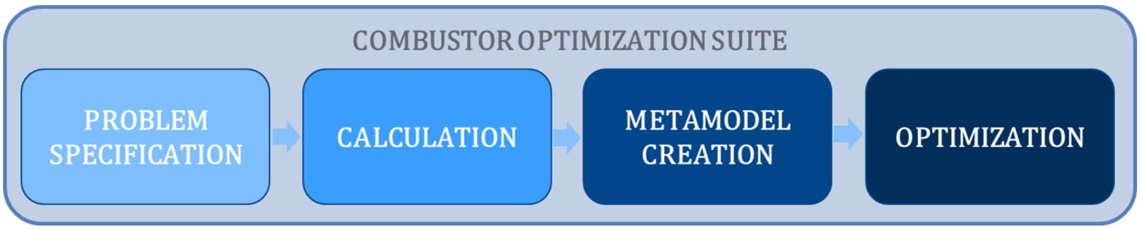


Figure 2.9 – Framework of the Combustor Optimization Suite (COS)

the study. Up to three sampling algorithms are made available by the procedure: the Sobol, the Hammersley and the Halton sampling algorithms. All of these are low-discrepancy quasi-random sequences, whose main property corresponds to a replacement of uniformly distributed random numbers, characterized by a low discrepancy subsequence for all the values of samples considered. Compared to the deterministic methods, the low-discrepancy quasi random methods present an enhanced accuracy when more datapoints are added and cover the domain of interest quickly and evenly. Although all the above-mentioned algorithms generate a uniformly distributed sampling pattern with low-noisy and anti-aliasing results [66,67], Sobol assures a better filling in the design space compared to Hammersley and Halton in the case of a not excessive number of the design points (DPs), as will be the case of this optimization activity.

The “calculation” step, instead, constitutes the generation process of a consistent number of system’s samples to be collected into a design database. Starting from the definition of each design configuration, which is specified through the set of DOF collected in the design space sampling, the analysis and/or simulation tools are iteratively executed to produce the system’s response, i.e. performance characteristics and functional parameters. Once all the configurations of interest are assessed, such information can be stored and collected in order to organize the data for the upcoming step: the training of the system’s metamodel. During the “metamodel creation” phase several advanced algorithms, as well as multiple training techniques, are made available for the generation of a mathematical model representative for the system’s behavior. Amongst all, the Artificial Neural Networks (ANN) algorithms will be adopted as metamodeling strategy according to the reasons which will be discussed in the next paragraph. The last task deals with the investigation of the meta-model through a defined research optimization function aimed at achieving the required optimized design candidate.

2.4 Providing an integrated design suite

In order to establish an integrated design platform, it has been necessary to implement a set of custom scripts aimed at enabling the communication between the different procedures which are aimed at multiple purposes, at all platform's levels.

2.4.1 Cooling design process

As it should be clear from the overview of Paragraph 1.2.1, the provision of effective and efficient cooling systems for the combustor's most susceptible components represents one of the greatest challenges in combustor's design. This has a direct impact in the durability of parts but has also a considerable influence on system's aero-thermal performance. If on the one the rate of mass flow required to comply with materials' thermal limits need to be defined, on the other hand the same quantity will be excluded from the core reactive process. In this context, combustor liners are showing up as the most critical components to be designed. The definition

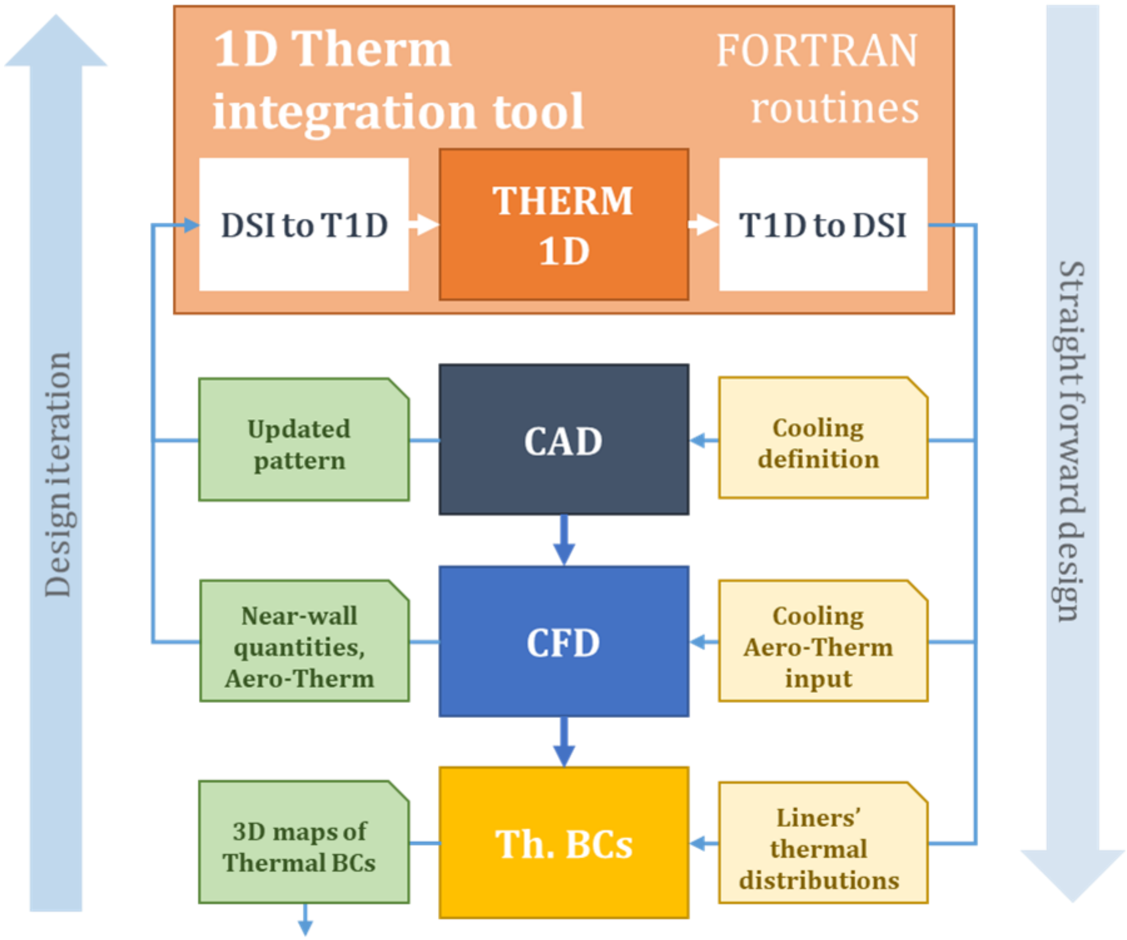


Figure 2.10 – Scheme of the framework implemented for integrating the cooling design tool

of a suitable cooling technology, together with a proper arrangement of the cooling features, takes place in the conceptual design phase. Given the low-order information available at such an early stage, one-dimensional approaches are more likely to be adopted for this purpose. According to the design process considered, the cooling definition for liner components is exploited by mean of Therm-1D. This in-house code is developed at the University of Florence and makes use of correlative models to perform conjugate fluid-metal analyses for the prediction of wall temperatures, especially for combustor applications [68–70]. In its generic form, a Therm-1D model for a combustor is composed of two mutual communicating main parts, which are iteratively solved within the procedure: a fluid network, reproducing fluid passages as geometries for holes, slots, etc. and a FEM model, representative for the metal parts (liners, coatings, etc.). In its core functioning, this tool allows to assess the thermal conditions of the modelled component given the geometrical definition of the cooling system and the boundary conditions corresponding to the system's operation.

In order to integrate this tool within the DSI procedure, a custom FORTRAN routine has been implemented for transmitting information across the design process. Still relying on the flowchart of Figure 2.1, specific scripts have been implemented to ensure the inclusion of Therm-1D in both of the two design paths identified in the preliminary design process:

- **Straight-forward design** – a group of scripts, collected in the "T1D to DSI" frame, enables the communication from Therm-1D to the DSI toolkit. With reference to the CAD tool, a specific routine allows to prepare the cooling and quenching geometrical specifications for the 3D model generation process. The aero-thermal characteristics, namely mass-flow and temperatures related to the cooling rows orifices, are exported as boundary conditions for the upstream CFD analysis step. Similarly, thermal quantities of interest referred to liner walls are elaborated to initialize the mapping generation process.
- **Design iteration** – with the same fashion, the scripts grouped in the "DSI to T1D" frame are completing the linking of the DSI tools with the Therm-1D

procedure. In general, this is aimed at processing the feedback of the CAD and CFD tools to re-run the 1D thermal model, thus obtaining updated thermal quantities. For the CAD tool, it is able to provide the revised cooling and quenching definition which may come from the CAD model iterative generation. With reference to CFD analysis phase, instead, it provides the reception of near-wall aero-thermal quantities

2.4.2 Design optimization process

Focusing on the explanation about the overall functioning of COS and DSI methodologies, the issues of mutual communication have emerged between the two articulated procedures, which exchange miscellaneous information each other and follow different functioning logics. Hence, the reasons why the development of an integration toolkit is necessary are well-known.

In particular, the introduction of a certain adjustment to the reference design shall define a specific design workflow within the procedure: the management of the different extensions becomes a central aspect, given that tools and functions are properly called on the base of the particular variation request. For the design problem which will be addressed in the discussion, concerning a CAD-CFD process, all cases can be traced back to three main scenarios:

- **Pure boundary-conditions problem** – the modification is not intended for the geometrical domain, but only for the conditions in which the configuration is considered to operate. The same baseline design is here evaluated under different boundary conditions (BCs) i.e., simulating the combustor behavior for different operating test points. This scenario represents the easiest and quickest case to be managed by the design system since there is no need to update any CAD model and only the step related to the CFD run and post-processing needs to be performed again. Since no change is applied to the geometry, the only journal file to be updated is the one devoted to the setup-and-execution of the CFD simulation; the post-processing journal is specified on the basis of a feature-recognition methodology, so there is no need to recreate it.

- **Pure geometrical problem** – the modification is intended for the geometrical domain only, while the operating conditions are fixed. Different geometrical characteristics are here evaluated for the same global boundary conditions i.e., combustor air-split, operating temperature and pressure, fuel rate, and injection. This one case represents a more complex process to be performed by the DSI procedure. The update of the CAD model means that the steps required to set up the CFD analysis must be performed again. Journal files devoted to meshing, pre-processing and post-processing need to be created from scratch, while the set-up and running journal are only updated to minor modifications. It is worth noticing that quantities such as the local air-split are resulting from the imposed geometrical configuration, therefore their evaluation is demanded to the CFD post-processing step.
- **“Mixed” problem** – the modification is intended for both the operating conditions and combustor configuration. If a relationship between the imposed BCs and the corresponding geometrical feature is deemed to be present, modifying one aspect will imply a change to the other, under certain conditions. This is the case when, for example, changing the diameter of a discharge hole while keeping constant the pressure-drop across it changes the mass-flow, which is driven by the definition of hole discharge coefficient. When the global operating condition and product requirements are set, a “mixed” problem is the most common situation in which the design system is called to operate. Indeed, relationships between geometries and boundaries must be expressed in advance to estimate each mutual magnitude. From a design process perspective, this represents also the most complex scenario since any modification will have an impact on both aspects.

This last scenario is representative for the modifications which shall be managed in the communication between the DSI and COS procedures. To this end, it became necessary to provide a custom toolkit able to process the information exchanged between these two structures have been developed. Taking into consideration the DSI procedure as the analysis-based process and the COS framework as the process automation tool, specific functions and algorithms have been implemented for executing calculations and editing procedure's support files. In the pre-processing step, the translator toolkit has been conceived to convert the system's explanatory variables into geometrical and aerodynamic input to the DSI, for the 3D CAD generation and the CFD analysis steps, respectively. In the same way, the post-processing phase requires the conversion of CFD results into response variables suitable for the optimization procedure. For the sake of simplicity, in this work we will refer at such conversion tools as "Geom/BCs" and "Aero/EI" calculators, respectively. The entire process is shown in the Figure 2.11 and it is aimed at exploiting the interfaces of the two existing procedures and the capabilities of the conversion tools for both the pre-processing and the post-processing. In the following paragraphs, it will be described the procedures and design rules based on parameters' variation featuring the translator functions, but also the outline of the implementation for both the pre-processing and the post-processing. Its general structure, together with the operations performed within the two phases, will be presented in the context of the design optimization, as the process in which such communication tool finds application.

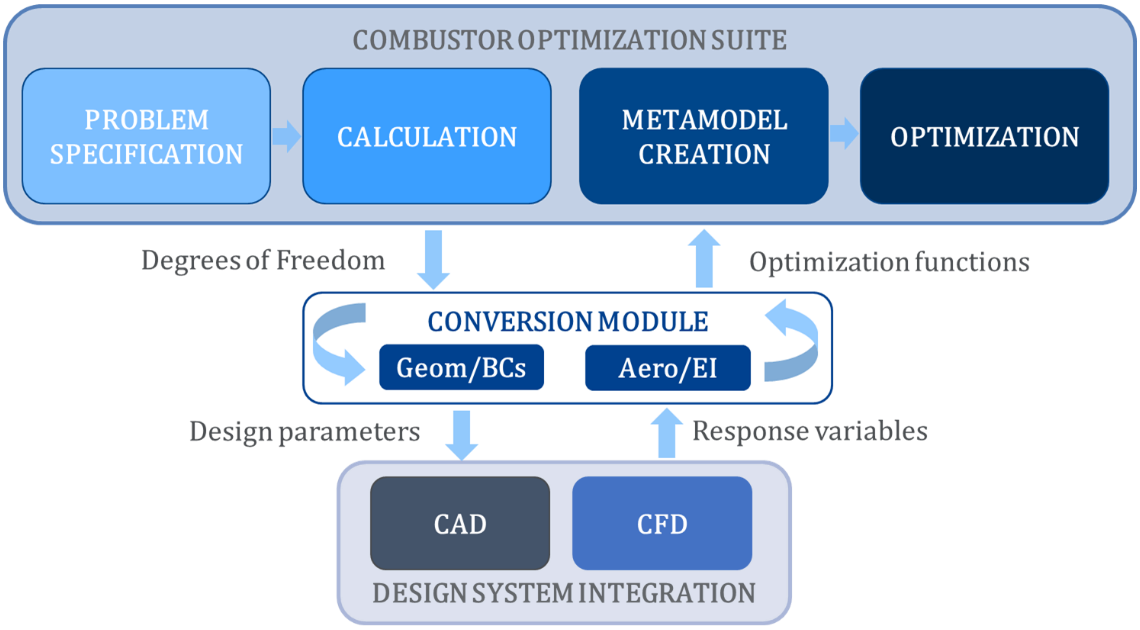


Figure 2.11 – Position of the custom "conversion module" within the design optimization platform

2.5 Evaluating the usability of the system

Since the DSI procedure is conceived for being adopted by combustor designers and analysts, an aspect that cannot be neglected when it comes to evaluate the performance of such a software-based methodology is the usability. Following the definition of "Quality in use" provided by UNI ISO 9241, it can be interpreted as the degree to which a software can be used by specified consumers to achieve quantified objectives with effectiveness, efficiency, and satisfaction in a quantified context of use [71]. This set of characteristics is clearly influenced by internal and external requirements that are applicable to a software.

The effectiveness deals with the ability of the system in enabling the user to complete their tasks with a high degree of accuracy, and its concept can be related to two attributes: robustness and flexibility. The first one represents the ability to process information without committing errors, which has been achieved through an extensive standardization of the operations to be conducted by the DSI. Standard interfaces between the tools, as well as fixed families of information exchanged within the workflow, makes the design process more dependable. The second one is instead the capacity to accommodate the different functionalities that a user could need to adopt to conduct its work, which has been pursued by implementing a high number of scripts with a progressively sophisticated functionality. Worth to notice is that if these aspects have made possible to express the potentialities of the DSI from an end-user perspective, they are also responsible for the increase in complexity of the code and the corresponding difficulty in back-end maintenance operations. The efficiency concerns instead the ability of the software to operate with a minimized consumption of resources, whether these are requested from the user or delegated to the computing systems. The concept of "added-value" played a significant role in the enhancement of this characteristic, in fact it has been driving the implementation of scripts in the reduction of the time-to-design and in the simplification of the interaction with the user. The first point has been addressed through process automation, intended as the measure by which repetitive and error-prone operations that are commonly performed by the user can be made directly executable by computer systems. The standardization of the process has been a prerequisite for implementing this solution. From what concerns instead the user's adoption, dealing with an intuitive and easy-to-use system is also an effective mean to enhancing the efficiency of the software. Dedicated GUIs have been implemented to this end for each tool, in order to allow the designer to walk through the tools' execution in a structured and comprehensive way. The study for the minimum number of entries to be provided to the tool has been essential to optimize this aspect, so as to minimize the impact of this measure on the versatility required to the tools. However, the effectiveness and the efficiency of a software must be complemented by the satisfaction of the user. Indeed, there are side aspects that are fundamental for meeting the usability standard, without which the possibility to adopt the tools would be severely compromised. First, the user must perceive the utility of the solutions proposed through the software: the target of people that were intended to use the tools have been involved in its development for the beginning, starting with the definition of the requisites and ending with functional test on real combustor cases. Then, in the perspective of scaling-up the adoption of the tool and implementing a user-independent, know-how-based design process, the ease of learning must be taken into consideration as well. Dedicated material as User's guides, tutorials and demos have been implemented to this end.

Along with the several benefits brought by the procedure, which is an aspect that will become even clearer in the context of the Chapters, it is necessary to mention the limitations that can be found in its use at this stage of development. The interfaces that the system shares with the user are currently based on standardized excel sheets and minimal user interfaces, features that make it extremely easy for the designer to use, especially for tasks such as updating an existing geometry. The standardization of processes, as mentioned, by definition limits the generality and flexibility of this approach, and in order to cope with this problem, a structured system requires sequential implementations and continuous maintenance. Furthermore, although the inputs provided to the system are standard, their preparation can sometimes be complex. It is due to this aspect that the processes of model generation and analysis can proceed in an agile manner, which is not a real problem if the user is an expert. Otherwise, educational support and practice are required to make the user more aware. This component is also relevant in troubleshooting, given the complexity of the entire system. Another condition to consider is the potential dependence on operating systems and software versions. Although the procedure has been tested on multiple versions and platforms, when methodologies are based on out-of-the-shelf tools, it is good practice to design them in a modular manner so as to prevent the replacement or introduction of new elements.

Chapter 3. Design through the Combustor DSI

The main purpose of this section is to illustrate the design approach proposed in the DSI toolkit, with an application of the processes depicted in the previous chapters to a real combustion system: the NEWAC concept. Right after introducing the key features of the test case, it will be highlighted the results of processing such configuration through the tools for CAD generation, CFD analysis and Thermal FE preparation. The numerical methods provided for the computational analysis are presented in the context of a straight-forward design activity - given the general intent of the study, over all the numerical disciplines considered in the DSI, the CFD simulative approach deserves a depth discussion. Since test cell data is available for this concept, the NEWAC combustor lends itself well to the assessment of the methodology embedded in the design tools. Furthermore, the demand in temporal and computational resources in conducting the design activity through the DSI approach can be estimated with the MBPB technique, by comparing the DSI-driven process with the traditional, user guided approach. In short, the intention of this discussion is to substantiate the benefits coming from rationalizing the resources and enhancing the reliability of the design workflow.

3.1 Test case: NEWAC combustor

In order to explain and demonstrate the functionalities of the presented procedure, in this section the results of applying the DSI procedure to a real-case configuration are reported: the NEWAC combustor, developed in the purpose of the "New Aero engine Core concept" EU project.

The prototype proposed by "Avio Aero – a GE Aviation business" (formerly "Avio") is shown in Figure 3.1. The combustor, a lean-burn concept with a straight-through layout, makes use of the PERM injector (Partial Evaporation and Rapid Mixing) to drastically reduce the formation of NOx. This injection system is developed to operate in the range of medium overall pressure ratios (20 < OPR < 35) and features a co-rotating, double radial swirler with a fuel staging between a pressure atomizer (pilot) and a film developed on inner's lip surface (main). Such arrangement enables a correct stabilization of the flame during its functioning. The reaction process, and hence the NOx formation, is also modulated by the injection of air through dilution holes, realized on metal liners and placed in the final section of the combustion chamber. As far as the combustor is concerned, part of the air passing through the dump diffuser is directed to the annuli where it is used for the liner cooling, the

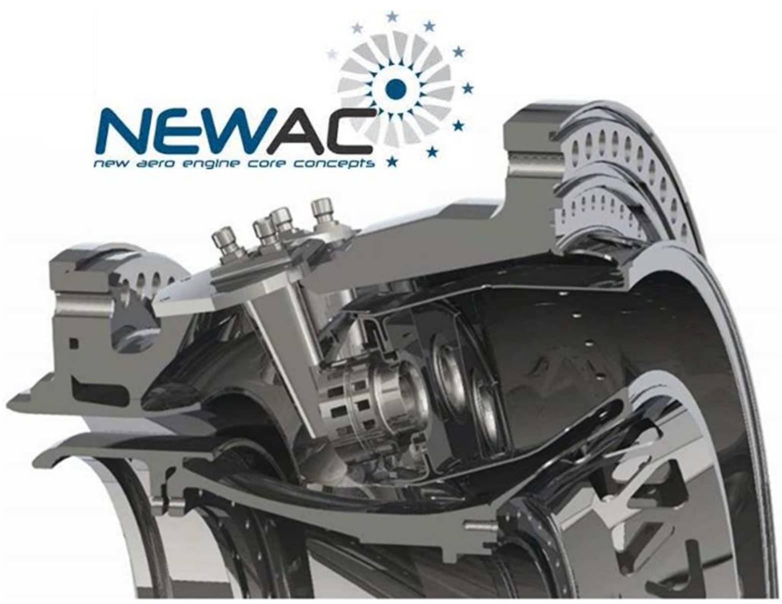


Figure 3.1 - NEWAC concept proposed by "Avio Aero – a GE Aviation business" (formerly "Avio")

dilution holes, and the bleeding holes. The remaining part is instead divided between the injection system and the dome cooling. To protect this last from high temperatures, indeed, a heat shield with a back-impingement cooling system has been provided. Purge air coming from this feature is adopted to produce a film covering effect in the very early section of the liners. A multi-hole system has been designed and displaced to keep such metal parts under acceptable thermal limits. To in-deep the discussion on this specific concept the reader is referred to the plethora of studies published in the numerical [68,72,73] and in the experimental field [74].

3.2 DSI baseline modelling

In the following sections, it will be reported the results of processing this configuration through the tools composing the DSI toolkit, retracing the design process from the CAD generation step to the preparation of thermal boundary conditions for FE analysis.

3.2.1 CAD geometry

The process conducted to generate the exportable 3D model of the NEWAC combustor can be considered to be composed of the four main steps depicted in Figure 3.2.

By relying on the one-dimensional information generated in the conceptual design, the first allows to initialize the geometry generation process and to perform general consideration on the arrangement of cooling and dilution holes. For this purpose, the cross-section of the combustor and the cooling and dilution row positions are imported in the system, in the form of a spline exported form the system's CAD definition and a set of X-Y coordinate specified in the NEWAC's Therm-1D model, respectively. A calculation of the relative position between these entities allows to detect which rows will be interested by local modification. The result of this evaluation is collected into dedicated process files, which will be used subsequentially in the stages of correction and adaption of the holes pattern. A preview like the one shown in Figure 3.2-a, in which an array of dummy cylinders is intersecting the liners' splines on the meridional plane, is prompt to screen by the system. This can be used by the designer to support configuration's definition, as well as verifying that the input provided for the upcoming preliminary phase are correct (i.e. rows axial

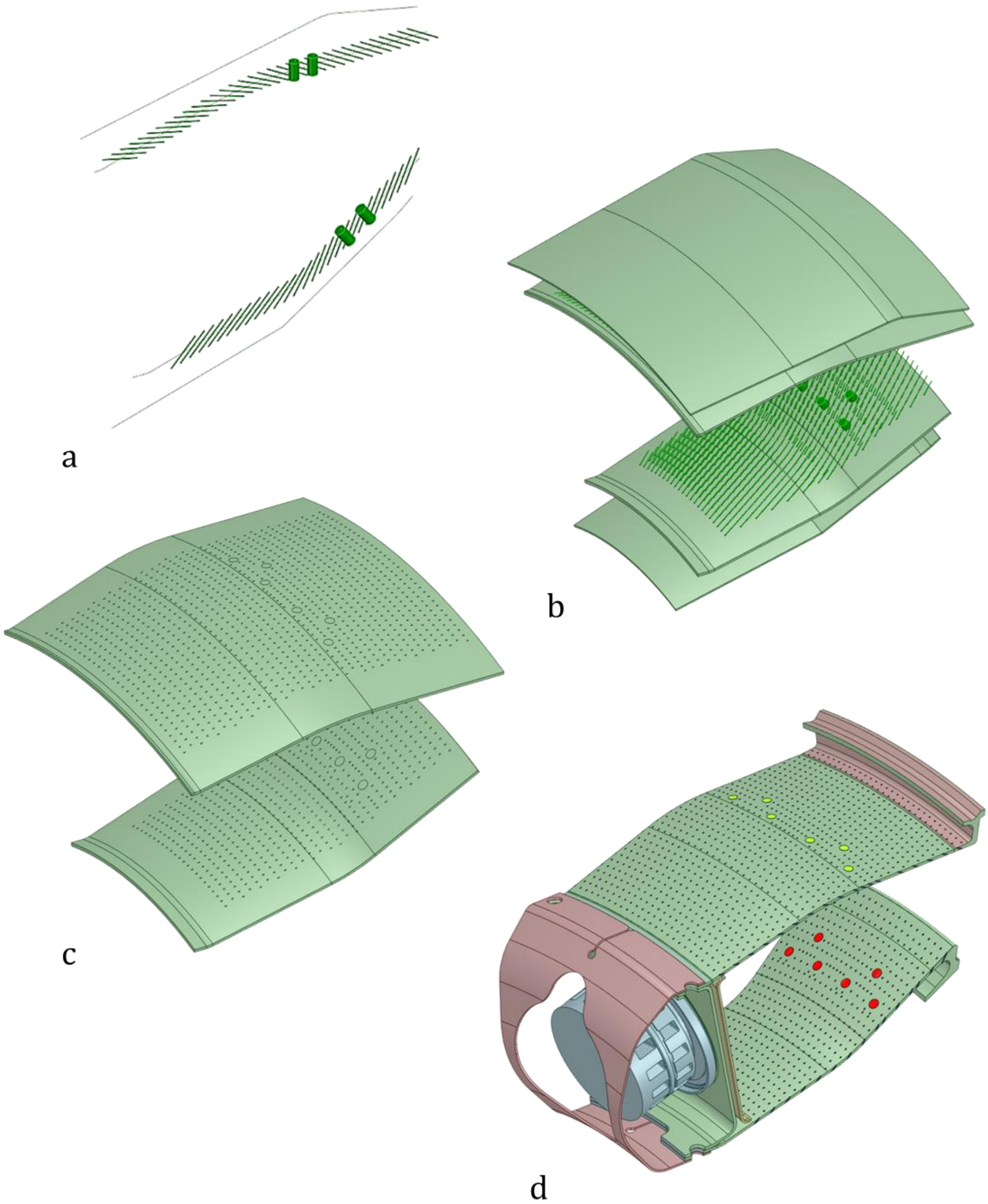


Figure 3.2 - CAD generation process applied to the NEWAC combustor

pitches and impact angles, holes' sizes…). Furthermore, in this step a check is performed on the number of holes specified in each row, to ensure that the pattern will later comply with the requirements for a symmetric and periodic arrangement.

The development of a three-dimensional geometry starts in the second step where, by means of a revolve operation around machine's axis, are created the plate components of the combustor: baffles. liners and possible TBC coverages. Information as plates' thickness and number of injectors are sourced from the geometrical repository file, in order to obtain the surface and the arc of revolution respectively. For the present design, no TBC coverage is provided, and the sector's number is up to 18 which is giving a periodicity of 20 ° (Figure 3.2-b). A "plain pattern", namely a definition of holes which is not taking into account any collision between geometrical entities, is created above the liners. The system is so allowed to perform a calculation over conflicting holes, in order to provide suggestion for the arrangement which will take place in the upcoming step. As usual, such consideration are updating and/or integrating the information stored in the system's file, where functional and feasibility requirement can be considered given the 3D development of the pattern generated.

The third step, instead, is dedicated to the operation which might be considered the most complex and advanced of the whole CAD generation process: the definition of 3D pattern of holes complying with both the constraints given in the design and the general/local requirements stated for getting a feasible configuration. in which both general and local constraints and requirements are resolved. By following the specific rules implemented in the system, it is proposed a different arrangement to the holes on the base of academic evidence and design lessons learned. These modifications are then suggested according to the relative position between cooling and dilution rows. In case the user is not satisfied with the proposed arrangement, or there is the need to superimpose a specific one, the systems make available a set of tools to enable this customization process. This is the case of the present design, in which is not expected an improved solution but there is the need to produce a combustor configuration as close to the original one as possible. As it

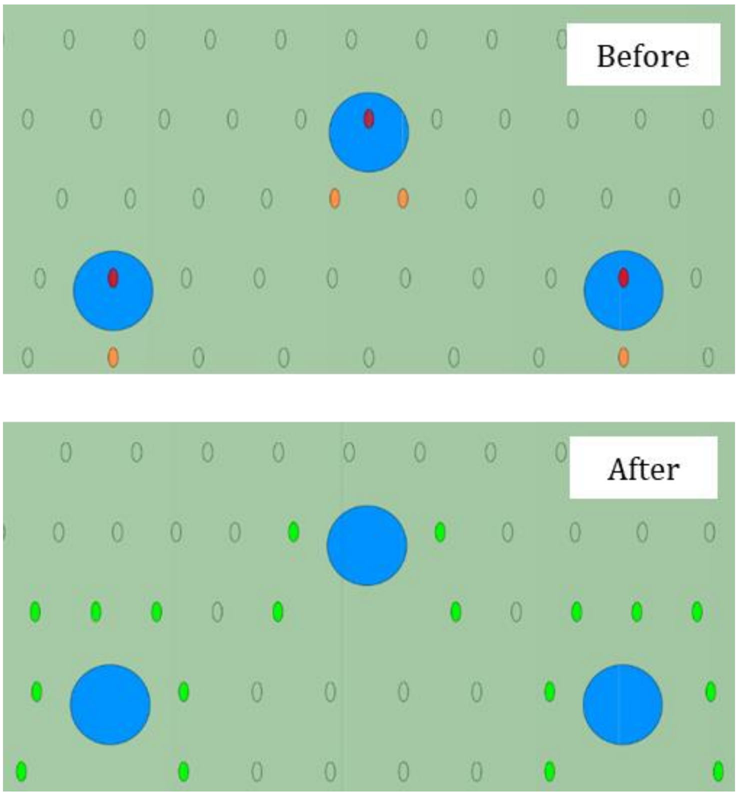


Figure 3.3 - Local correction of holes provided by the system

might be seen from Figure 3.3, this led the effusion holes to be split in the spaces between the dilution one.

The generation of the exportable CAD model takes place in the fourth and last step. It is implemented with an operation of geometrical merging between what obtained from the previous step and the group of external geometries grouped in a standard dedicated input file. For the present design, this latter is made of the dome components, comprising the homonymous plate and the head shield protecting it, the PERM injector and front/rear mounting flanges. The repeatable combustor sector of the NEWAC combustor obtained with this step represents the collector for all of the geometrical information of the configuration, and in addition of constituting the CAD reference it is also the baseline for the process model exporting to the downstream simulative steps.

Figure 3.4-a shows the fluid domain to be adopted in the CFD analysis phase, as a result of a Boolean subtraction of the CAD model and a generic starting volume. The preparation of this latter represents the most important preparatory operation

in the DSI modeling, since giving a robust definition of this input allows the process to rely on a single geometrical basis for all of the possible design iterations, which can occur by apporting modifications to the combustor baseline design. It is properly on that element that operations of geometrical defeaturing, which are useful to simplify and rationalize the simulative domain, model can be conducted, as well as a definition for bodies of influence can be provided in order to establish areas of refinement during the meshing process (b). Since these aspects has a direct impact on both the accuracy and the representativeness of the CFD results, the actions envisaged for the NEWAC model will be deeply discussed in the next paragraph. Besides its purpose in fulfilling all the geometric functions, this input is also the collector for all kind of named selections: "static", defined on the geometry and not supposed to be modified during deign iterations, and "dynamic", generated during the export process. Considerable importance is taken over by the effusion holes named selections are modeled by means of the geometrical footprint on both hot and cold sides of liners. Following a comparable process, the regions of the domain which are interesting from a post-processing standpoint are automatically identified and exported (i.e. hot sides of the liner and surfaces passing through the quenching module). For the case in question, the planes perpendicular to the quenching system and those parallel to the axes of the dilution jets are taken into consideration. All of this information is collected within a dictionary system file which, as described in the DSI process, is structured in such a way as to ensure a streamlined reading of its contents.

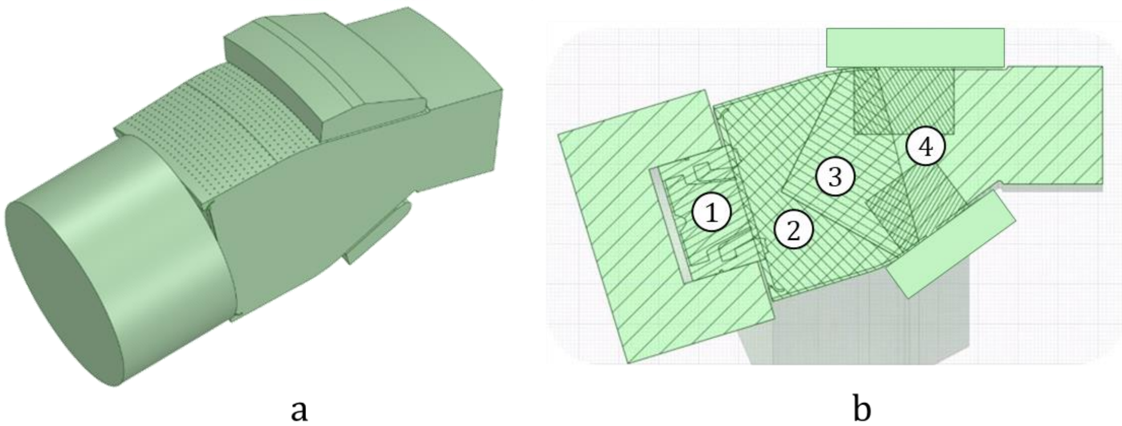


Figure 3.4 - Exported fluid volume of NEWAC combustor, with evidence of the four bodies of influence to be considere in the meshing process.

3.2.2 CFD analysis

The preliminary activity for pursuing the CFD process consists in binding the CAD entity with the physical input from the conceptual design. Basically, the BC type, and if specified its value, is associated to the corresponding named selection present in the fluid domain. The constant linking with the 1D aero and thermal tools is realized by keeping the same naming, while the type is automatically recognized by means of specific NS classifications. At this level, additional information is required from the user: the mission point, selected as Approach 272 ICAO test condition, and the injection system characterization, here specified with a double injection to best represent the behavior of the PERM system. Furthermore, details needed for the post-processing phase are requested here. All this input is stored into a recap excel file that can be specified once in the process (i.e. model preparation phase) and it is not supposed to change during the iterations.

With reference to the computational domain, specific measures have been employed to drastically reduce the volume size while maintaining the fidelity of the model. With the aim of reducing the computational costs, and hence the overall time for a design iteration, some regions of the calculation domain have been simplified geometrically. This activity has been supported by a specific CFD-based sensitivity campaign, in which results of multiple simplified domains have been compared with those of the full-domain simulation from the work of Mazzei et al. [73]. With reference to Figure 3.5-a, such volume locations are briefly described here:

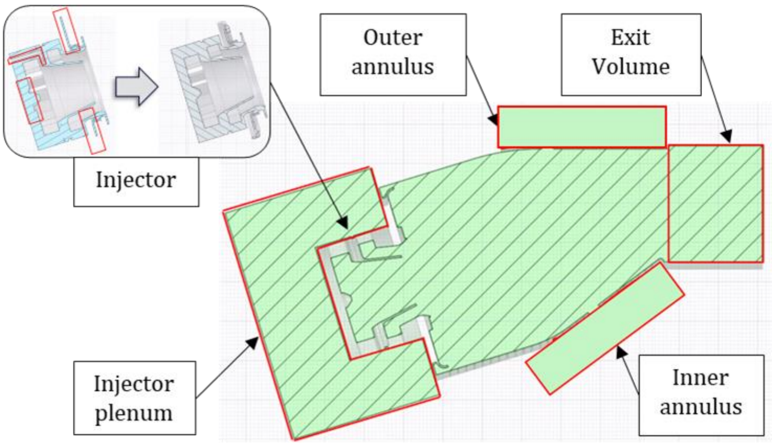
- **Outer & Inner Plenums** – limited in upstream direction, while the downstream bleeding ports have been simplified from shaped passages to rectangular patches of the same cross-sectional area.
- **Exit Volume** – added to make the flow field develop after the combustor's physical outlet; furthermore, this region is the location of the experimental measurement plane and it is therefore mandatory to include it in the overall fluid volume.
- **Injector Plenum** – modeled as a cylindrical volume concentric to the injector body; cowl and bolts geometries have been suppressed but

local conditions are replicated through adequate mass-flow boundary impositions and volume dimensioning. The Injector geometry, fuel pipes and local complex geometrical features were also removed. The fuel inlet has been preserved to provide the two points of injection, namely main and pilot.

- **Main volume** – comprising the flame-tube mostly. The cooling features have been modeled as patch footprints, while dilution ports have been included explicitly.

The resulting computational domain is reported in Figure 3.5-b, which was limited to a single annular sector of 20° by considering its geometrical periodicity.

a



b

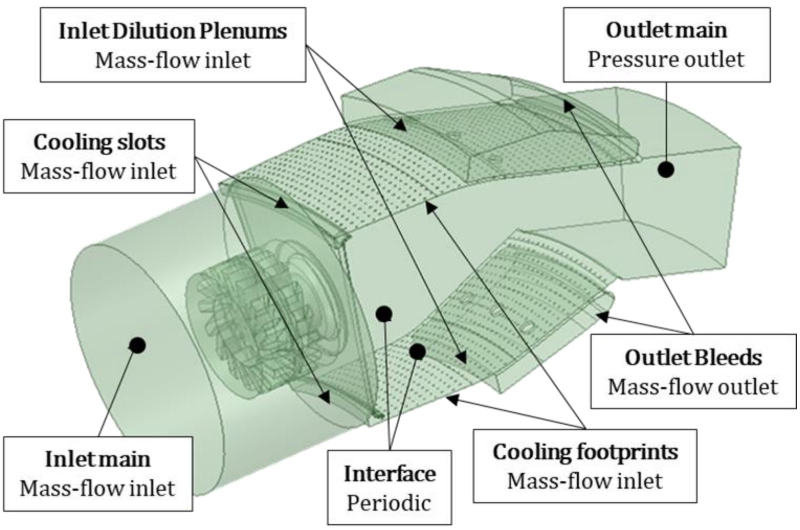


Figure 3.5 -Details of the CFD reference domain (a) and the resulting Fluid Volume (b)

The inlet and outlet boundary conditions, for quantities such as mass-flow, pressure, and temperature, were imposed according to a 1D flow-network model representation of the combustor. Such air-split definition has been retrieved for the specific operating condition and validated through direct comparison with test data.

The numerical setup has been defined for solving in Ansys Fluent, as a 3D RANS reacting flow calculation without conjugate heat transfer. The operating condition are retrieved from the ICAO test point specification in the repository file. Compressible Navier-Stokes equations (RANS) are solved considering air, Jet A-1, and combustion products as a reacting mixture. Turbulence was modelled with the k-e realizable model due to its capability in the prediction of the key features of swirling flow-fields. A conventional Eulerian-Lagrangian discrete particle model was employed to track liquid particles, and fuel is injected directly at the end of the lip, i.e. modelling the processes of film formation and primary break-up. The resulting spray is characterized by means of temperature, direction, and velocity magnitude of the particles, where a Rosin-Rammler distribution was considered for the droplet size. Secondary particle breakup effects are included using the CAB model. Following the approach defined in [75], a combined Finite-Rate Chemistry/FGM (Flamelet Generated Manifold) model has been adopted. Here, a low-dimensional chemical manifold is created based on one-dimensional flame structures, including nearly all of the transport and chemical phenomena as observed in three-dimensional flames. A set of 64x64 non-premixed flamelets has been used to generate the manifold since such an asymptotic flame assumption proved to be able to represent the phenomenon under investigation. In addition, the progress of the flame is generally described by transport equations for a limited number of control variables. In order to include the turbulence-chemistry interactions, laminar quantities of the manifold are integrated into a pre-processing step using a presumed b-Probability Density Function (b-PDF) for both mixture fraction and progress variable. In all simulations shown here, Jet-A1 has been modelled assuming C10H22 (n-decane) as single species surrogate, and a detailed reaction mechanism, taken from [76] with 96 species and 856 reactions, has been used.

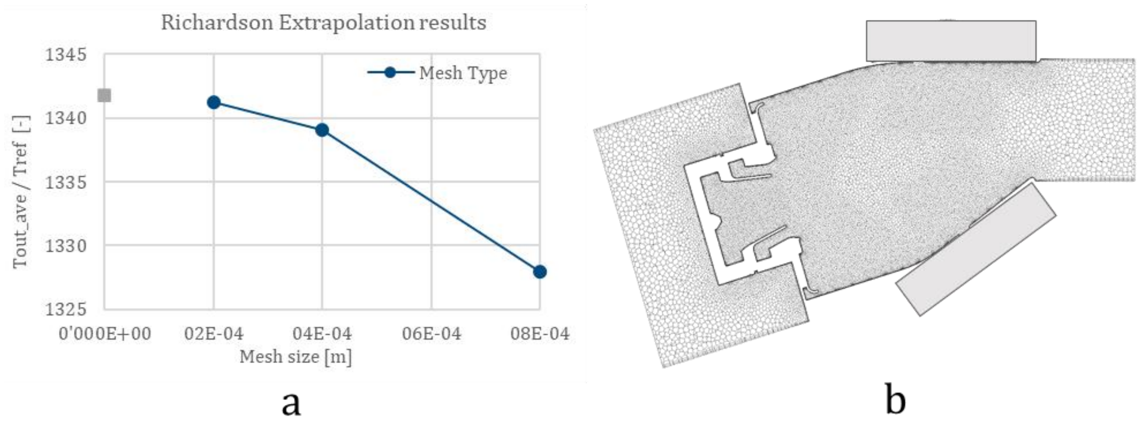


Figure 3.6 - Mesh independency from Richardson method (a) and result of the meshed domain (b)

To ensure the accuracy of the model, a mesh sensitivity analysis has been carried out through a Richardson extrapolation approach [77]. An optimal grid resolution has been defined by evaluating three different global mesh sizing: 8×10^{-4} m, 4×10^{-4} m, and 2×10^{-4} m. The trends of average gas temperature at the combustor's exit, depicted non-dimensionally in Figure 3.6-a, have shown that a global sizing of 4×10^{-4}m can be deemed acceptable if compared to the Richardson threshold. Furthermore, specific local sizing and dedicated Bodies of Influence (BoI) have been set to guarantee different model requirements: y+ levels in the range of 30-100 as requested by k-ε turbulence theory, a minimal local numerical dissipation, and sufficient grid resolution to correctly reproduce the flame front where combustion occurs. ;These refinements in, and in particular the flame zone area, have been based on [73]. The resulting grid is shown in Figure 3.6-b, which counts nearly 6.8M polyhedral cells and 29M nodes.

Results, postprocessed making use of dedicated macros, are reported in Figure 3.7-a. As an example, contours of velocity, temperature and mixture fraction extracted on the meridional plane can be generated. The evolution of integral quantities such as temperature and emissions are extracted on the flame tube mean-line, while PrF and PtF at the combustor exit are elaborated and show in a 5-probe view (Figure 3.7-b). By leveraging on the maps of contours it is possible to comment the overall functioning of the combustion system. As from design specification, the main split of air is processed through the injector. It can be seen by both the velocity and temperature contours that the recirculating fluid structure, which is promoted by this component, is responsible for the development of the flame. Its shape is limited downstream by the introduction of air from the dilution ports, with a generation of crossflow jets influencing the chamber's flow field. Nevertheless, the main impact of these fluid structures can be noticed at the combustor's outlet and, in particular, on temperatures distributions. From both the profile and pattern calculated among 5 averaged point at the outlet span it can be noticed their influence in dominating the

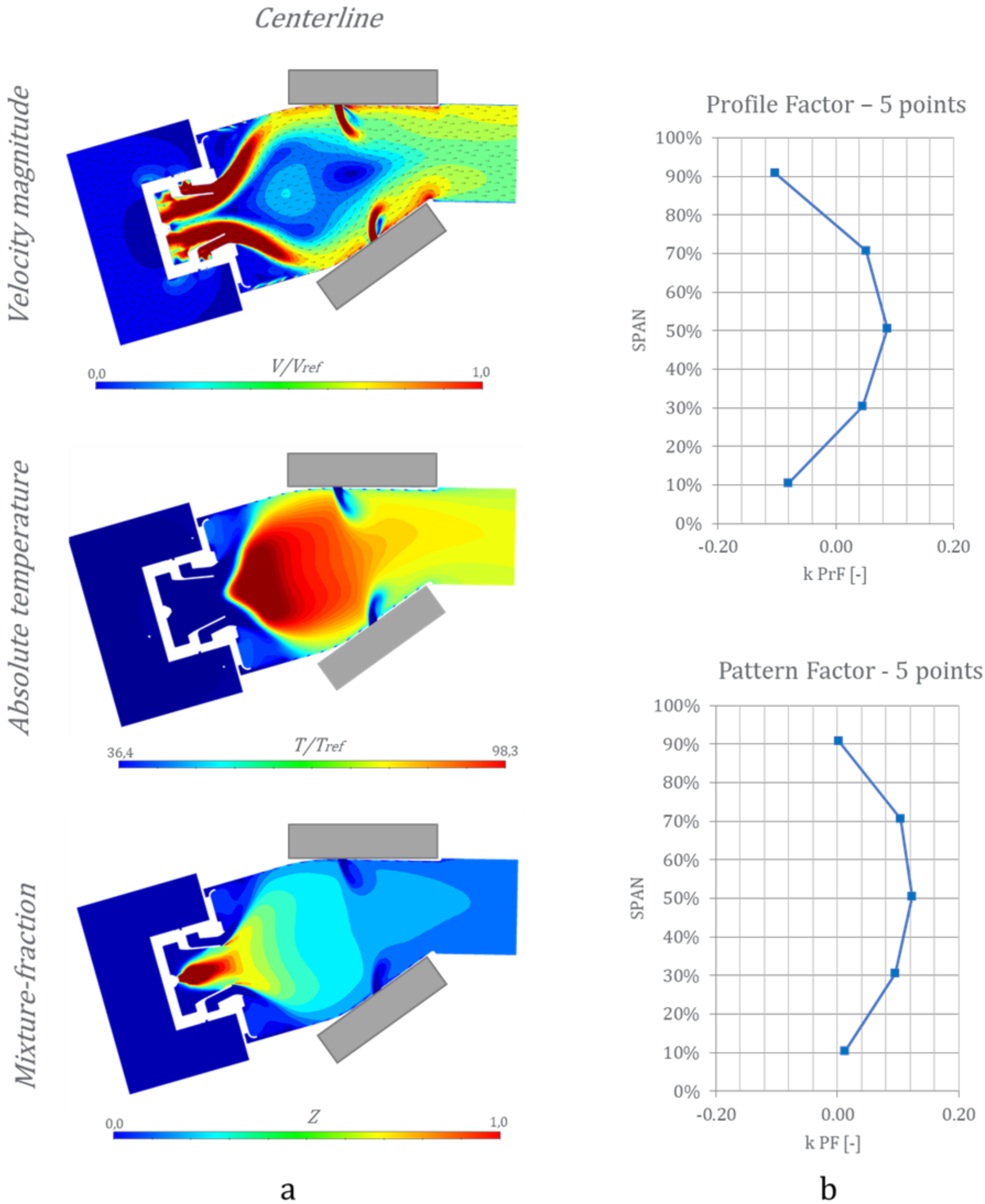


Figure 3.7 - Contour plot (a) and Profile/Pattern factors results (b) of the NEWAC model

factor shapes. The impact on mixture fraction Z is instead limited, since only a few parts of the air is made available at dilution stage. The mixing process, indeed, is developing right after the core of fuel injection which can be noticed inside the PERM geometry.

3.2.3 Thermal boundaries for FEA

To initialize the map generation process, the input to the Therm-1D network of the NEWAC system have been refreshed by superimposing the set of dedicated aero-thermal quantities resulting from the CFD simulation, in the near-wall locations. For each liner, it is possible to extrapolate update values of coefficient of heat transfer HTC and adiabatic wall temperature $T_{ad_{wall}}$ to be processed with the DSI tool. The result is shown in Figure 3.8, where the process presented in Paragraph 2.2.3 is performed for the system under analysis. As an example, it is reported the preview of two cloud points of interest: on the left it is presented the HTC for outer liner's cold side, while on the right are depicted the levels of adiabatic wall temperature $T_{ad_{wall}}$ for the hot side of inner liner. These boundary conditions are functional of the upstream process of thermo-structural FEA and are generated by considering two combustor locations (centerline and mid-cup). The map is composed of 1800 points in total, defined as 60 axial-wise per 30 span-wise set. The thermal data considered for this work is interpolated with a common, custom interpolation law, even though the procedure gives complete flexibility in specify different interpolating rules: a linear distribution is provided from ±10° to ±7.5°, while a polynomial function is employed in the range ±7.5° to 0°. Since in this study is considered only a single ICAO test point, the functions to scale up the maps over different mission points have not been adopted.

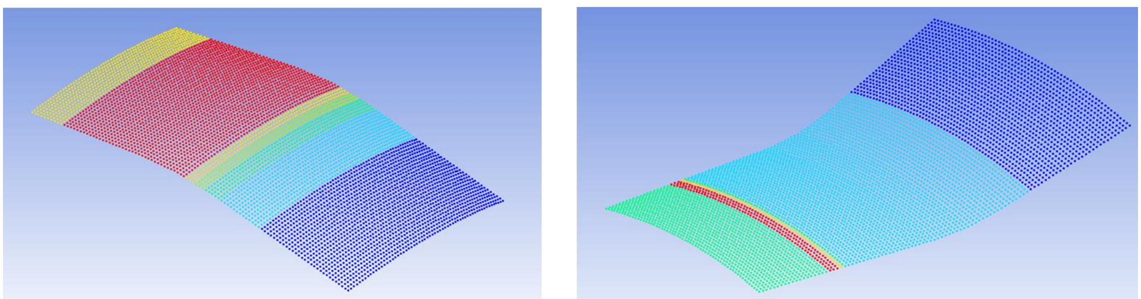


Figure 3.8 – Preview of cloud-point maps generated for NEWAC's thermal data

3.3 Results

In this Chapter is going to be performed a general assessment on the DSI procedure, both in processing combustor's configuration data and providing a preliminary design evaluation. By comparing its results with information of the real combustor case, it will be possible to evaluate the level of accuracy which can be achieved through such integrated approach. Furthermore, several considerations can be carried out on the process execution level, since the MBPM assessment of Chapter 2.2 allows to estimate the resource saved by adopting the DSI approach.

3.3.1 Assessing the methodology

Since the intention of the DSI procedure in enhancing the preliminary phase cannot prescind from the reliability and the accuracy of the numerical models, it is mandatory to provide an assessment to the tools processing the design information. Given the core capabilities of the toolkit detailed in this Chapter, as well as the study which will follow in Chapter 4, particular emphasis must be given to the results of the processes for the CAD generation and the CFD simulation.

In this context, the main purpose of the CAD tool stands in the ability to generate a CFD-compliant fluid volume, in which the arrangement of holes on liners results in line with constructive and functional requirements. The first aspect deals not only with the generation of an effective fluid volume, but also depends on the set of topological information related to it: i.e. named selections, post-processing areas, refinement regions, etc. In order to be verified under this aspect, the resulting CAD model must be processed through the downstream analysis process. The results presented in the previous Paragraph are demonstrating the NEWAC geometrical model has undergone all the tasks comprised in the CFD simulation and can be hence considered robust for the DSI purpose. To evaluate instead the capabilities of the CAD tool in generating an effective cooling arrangement for liners, it is required to direct compare the pattern produced by the DSI with the design reference. The reason for adopting such criterion can be found in the intention to evaluate the automated procedure in replicating the pattern of cooling of the design reference, and in

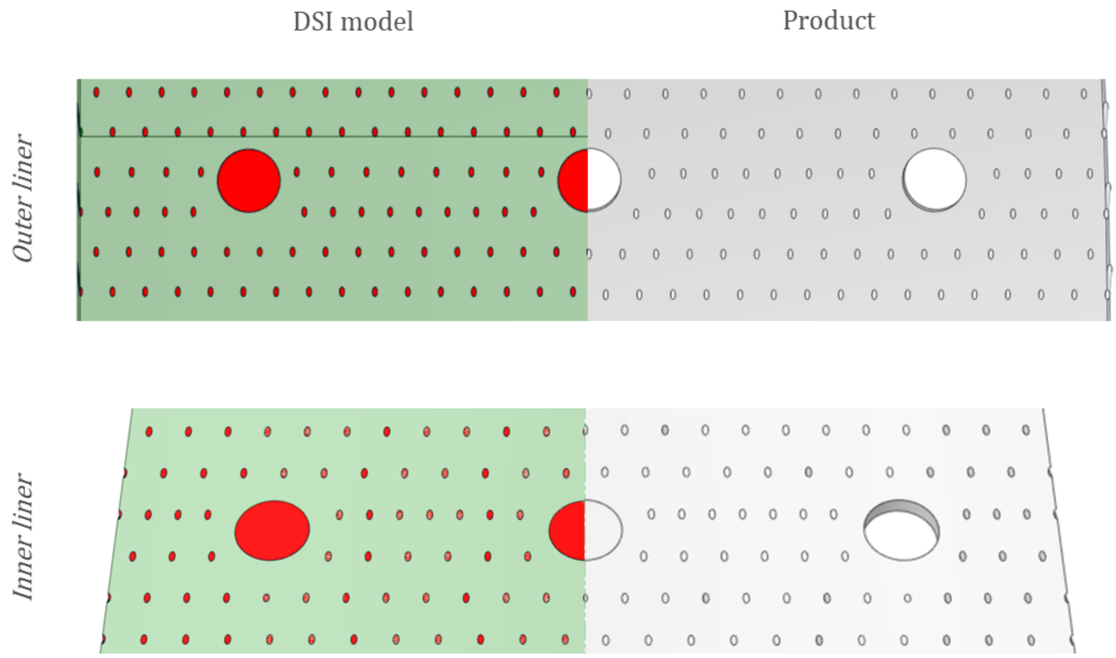


Figure 3.9 - Arrangement of holes on liners' location: comparison between DSI modelling and product specification

fact to replicate the cooling solutions which reflect the design choices originally made by the designer, which were defined by means of an iterative, user-driver design process. In Figure 3.9 it is compared, for the outer and the inner liners, the configuration of the product, on the right side, and the results of the DSI procedure, on the left. To this end, the CAD tool has been provided with the set of input specific of the product, which corresponds to the 1D cooling configuration designed through the Therm-1D procedure. It can be noticed that for all the cooling rows affected by a correction of pattern, the configuration proposed by the DSI results to be able in reproducing the reference pattern with a high level of accurately. The errors made by the cooling generation procedure are affecting only a limited subset of cooling holes and are materializing exclusively for the tangential relative positioning with a maximum value of 5% on the corresponding geometrical features. By taking advantage of this results, while keep considering as threshold for accuracy acceptance the error which a typical manufacturing process as the laser drilling (which can run up to 20%) may materialize on the holing generation, the correct functionality of the logics devised and implemented in the CAD tool can be verified. These settings, as already described in Subsection 2.2.1, were conceived based on legacy cooling solutions and developed considering further geometrical considerations and literature studies.

The main purpose of the CFD tool is instead to simulate the gas and fluid dynamic behavior of the combustion system within a certain range of confidence, it is therefore necessary to assess the consistency of the numerical models and to estimate their ability to reproduce the complex mechanisms occurring in the real combustor. In analogy to what was done for the cad tool, a direct comparison between the DSI model and the product configuration is the criteria adopted to conduct the assessment. To this end, the numerical results have been confronted with the data from test cell for the aero-thermal end emission parameters: these quantities are indeed accounting for the performance of the system, being used as drivers during the baseline design of the product and its optimization as well. In Figure 3.10 the Profile and Pattern Factors from the simulation process and the experimental campaign are set against each other, with the intent to highlight the deviations between the temperature distribution at the exit of the combustor. The prediction of these parameters through RANS leads to slightly different values, where the maximum error can be found at 95% of the span (-0.11 PrF*k and -0.13 PF*k, where k is a constant multiplier in the range 0 to 1). The minimum error is +0.02 Prf*k and less than +0.01 for PF*k, located at 55% and 25% of the span, respectively. For the pollutant emissions, an additional calculation was conducted to evaluate CO and NOx levels.

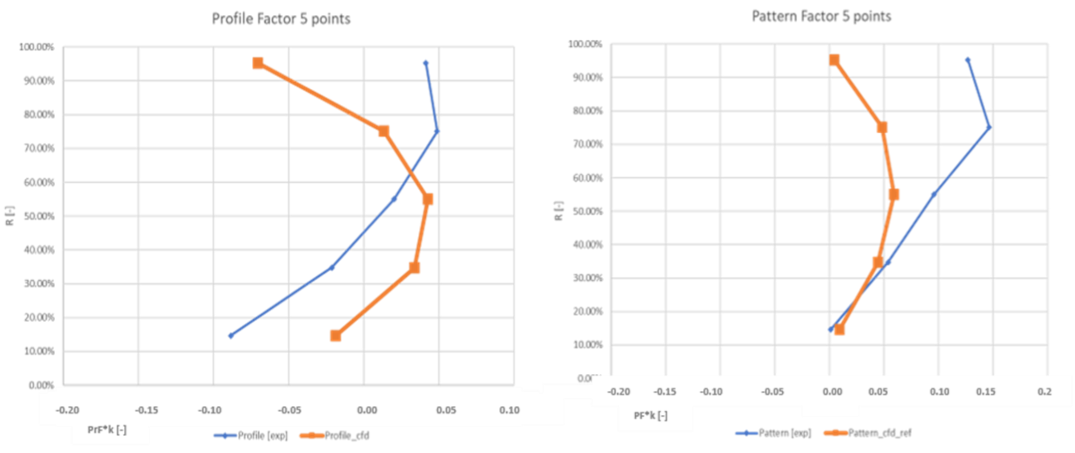


Figure 3.10 – Comparison of Profile and Pattern Factors: DSI model (orange) VS test cell data (blue)

CO estimation is embedded in the combustion model if a PDF and mixture properties are given, NOx evaluation required a dedicated NOx model with turbulence interaction to be set. As expected, predictions of Emission Index (EI) for CO were underestimated compared to the experimental data. On the contrary, EI of NOx shows a good agreement with an error under 5%. It can be concluded that despite the resulting discrepancies, the level of accuracy can be considered sufficient to tackle the preliminary analysis phase. In fact, on the basis of a more extensive set of simulations of other cycle points, it was possible to verify that although the shapes of the profiles cannot be accurately captured, they generally tend to follow the trend of the experimental data: the maximum temperatures rise equally, the curvature of the profiles in the DSI generally tends to follow the trend of the experimental results. The level of representativeness achieved by the CFD of the DSI was therefore deemed sufficient for analysis in the context of preliminary combustor designs.

3.3.2 Resources

To assess the extent to which the measures introduced in the design workflow have contributed to reducing the resources required for the preliminary evaluation process of a combustor, the results of the Metric-Based Process Mapping are presented in the following. The reference configuration adopted to calculate the percentages of time-savings is NEWAC combustor, which figures were nevertheless reconfirmed by other products processed through the DSI procedure. This have made it possible to validate the generality of the approach and the accuracy of the values obtained, that are going to be discussed in the following for each step with reference to Table 3.1 for two cases: the “new design”, which includes the generations of the DSI models starting from scratch, and the “design iteration”, in which modifications of different magnitude are applied to already existing DSI models.

From an analysis of the baseline CAD process, this step was characterized by complex and time-consuming operations aimed at arranging the cooling holes on liners. This task represented almost 35% of the overall time, that in addition to the definition of the cooling pattern and the geometry export for the downstream activ-

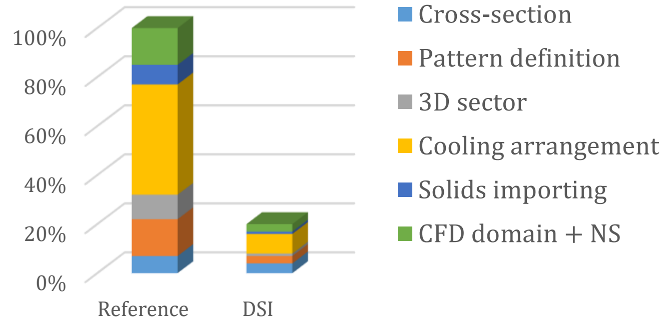
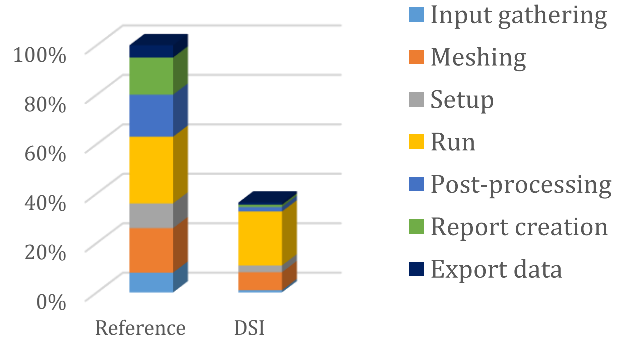
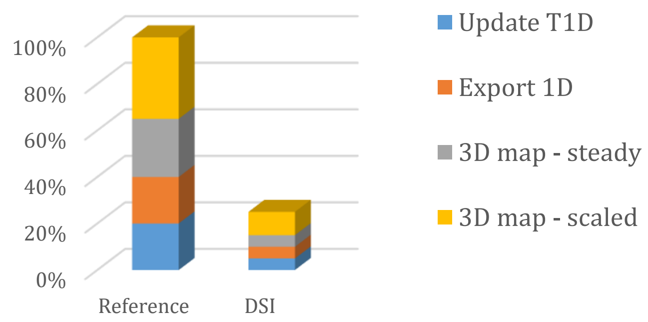
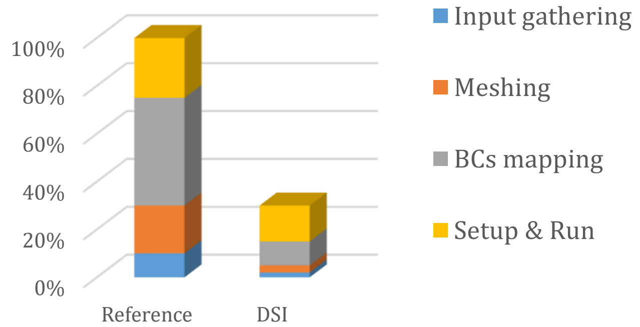
Step	Histogram	Iteration	New
CAD		-85%	-60%
CFD		-65%	-50%
Th-BCs		-80%	-60%
FEA		-70%	-50%
Complete design loop		-75%	-60%

Table 3.1 - Saving of temporal resources by designing with the DSI, result of MBPM evaluation

ities leads to an overall value of 70%. The solutions introduced within the DSI allowed a reduction of the time required for creating the geometry up to -60% for new design and to -85% for a design iteration. The CFD step was instead affected by the difficulty in linking the CAD geometry to the mesh and simulation process. This is a problem that traditionally affects integrated design procedures, which can be addressed by a proper generation and a consistent management of the model's information throughout the design workflow. The logics conceived into the DSI were based on a feature recognition-based method, which allowed to keep coherence until the post-process step thus streamlining this part of the analysis as well. This led to an overall reduction of -50% for a new design and -65% on a design iteration. Despite these figures may seem lower than those obtained for the CAD process, it is worth noting that the mesh and simulation steps represent about 40% of the overall time, which means that that the manual operations have been reduced up to -90% if the DSI process is compared to the traditional one. Concerning the Th-BCs processing, the steps intended to prepare the input from the 1D cooling design tool and to generate the maps of thermal data represented the largest contribution in terms of resource utilization. Two measures have been introduced by the DSI to this end: first, it has been developed a translation tool for the preprocessing of 1D information; then, rules and best practices for the map generation that were located in different spreadsheets and files have been collected and implemented in a common tool with a GUI. This resulted in a -60% for a new design and -80% for a redesign. Like the CFD simulation step, also the FEA process was subject to the manual and repetitive activities needed to prepare the geometrical model for the meshing and finite element analysis. This case was also complicated by the direct mapping boundary conditions of different nature and the application of loads and constraints, which were addressed through automated routines that helped achieving -50% on a new design and -70% on a design iteration.

Overall, it can be said that by using the procedure, the resources can be globally reduced by 60% for a "new design" activity and by up to 75% for a "re-design/re-run iteration". This estimation has been made on the basis of the relative weight that each of the design steps have on the overall process. An additional contribution to the targeted improvements applied at tool level has been given by the general rationalization of information across the whole process, an objective pursued via the standardization of the exchange files used by the procedure: this means not only a shorter time frame for the design loop but also a more reliable process, results in more resources being available for the design space exploration.

Chapter 4. Combustor DSI applied to design optimization

Upon arriving at this point in the discussion, it is possible to prove how the development process of combustors products could benefit from the adoption of integrated design suites. The relevance in standardizing the design process has been addressed in Chapter 2, in which the description of DSI and COS workflows has also drawn the attention to ensuring an integrated and interconnected framework. Then, in Chapter 3, the methodological approach exploited by the DSI tools in carrying out the simulative process has been described. In this chapter, instead, these tools will be embedded in the COS structure in order to perform a multi-objective optimization, by leveraging on a joint operation of these procedures. It will be presented the test-case selected to support this activity, thus moving through the steps in which the optimization process has been defined and unfolds. By presenting the resulting optimized design, it will be finally possible to make some considerations on the advantages brough by a full-automated and water-tight approach, in comparison with the user-defined and trial-and-error baseline process.

4.1 Test case: LEM-RQL concept

The LEMCOTEC Rich-Quench-Lean, briefly LEM-RQL, is the combustor concept provided for the purpose of this activity. Its design has been originally retrieved from the LEMCOTEC combustion system, developed and tested by *Avio Aero - a GE Aviation Business* (formerly *Avio*) in the context of the European research project for Low EMission COre-engine TEChnologies [78]. The LEMCOTEC prototype consisted in a full, single-annular system in which the control of emission levels was achieved through the development of a lean combustion. By analogy with NEWAC combustor of Section 3.1, working in a narrow range of flame temperature and local equivalence ratio allowed the NOx and soot formation to be limited. Unlike such concept, however, dilution holes were not present, and the control of exit temperature profiles was thus demanded to the aerodynamics of the PERM burner.

The LEM-RQL combustor, instead, has been designed to work as a rich-burn system, featuring a quenching module operating in the chamber region and an injection system defining the behavior of the primary zone. The transition from LDI to a RQL technology has been managed through a redesign activity of the LEMCOTEC concept itself, in which operating conditions and construction constraints have been

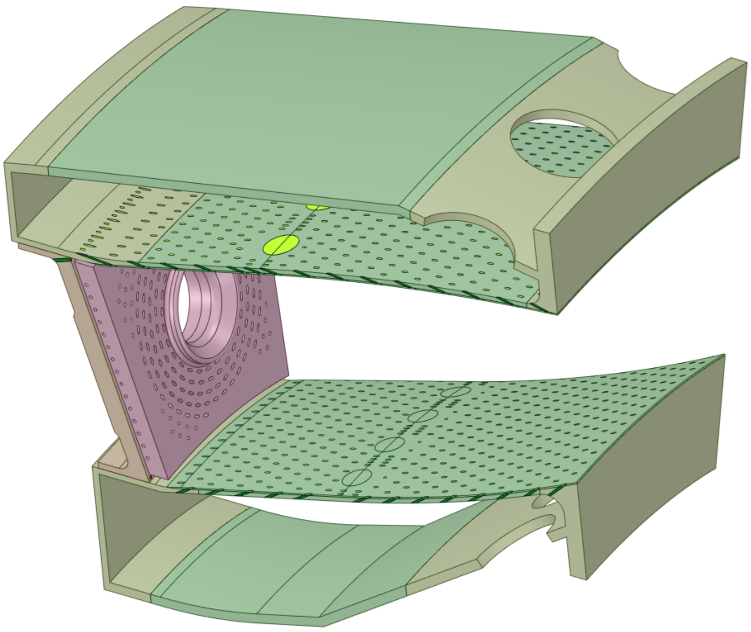


Figure 4.1 - Single sector of the LEM-RQL combustor concept

kept constant. Aspects as volume of the chamber, shape of the flame-tube and number of injectors (20, leading to a sector extension of 18°) have been here revised to comply with the set of functional requirements induced by the rich-burn functioning. The internal flow split has been redefined with the same intent, making it possible to size air passages through the different combustor regions.

As it can be noticed from Figure 4.1, the LEM-RQL is still defined as a single-wall combustor in straight-through configuration. The injection device, which cannot be disclosed for reasons of procedural confidentiality, is a fuel-staged system with a double radial and co-rotating configuration, aimed at promoting the conditions for flame stabilization. In order to be housed in the dome plate, a different mechanical arrangement is proposed for this latter, which is also equipped with a double-wall cooled heat shield to provide protection from high temperatures. Two rings of purging holes are arranged upon the dome borders, at tip and hub locations respectively, to provide a starter film covering effect in the very early section of the liners. These last components, intended to be realized in specific metallic materials, are featuring a Thermal Barrier Coating (TBC) full coverage to prevent damage from peak heat loads. A multi-hole cooling system is arranged over the whole liners to keep the parts under acceptable thermal limits, while a single row of cylindrical dilution ports is defined to control the reactive process, so that a rapid quenching of the mixture can be ensured.

A summary of the most relevant characteristics for the LEM-RQL concept is reported in Table 4.1 and Table 4.2. The reference operative condition considered is an ICAO Maximum Take-Off (MTO), which led to a global air split definition prevailing on liners locations, i.e. $\simeq$25% dome and injection is $\simeq$75% cooling and dilution. The corresponding arrangement for effusion and dilution holes can be expressed though a non-dimensional quantity for tangential and axial directions (tg and ax respectively) as a ratio between the pitch and the hole diameter P/D both for the inner inn and the outer out liners, referred as inn and out subscripts. This redesign phase allowed to derive the complete set of information defining a conceptual design, thus a preliminary baseline combustor can be processed through the

DSI tools in order to evaluate its performance and, subsequently, initialize a design optimization activity based on specific product's CTQs.

Operative conditions (Reference Design Point)		
ICAO Maximum Take-Off		
Internal flow split		
Dome	Injector, Dome cooling and Starting slot cooling	26.4%
Outer liner	Effusion cooling and Dilution	29.9%
Outer liner	Effusion cooling and Dilution	43.7%

Table 4.1 – Summary of the aerodynamic characteristics of the LEM-RQL

General characteristics		
Combustion technology	Rich burn – Quick Quench – Lean Burn (RQL)	
Layout	Straight through	
Injector	#20 double radial, co-rotating system (fuel staged)	
Dome	Metal plate with double-wall cooled heat shield	
Liners	Metal plates with TBC, start slot and effusion cooling	
Holes definition for liners		
Outer effusion	$P_{tg}/D_{eff_{out}} = 6.8$	$P_{ax}/P_{tg} = 1.3$
Inner effusion	$P_{tg}/D_{eff_{inn}} = 7.3$	$P_{ax}/P_{tg} = 1.1$
Outer dilution	$P_{tg}/D_{dil_{out}} = 2.1$	
Inner dilution	$P_{tg}/D_{dil_{inn}} = 1.9$	

Table 4.2 – Summary of the geometrical characteristics for the LEM-RQL

4.1.1 DSI physical numerical model

If the DSI methodology in featuring the physical numerical models is standard and follows the description of the NEWAC combustor at Section 0, it is worth to discuss the requirements which arises from the enablement of a full-integrated and water-tight process within the optimization framework. In this preliminary step, indeed, numerical results of the LEM-RQL combustor are only providing a performance's evaluation of the design baseline. Instead, to verify the robustness and the minimum-resources-consumption of the related DSI models is crucial for ensuring a proper running of the tools within the design loops, as well as a time-and-computational cost aligned with availability of design resources. Given the intent of the upcoming design optimization activity, the LEM-RQL combustor has been modelled through the DSI tools for CAD generation and CFD analysis, by following the processes reported in Section3.2.

The reference geometrical model is shown in Figure 4.2-a. It is a 18° single-sector representative of the annular combustor periodicity. Wall geometries were traced out from concept design specifications, while the liner's aero features were specified through the dedicated Excel template, in which all of the information related to the liner's holes' definition (i.e. number, dimension and impact angle for cooling and dilution holes, as well as minimum distance between hole features) are collected. External parts and model interfaces were then extracted from the original Parasolid, in order to generate the 3D exportable model of this configuration. It was possible to solve the patterning issue of effusion holes across the dilution area automatically, exploiting the specific tool's capabilities and providing a dedicated tuning of the advanced holes' arrangement settings. The corresponding fluid volume of Figure 4.2-b was obtained from both a domain's limitation, in order to restrict the simulation efforts exclusively to the regions of interest, and a defeaturing of the geometrical details which may lead to a dummy increase of mesh nodes. Furthermore,

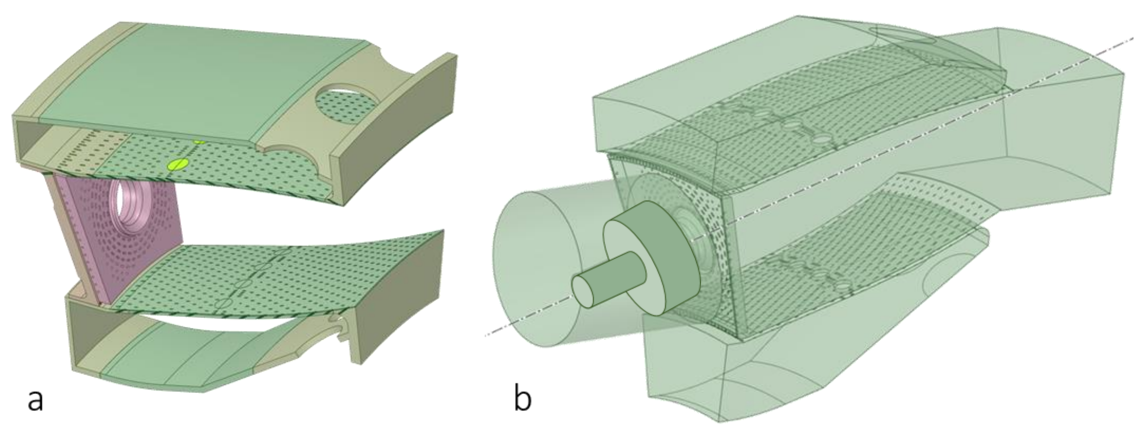


Figure 4.2 – DSI exportable CAD model (a) and fluid volume (b) of the LEM-RQL combustor

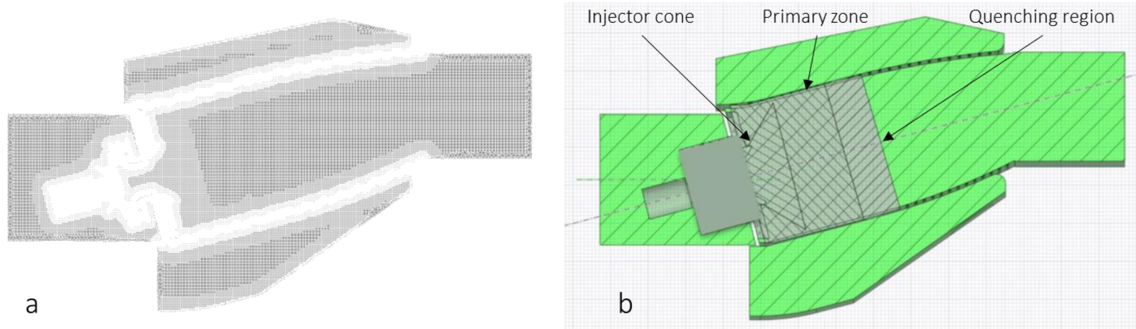


Figure 4.3 – Depiction of the resulting mesh for CFD analysis (a) and the model's Bodies of Influence (b)

standard named selections were provided to keep the consistency of information between the ready-to-mesh numerical domain and the requirements of the RANS numerical approach.

For this specific design, the robustness of the CAD generation process has been assessed by processing a set of LEM-RQL configurations (20 designs), to which a variation to the dimensions and the pattern of dilution ports is proposed. All of the configurations have been successfully processed from the holes' specification step to the CFD fluid-volume exporting, with holes' patterning in compliance with both the constructive and simulation requirements.

The model for CFD simulation was set up in accordance with the practices already presented in Paragraph 2.2.2, dedicated at managing a 3D RANS reacting flow calculation without conjugate heat transfer in Ansys Fluent. In analogy with the NEWAC numerical model preparation, a mesh sensitivity analysis was carried out through a Richardson extrapolation approach. An optimal grid resolution was defined by evaluating three different mesh strategies (tetrahedral, polyhedral and poly-hexcore) and for three global mesh sizing: 8×10^{-4} m, 4×10^{-4} m and 2×10^{-4} m. The resulting computational domain is depicted in Figure 4.3-a and resulted in a ≃55M elements (4×10^{-4} m global sizing), poly-hexcore mesh whit standard local siz*000*ing aimed at maintaining the y^+ levels in the range of 30-100 as requested by k-ε turbulence theory. Furthermore, the three BOIs represented in Figure 4.3-b were proposed to ensure a minimal local numerical dissipation and sufficient grid resolution.

This last study has also allowed a trade-off between model's representativeness and computational costs to be performed, by taking into account both the different mesh strategies and the mesh global sizes. According to a total amount of 200 CPUs, the selected meshing setup has made possible to perform an entire CFD process (from volume's meshing to result's post-processing) in about 70h, and up to

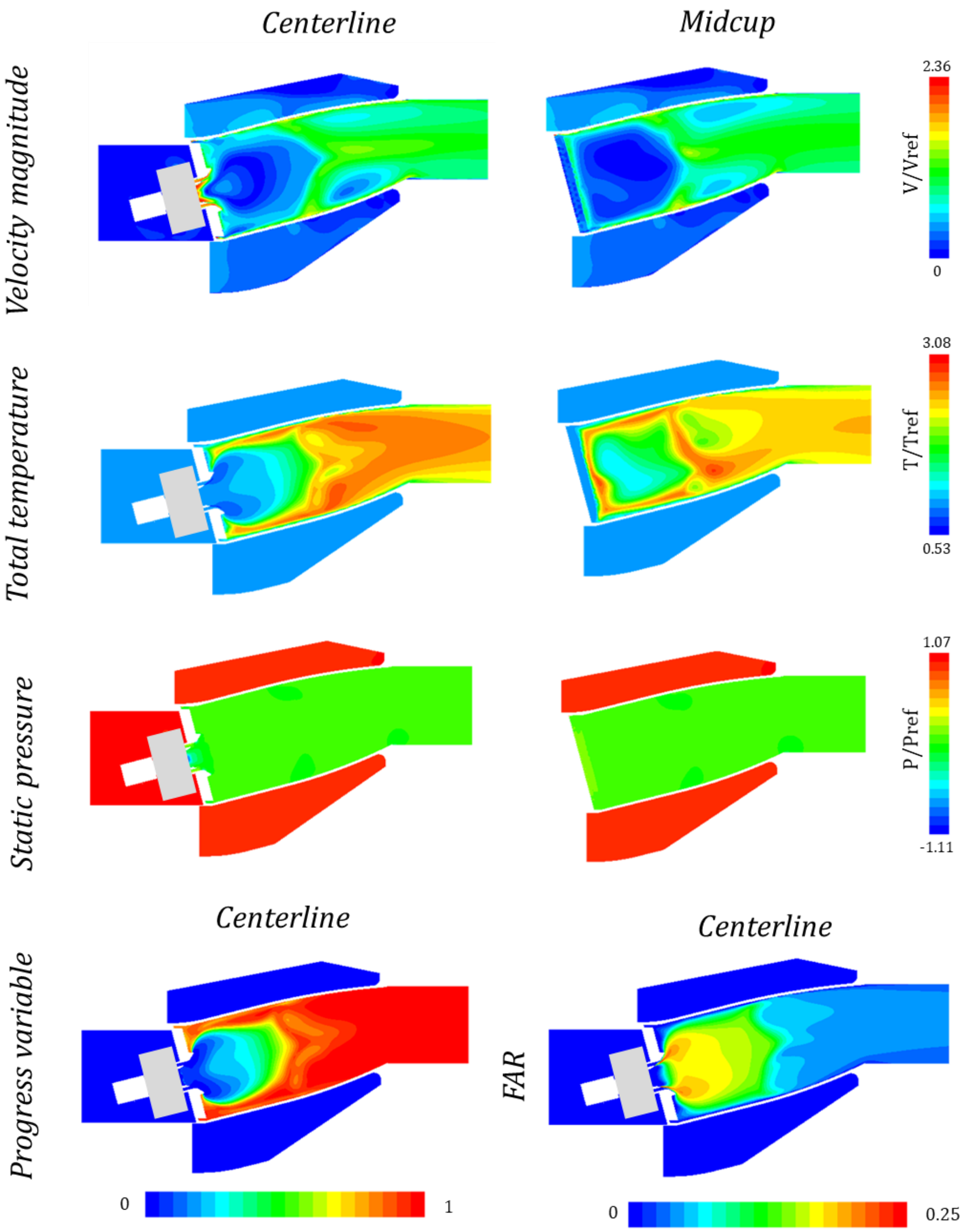


Figure 4.4 - Contour maps of the most relevant physical quantities for the LEM-RQL baseline design

30h starting from an interpolated solution. The Fluent journal file generated through the DSI tool for CFD analysis also ensures the robustness of the overall simulation step. Here, model's best practices and run setups are collected with few local modifications aimed at integrating the process into the optimization workflow.

The contour plots of Figure 4.4, resulting from the execution of this standard Fluent journal and presented as non-dimensional quantities, are showing the most relevant physical quantities for both the chamber's centerline and mid-cup regions. These exported maps allow to describe, at least qualitatively, the overall aero-thermal behavior of the LEM-RQL baseline model, as well as the development of the reactive process within its flame-tube. The velocity magnitude plots are presenting an internal aero-dynamic field typical of a RQL combustor. A recirculating structure can be indeed noticed in the primary zone, resulting from the development of the swirling flow promoted by the injector. As it might be seen from the temperature and progress variable maps, this defines the conditions for the stabilization of the flame, by providing both high turbulence levels near to the injector's lips and massive recirculation of hot gases at the swirling flow's core region. The rich mixture leading this zone (see the FAR contour plot) is diluted by the air jets generated from the dilution ports: a rapid mixing is here ensured by a crossflow development of these high speed, penetrating fluid structures. Besides the holes' geometry and the relative position of the dilution rows, the quenching process of the flame is driven by the pressure drops across the liners, which may be seen from the pressure levels of the absolute pressure maps and in the summary of Table 4.3. These values, expressed as a percentage of pressure drop, are calculated by a collection of static-and-total values for specific pressure taps stations; a comparison between the CFD model and the one-dimensional FNS design tool it is also possible, resulting in a maximum discrepancy of about 5% which is acceptable for the intent of this study. Downstream of the quenching region, the combustion goes towards its fulfillment with a flow field strongly influenced by the mutual interaction between the quenching jets. The reactive process turns out to be slow and incomplete in the primary zone, hence the formation of CO emissions is substantial, reaching its maximum peak upon completion of the primary zone where the values of progress variable are high. On the other side, the lean zone is characterized by the exhaust gases at high temperatures near stoichiometric conditions next to the outlet plane of the combustor, where most of the NO formation mechanisms have been activated, as shown in the mass fraction NO contour plot.

	Outer liner	Inner liner	Injector	Combustor
dp/p, total	3.54%	3.43%	3.71%	3.59%
dp/p, static	3.43%	3.42%	3.78%	3.99%

Table 4.3 - Pressure drops levels across combustor's main locations, for total and static values

It is worth to present and discuss the results of temperature and emission levels at combustor's exit, quantities which will be driving the design optimization study of this work. Briefly, not uniform temperature distributions can be noticed from both the contour maps of Figure 4.5-a, showing a hot spot in the central location of the outer plane, and from the 5-points profiles of Figure 4.5-b. The non-dimensional mass-flow averaged temperatures are reaching values of 2.33 for the average $Tave/Tref$ and a peak of 2.74 for the maximum $Tmax/Tref$. Concerning the pollutant emissions, the EI of CO and NOx are increased by 30% and 45% respectively if compared to LEMCOTEC combustor. Against this background, the LEM-RQL performance are showing significant rooms for improvements, and it will be thus exploited in the following optimization process.

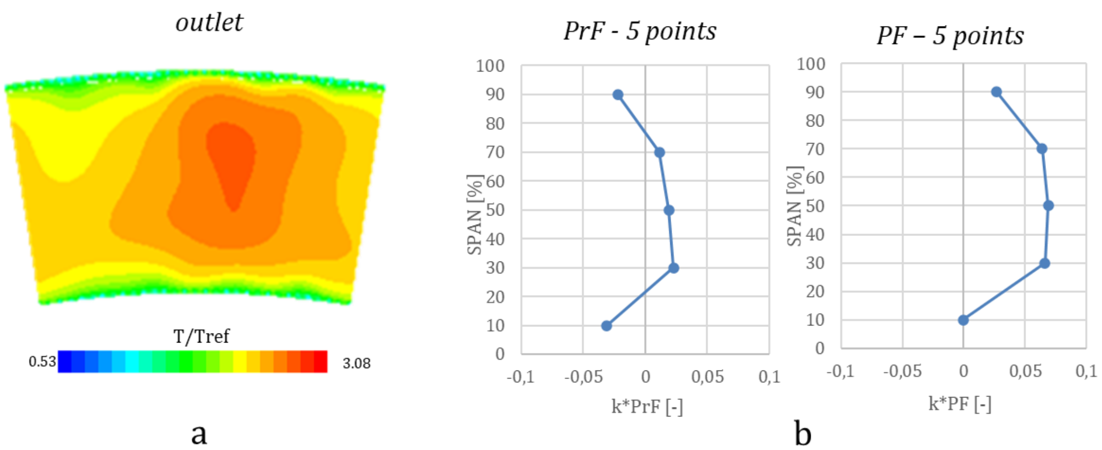


Figure 4.5 - Outlet temperature distribution, presented as contour map (a) and 5-points Prf PF(b)

4.2 COS optimization process

Besides scripts and models developed to establish the optimization framework, the central part of this activity is represented by the definition of the optimization process itself. Ranging from the formulation of a representative design problem up to the selection of an optimal design candidate, the description is organized in three paragraphs which will trace back the main step of implementation. According to the intention of setting up a design workflow driven by the COS procedure, a special mention will be given to the input and output files enabling the optimization study. By the same logic, functions and algorithms aimed at integrating the DSI tools in the design framework will be taken into account, detailing the custom conversion toolkit already presented in Paragraph 2.4.2.

4.2.1 The design optimization problem

It should be clear so far that the quality of combustion process is a crucial aspect for the performance of gas turbine engines. To guarantee optimal functioning of the entire system it is therefore fundamental to have control of the complex phenomenon occurring in the combustor. Aspects such as the turbine's life durability can be related, especially for the first stages, to maximum temperature levels and temperature field distortions reached at the combustor's outlet. The efficiency of the combustion process is a crucial point for emission levels too, where different strategies, not least the dilution area definition, may help in limiting these values. In both contexts, the optimization of the mixing zone represents one of the most relevant drivers for designing this component.

the design optimization problem which will be carried out is based on the dilution mixing efficiency. Dwelling indeed on problem that have been addressed in many studies, the dilution jets are used to oxidize the remaining fuel from the main flame zone and to homogenize the exit-combustor temperature field upstream of the turbine section through highly turbulent mixing, in order to increase the durability of the subsequent turbine vanes, thus avoiding of reaching their melting temperature. In more detail there are two aspects of exit temperature profiles to consider: the average radial temperature profile is critical for the life of first stage rotor blades and the maximum spatial temperature which could lead to the stress and erosion of the turbine inlet guide vanes. Accordingly, the arrangement and configuration of the dilution holes are relevant. Combustors continue to shorten in length, potentially positioning dilution jets closer to the downstream vanes. As an instance, shifted dilution hole pattern for two positions show that the large dilution jets, located directly upstream of a turbine cascade, have a significant impact on the magnitude and orientation of the flow entering the turbine, as demonstrated by the Particle Image Velocimetry (PIV) study in [63]. As regards to a reverse flow gas turbine combustor, conventional radially injected dilution jets couldn't effectively mix out circumferential non-uniformities of the flow, for which it is widely used another dilution holes concept: dilution air jets deflected with a high circumferential component and angled in the opposite directions between outer and inner liner have the key task of producing a high swirl velocity component and enhancing circumferential mixing. In the work of Crocker et al.[79], the result of the CFD campaign shows that this concept has the potential for reducing pattern factor as much as 60 %, compared to the baseline dilution hole configuration, but also thanks to the increase of the dilution mass flow split (percent) from the outer liner. Besides, adding one more dowel, the staggered configuration (compared to in-line concept) allows a more circumferential exit temperature profile while leading to a higher pattern factor. Nevertheless, by means of CFD simulations it is possible to prove an improvement of the mixing process due both to the jets' mutual interaction and to the filling of the "dilution-to-dilution" gaps [80]. Another preliminary design methodology has enabled to define a reverse flow combustor configuration to be manufactured and tested: exit temperature, maximum temperature, pattern factor and pressure losses are plotted at different equivalence ratio to evaluate the combustor's performances at different design points, both in design and in off-design conditions[81]; the prediction of the mixing performances (pattern factor, profile factor, exit temperature profile) was carried out by assessing the interaction between swirling flow and primary/dilution jets in a specific range of Fuel-Air Ratio (FAR): under the identical air conditions, the FAR variation doesn't involve any substantial difference in the mixing performances.

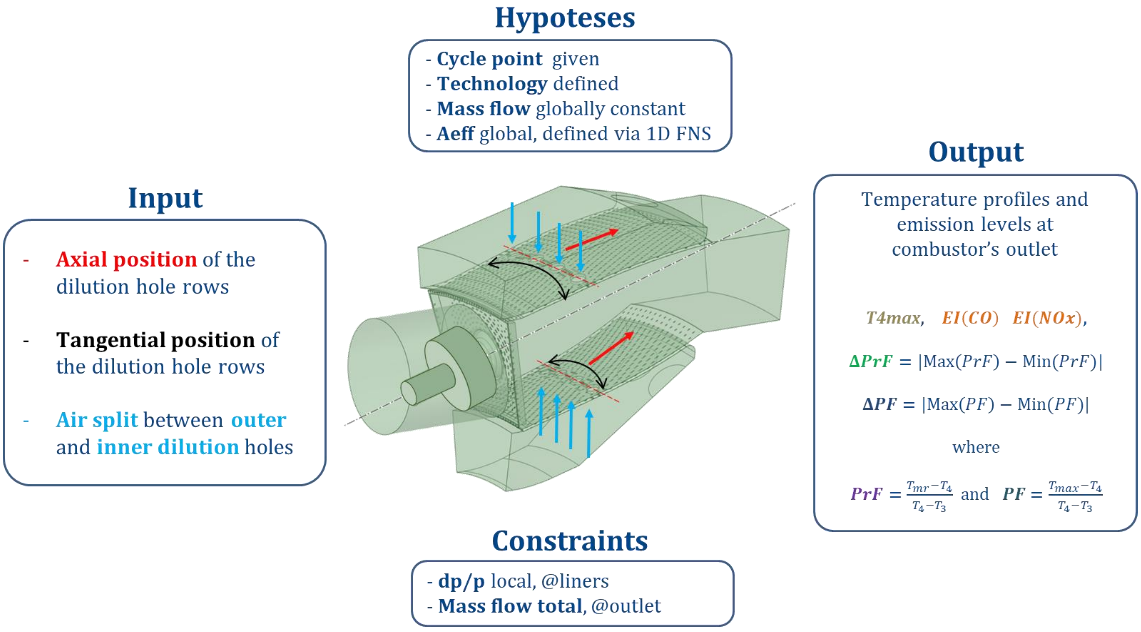


Figure 4.6 - The design optimization problem

The design problem presented for the LEM-RQL combustor is summarized in the iconographic of Figure 4.6. By referring to combustor's emission levels and temperature distributions at its exit, the following five objectives have been set:

- $EI(NO)$, as the index of emission for the NOx species;
- $EI(CO)$, as the index of emission for the CO species;
- T_{max} the maximum value of temperature, calculated with a mass-flow averaged approach at combustor's outlet plane;
- $\Delta PrF = \max\ |(PrF) - \text{Min}\ (PrF)|$ Equation 4.1
  as the difference between the maximum and minimum values of PrF, calculated with the 5-point method and expressed in absolute value;
- $\Delta PF = \max\ |(PF) - \text{Min}\ (PF)|$ Equation 4.2
  as the difference between the maximum and minimum values of PF, calculated with the 5-point method and expressed in absolute value.

where, for a baseline representation of 5-points profile and pattern factors, ΔPrF and ΔPF are assuming the meaning reported in Figure 4.7.

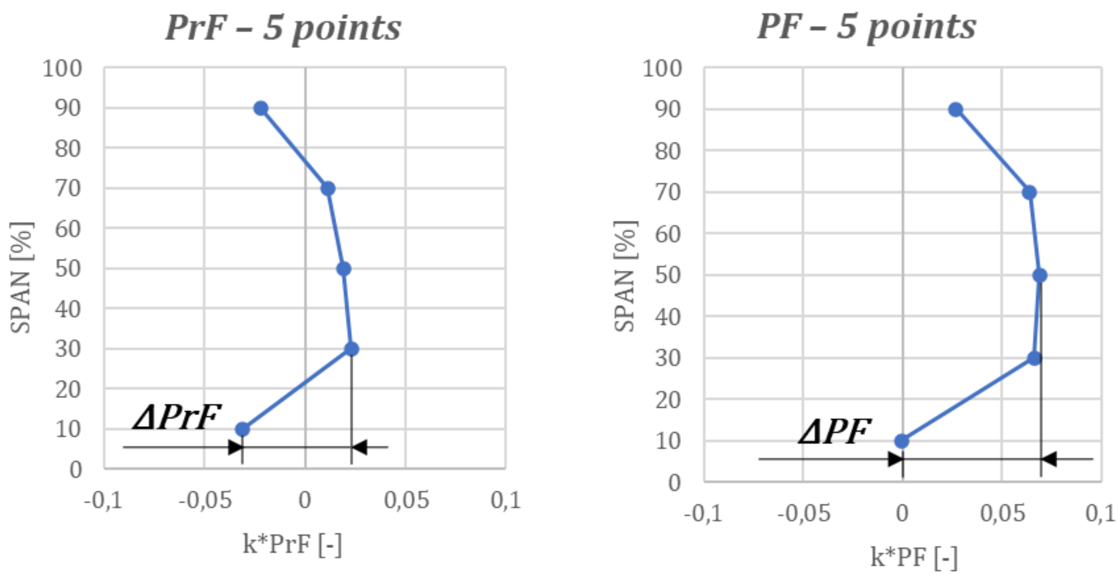


Figure 4.7 - Graphical representation of ΔPrF and ΔPF

This set of parameters is referred to as the Optimization Factors (OF) of the system, since in the present optimization problem it can be considered representative of the main aerodynamic-and-emission performance of the combustor.

According to the intention of considering the dilution mixing as the key aspect for analyzing the LEM-RQL concept, up to four linearly independent variables related to the definition of combustor's quenching module have been specified as Degrees Of Freedom (DOF) of the system:

- Axial pitch dS, as the rigid translation of the quenching module along the axial position, taken consistently for the outer and the inner dilution rows and expressed in term of liners' curvilinear abscissa;
- Outer row tangential pitch $P_{tg_{out}}$, as a non-dimensional circumferential pitch of the outer dilution row with respect to the injector axis.
- Inner row tangential pitch $P_{tg_{inn}}$, as a non-dimensional circumferential pitch of the inner dilution row with respect to the injector axis.
- Dilution air split μ, as the distribution of the total quenching mass-flow between the outer $\dot{m}_{dil_{out}}$ and inner $\dot{m}_{dil_{inn}}$ dilution ports, expressed in term of ratio as reported in Equation 4.3

$$\mu = {\dot{m}_{dil_{out}}}\big/{\dot{m}_{dil_{inn}}} \qquad \text{Equation 4.3}$$

In their formulation, constraints are specified to narrow the plethora of possible design candidates to a subset of solution respecting specific requirements. These, expressed in terms of performance checks, are acting as filters for the design candidates not compliant with design requirements: i.e., pressure drops across combustor locations and mass-flow balance at its exit. Problem hypotheses are set as well to regulate the condition under which design candidates must be generated while building up the design database. Basically, they provide the standards to create-and-simulate combustor's models during the optimization stud in terms of technology adopted, reference cycle point and most importantly the aerodynamic characteristics of the combustor.

The last step for initializing the optimization activity is the definition of a suitable design space. To focus the study on a multi-dimensional range of interest, indeed, it is widespread practice to set a maximum and minimum value for each of the system's DOF. The set of 20 combustor configurations generated to ensure the robustness of the DSI process have been considered to support this task. Through a preliminary sensitivity analysis based on common technique for data reduction [82], it has been possible to identify the main correlation between output and input parameters, and hence to derive both the range and the number of DOFs to be effectively consider in this study.

	Initial range		Optimization range	
Degree of Freedom	Lower bound	Upper bound	Lower bound	Upper bound
dS [mm]	0.00	32.80	9.00	18.00
$P_{tg_{out}}$ [-]	-0.50	0.50	-0.50	-0.50
$P_{tg_{inn}}$ [-]	-0.50	0.50	-0.50	0.50
μ [-]	0.80	2.20	1.35	1.65

Table 4.4 - Design space definition for the LEM-RQL dilution mixing problem

Table 4.4 is reporting the bounding for the initial design space, which is defined by the 20 initial combustor configurations, together with the range to be analyzed in the design optimization activity. By adopting the performances of the LEM-RQL baseline configuration as a constraint to the initial range, the optimization design space has been defined as the subset of the initial range in which the performances of the simulated configuration were providing better results in terms of output parameters. As a result, the ranges of dS and μ have been limited to maximize the system's response. $P_{tg_{out}}$, instead, has been set to a fixed value since given its loose influence on the output factors. These aspects will be deepened in Paragraph 4.3.1, where a wider discussion over parameter sensitivity is addressed.

With reference to the COS procedure, this information defines the groundwork of the optimization process. The DOFs to be used and the ranges to be considered in the study are specified through a dedicated support file included in the "PARAMETERS" step. The parameters are then ready to be processed into the next task: the design space sampling. Among the algorithms made available by the procedure (see Chapter 2.3), the Sobol sequence has demonstrated to be the more effective in generating a quasi-random, uniform distribution of samples when the number of configurations to be evaluated is relatively low, as in the case of the presented optimization study. For each design space sample, the set of DOF values is defining a Design Point (DP) to be analyzed. The collection of DPs, in turn, constitutes the step of optimization to be performed.

4.2.2 Creation of the database

For the present study, up to 20 of the 100 different samples generated with the Sobol algorithm have been considered to support the optimization activity. The resulting DPs have been iteratively processed by the COS procedure through the embedded DSI tools. In order to water-tight the process and so to enable such an integrated design workflow, it has been taken advantage of the conversion toolkit presented in Paragraph 2.4.2. A continuous and coherent communication between the two procedures has been ensured by implementing the functions and scripts reported in the following, which are peculiar of the dilution mixing design problem.

For the sake of simplicity, the set of operations provided for the pre and post processing operation are summarized in *Table 4.5*.

Pre-processing operations		
COS degree of freedom	Conversion function and criteria	DSI input parameter
ΔS	Interpolation over liners' curvilinear abscissa	$(X,Y)_{dil_{out}}$, $(X,Y)_{dil_{inn}}$
$P_{tg_{inn}}$	$\theta_{dil} = P_{tg_{dil}} \dfrac{360°}{N_{dil}}$	$\theta_{out_{dil}}$
μ	$N_{dil_{out}} = cost,\quad N_{dil_{inn}} = cost$ $C_{D_i} = cost,\quad A_{eff_i} = cost$ $D_{dil_i} = 1/2\sqrt{A_{geom}/\pi\, N_{dil}}$	$D_{dil_{out}}$, $D_{dil_{inn}}$
N_{eff_0}	Boolean operations	N'_{eff}
Post-processing operations		
DSI performance factor	Conversion functions and criteria	COS optimization factor
mass-flow averaged $T_{ave}, T_{\max}$ *@outlet, @ 10%, 30%, 50%, 70% 90%span*	$dPrF = \llbracket\lvert Max\rrbracket\ (PrF) - \mathrm{Min}\ (PrF)\rvert$ $PF = \llbracket\lvert Max\rrbracket\ (PF) - \mathrm{Min}\ (PF)\rvert$	$T_{max_{40}} PrF,\ \ dPF$
mass-flow averaged p_{stat}, p_{tot} *@injector, chamber, inner liner, outer liner, outlet*	$\dfrac{dp_i}{p} = \dfrac{p_i - p}{p_i} \cdot 100$	dp/pd *inner liner, outer liner, injector, total*
$w_{CO},\ \ M_{CO}$ w_{NO}, M_{CO}	$EI(i) = \dfrac{w_{s,mean}}{Z_{mean}} \cdot \dfrac{M_{fuel}}{M_i}$	$EI(NO), EI(CO)$

Table 4.5 - Summary of the conversion functions operated in the pre and post processing phases

About the pre-processing phase, the generation of the CAD and the CFD models is enabled through 4 main functions. As from DSI standards, the position of hole rows is expressed in terms of cartesian coordinates (X_0, Y_0). For the outer and inner dilution rows, the starting location over the liners' curvilinear abscissas S_0 are considered, for each liner. Equation *4.4* provides the updated S by adding the dS provided by the DP definition. Through the first function, the (X, Y) values are obtained by a linear interpolation of the abscissa coordinate (Equation *4.5*), in which upper and lower limits to the reference value are reported with subscripts 1 and 2, respectively.

$$S = S_0 + \Delta S \qquad \text{Equation 4.4}$$

$$i = \frac{j - j_2}{j_1 - j_2} \cdot i_1 - \frac{j - j_1}{j_1 - j_2} \cdot i_2 \qquad \text{Equation 4.5}$$

The second one exploits the definition of the non-dimensional tangential pitch of Equation 4.6 to calculate the relative angular position between the dilution row and the injector's axis θ_{dil}:

$$\theta_{dil} = P_{tg_{dil}} \frac{360°}{N_{dil}} \qquad \text{Equation 4.6}$$

Given the definition of μ, the third function is dedicated at managing the mutual dependency existing between mass-flow and holes diameter at dilution ports. By relying on the following hypotheses

- Fixed number of dilution holes N_{dil};
- Constant $\frac{dp}{d}$ through liner location;
- Given global discharge coefficients C_D and effective areas A_{eff};

Where C_D and A_{eff} are already defined in Equation 1.1 and Equation 1.2, bringing the calculation of the dilution diameter to be simplified:

$$D_{dil} = \frac{1}{2} \sqrt{A_{geom} / \pi \, N_{dil}} \qquad \text{Equation 4.7}$$

The last function is formulated to optimize the number of effusion holes in the dilution row location, in order to help the DSI process in complying with constraints of holes minimum distances. It is composed of a set of Boolean operators aimed at identifying the cooling rows potentially impacted by dilution features, so that an update to the effusion hole numbering N_{eff} can be provided.

The management of the post-processing phase, instead, is fairly straightforward. Here, quantities of interest resulting from the simulation of DPs are elaborated to generate a database for the system's response. Up to 3 main functions are made available to the python script for post elaboration, implementing the calculation of the temperature profiles variations ΔPrF and ΔPF, the pressure drops across main combustor's locations (Equation 1.4) and the emission indexes for NO and CO species (Equation 1.11). In this way, the performance factors of the DSI procedure can be converted in OF of the optimization process.

The creation of the database has been completely performed through the COS procedure in its "CALCULATION" step, resulting in an integrated and full-automated simulation process. All the 20 DPs have been generated correctly, respecting both the requirements for being processed through the DSI tools and the manufacturability constraints related to minimum distance and collision problems between the hole features of liners locations. Such conditions are thereby confirming a proper implementation of the presented conversion functions. In terms of resources, the lead time to generate this simulation database stands at around 25 days. For the CAD generation process, about 1 hour is required on 4 CPUs; instead, the CFD process performed on 240 CPUs led to an overall simulation time of about 30 hours.

4.2.3 Metamodeling and optimization

The collection of results obtained in the simulation phase provides the dataset for creating a surrogate model representative of the combustor's functioning. As already mentioned in Section 2.3, the COS procedure takes advantage of Artificial Neural Networks (ANNs) for emulating the behavior of the system, a condition achieved through a training phase in which input-and-output are related within the algorithm. Given the optimization factors to be considered in the optimization problem, a neural network (NN) is trained for each the OF by considering all the system's

DOFs as input. The metamodel for the prediction of the overall system's response is then implemented as an ensemble of networks, by providing a weighted average of the single resulting models. In order to ensure its consistency, the normal practice consists in assigning the same structure to all the NNs [83]. This leads the design process of the network to be a central aspect in the definition of the surrogate model. The number of hidden layers, as well as the number of nodes which compose them, are of crucial importance for model's performance and requirements.

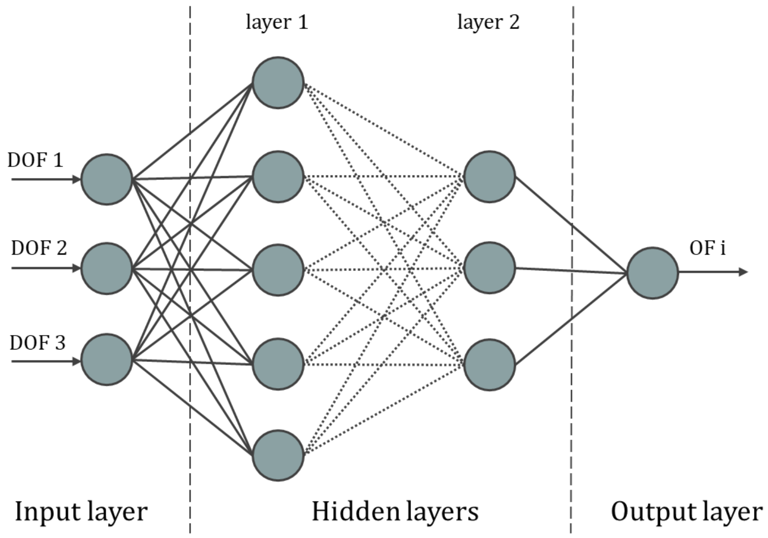


Figure 4.8 - Baseline structure of the NN

For the specific problem, 4 different networks have been combined in order to build up the LEM-RQL combustor metamodel: two are considering the temperature profile responses ΔPrF and ΔPF, while the other two are concerning the emission levels $EI(NO)$ and $EI(CO)$. By means of preliminary sensitivity studies aimed at assessing the baseline structure of the NN, the most promising arrangement for the network's layouts has been defied. As shown in Figure 4.8, for each OF defining the output layer there are 3 input nodes corresponding to system's DOFs; the hidden part is structured in two layers made of 5 and 3 nodes respectively. Given the relatively small number of DPs populating the database, this arrangement has shown the best trade-off between networks' convergence and accuracy conditions. For this structure, indeed, a limited number of iterations (about 600) are required to train an ANN able at returning a maximum error of 0.5%, detected on OF. By these considerations, the metamodel designed to support this optimization study can be considered acceptable. To corroborate this finding, it will be shown later in the discussion the result of a cross validation check provided for the optimized design candidates.

Parameter	Type	Action	Value
ΔPrF	Objective	Minimize	-
ΔPF	Objective	Minimize	-
$EI(NO)$	Objective	Minimize	-
$EI(CO)$	Objective	Minimize	-
$\frac{dp}{p}$ Outer liner	Constrain	Range	3.43% ±0.05%
$\frac{dp}{p}$ Inner liner	Constrain	Range	3.42% ±0.05%
$\frac{dp}{p}$ Injector	Constrain	Range	3.78% ±0.05%
$\frac{dp}{p}$ Combustor	Constrain	Range	3.99% ±0.05%
$Tmax/Tref$	Constrain	Threshold	< 2.740
$k \cdot \Delta PrF$	Constrain	Threshold	< 0.043
$k \cdot \Delta PF$	Constrain	Threshold	< 0.062
$k \cdot EI(NO)$	Constrain	Threshold	< 11.007
$k \cdot EI(CO)$	Constrain	Threshold	< 33.148

Table 4.6 - Setup for the LEM-RQL dilution mixing, multi-objective optimization problem

Response surfaces of the system have been generated by means of multiple surrogate solution. The resulting models, obtained through a set of random configurations processed with the described ANN, can be used both for predicting the behavior of the combustor and deriving a suitable configuration based on its performance. It is precisely on this aspect that metamodel-based, design optimization approaches leverage. First, a set of conditions should be expressed in order to initialize the design optimization step. As it is common in modern engineering problems, the parameters required to be minimized/maximized in order to fulfill product's requirements are several. Very often, as in this case, such multiple objectives are in mutual conflict, leading the optimization problem to have no closed, univocal solutions. In order to ease the optimization process, it is common practice to constrain the space of possible solutions by limiting it to ranges and threshold of validity. In the LEM-RQL study, the 4 OFs selected for training the metamodels have been set as design objectives to be minimized: ΔPrF, ΔPF, $EI(NO)$ and $EI(CO)$. The overall response surface has been limited to the solutions complying with the concept aerodynamic requirements, i.e. configurations performing dp/p values in the range of ±0.05% of what expressed in Table 4.3. Furthermore, a filter has been applied to exclude the candidates behaving worse than the baseline combustor design in terms of T_{max} and OF characteristics.

The present optimization study has been implemented in COS environment by specifying the maximization, minimization, and constraint conditions into a dedicated support file. Among all of the solutions which might be generated by the surrogate model, it makes possible to narrow down to the group of candidates which are efficiently responding to the design problem: such set of points is defined as Pareto front. In multi-objective optimization it is used to support the selection process by means of a trade-off between the different, and possibly conflicting, design drivers. Therefore, its frontier is including the dominating solutions, thus enabling to limit the research of optimal candidates to this region.

Based on this set of configurations, the search for optimal design candidates has been enabled by the definition of an overall optimization function OF_{tot}, defined as a weighted function of the 4 OFs:

$$OF_{tot} = \frac{\sum u_i \, OF_i}{\sum u_i} \qquad \text{Equation 4.8}$$

in which u is the weight associated to the i-th OF of the system. Since in this problem all the OFs should be minimized, potential optimal candidates can be found by minimizing the overall optimization function itself, by following Equation 4.9.

$$\min\left(OF_{tot}(u_i, OF_i)\right) \qquad \text{Equation 4.9}$$

In Figure 4.9 it is reported the 2D boundary for two out of the four OFs in this problem, ΔPrF and $EI(NO)$. This is the result of filtering 100000 surrogate points with the conditions stated in Table 4.6. By considering the current constraints, the set of feasible candidates have been shrunk to 3000 solutions, from which can be then selected the candidates minimizing the optimization drivers. The Pareto front thus obtained is made of 40 designs only, corresponding to the 0.04% of the original dataset. Adopting Equation *4.9*, up to 3 combustor configurations have been evaluated and compared with the baseline design, as it will be described in the next chapter together with the main findings and derivatives of the LEM-RQL optimization study.

With reference to the optimization process, the temporal and computational resources needed to perform this activity can be neglected since are in the order of magnitude of the ANN training (up to 10 s on 3 CPUs).

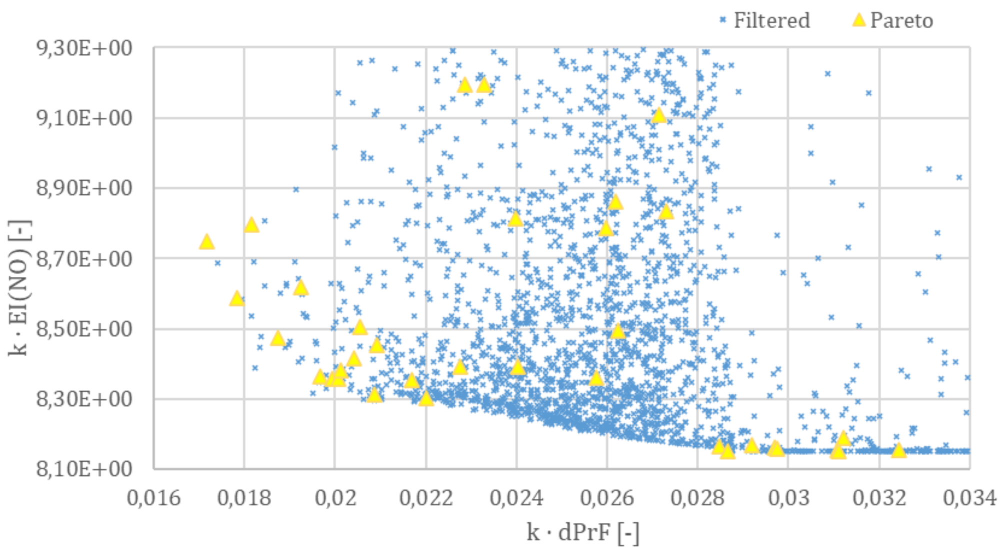


Figure 4.9 - Filtered and Pareto front solutions

4.3 Results

The results coming from the application of the process detailed above will be reported in this chapter in their entirety. First, the main design derivatives and the most relevant outcomes of the study will be discussed, in order to provide an answer to the stated design optimization problem. The temporal and computational resources required to carry out the activity will be then reported, with the intention to emphasize the potentiality of designing combustor's products through the presented approach.

4.3.1 Optimized design

Before focusing on the search for an optimal design candidate, it is worth to analyze the database of combustor's simulations. As it is usual in surrogate modelling, this information is adopted as a preliminary but powerful mean to retrieve the general behavior of the system under investigation. Through the set of the collected data, it is indeed possible to initialize a Design of Experiment (DoE) study, thus providing a standard and efficient method to study the dependencies between input and output variables. Consistently with the classification adopted throughout the work, the DOFs constitutes the main design factors, whereas the OFs are corresponding to the key system's responses. The resolution of the design space, by analogy, is represented by the DPs generated in the sampling step, resulting in a quasi-random set according to the properties of the Sobol algorithm.

Factors of weight			
Weight	CASE 1	CASE 2	CASE 3
w_{dPRF}	3.5	2.5	1.5
w_{dPF}	3.5	2.5	1.5
$w_{EI(NO)}$	1.5	2.5	3.5
$w_{EI(CO)}$	1.5	2.5	3.5
Metamodel's predictions			
DOF	CASE 1	CASE 2	CASE 3
$dS\ [mm]$	15.350	15.290	13.400
$TgInn$ [°]	-0.070	-0.028	-0.343
μ $[-]$	1.507	1.566	1.485
OF	CASE 1	CASE 2	CASE 3
$dPrF\ [-]$	0.053	0.061	0.146
$dPF\ [-]$	0.096	0.107	0.176
$EI(NO)$ [%]	-9.43	-13.67	-25.91
$EI(CO)$ [%]	-5.39	-7.11	-13.38

Table 4.7 – Summary of the weighting factors and the corresponding ANN solutions

The association between parameters can be evaluated by using the Pearson's product-moment correlation coefficient *r*. This method measures the linear strength between two variables, by attempting a best fitting regression of the respective data. It ranges from -1 to 1 according to the occurring dependency: the stronger the association of the two variables, the closer the coefficient will be to either +1 or -1, depending on whether the relationship is positive or negative, respectively. A value greater than 0 indicates a positive association; that is, as the value of one variable increases, so does the value of the other variable. A value less than 0 indicates a negative association; that is, as the value of one variable increases, the

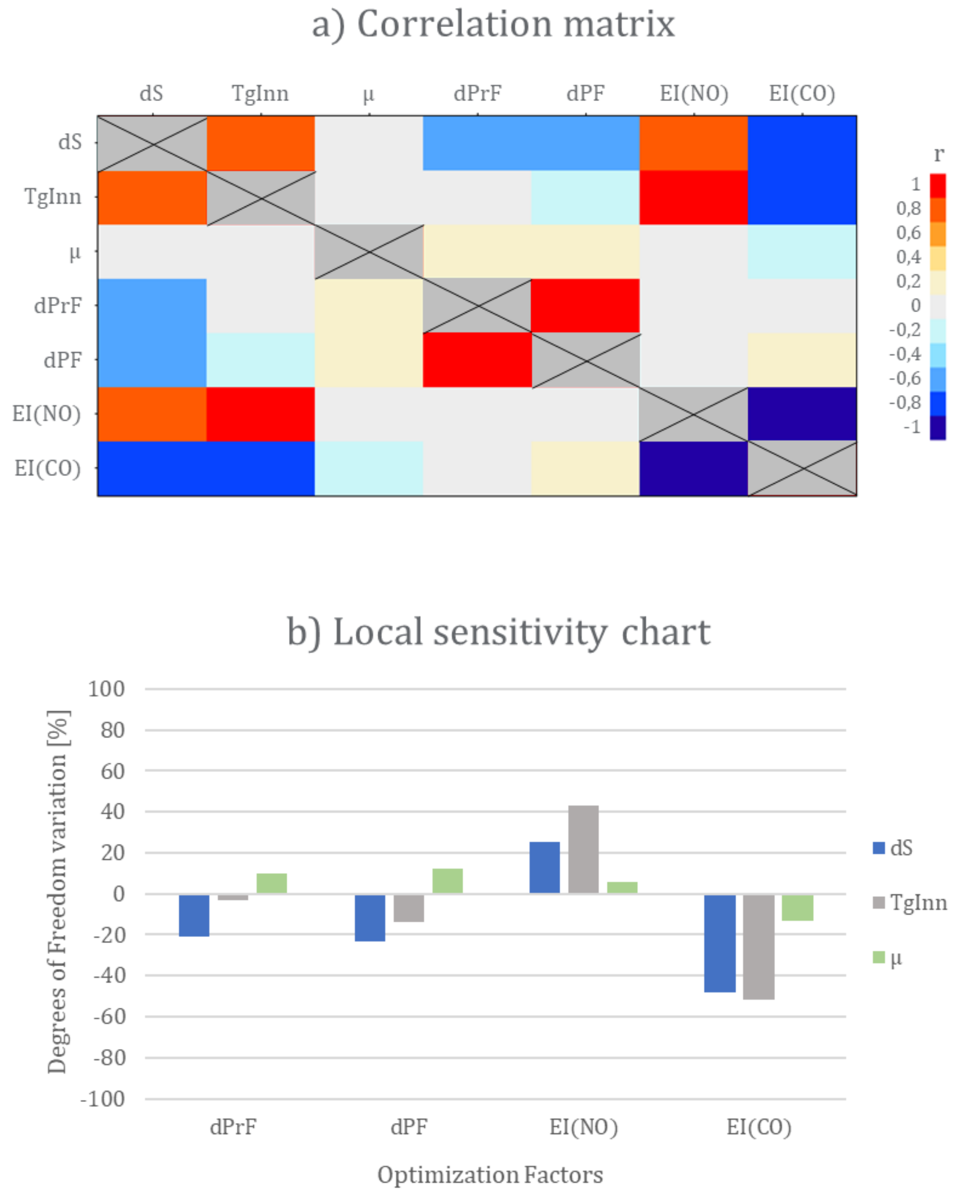


Figure 4.10 - Parameter correlation matrix (a) and Local sensitivity chart (b)

value of the other variable decreases. The value of 0 indicates that there is no association between the two variables. In preliminary steps of analysis, this technique allows to minimize the number of DPs to be simulated by excluding the DOFs which are influencing the response weakly. In advanced steps, in which instead the number of DPs is given, it is helpful for assessing hierarchy of influences and trends between the variables [84].

A visual render of the dependencies existing in the present study is reported in the correlation matrix of Figure 4.10-a, in which values of Pearson's coefficient r are associated to a red-blue color code. Given the number of output variables interested by the coefficient's variation, as well as their entities, the dilution row axial shift dS results the most influential parameter on system's response variables. It shows an inverse proportionality with temperature quantities $dPrF$, dPF and emission $EI(CO)$, whilst $EI(NO)$ appears in a direct one. A similar trend could be noticed for the inner dilution tangential shift $TgInn$, although the influence tends to be weaker for temperature quantities and higher for emission indexes. The air split between dilution ports μ behaves in contrast, despite its influence on the output variables results the weakest among the input factors. The same derivatives can be evinced through the local sensitivity of Figure 4.10-b. This chart allows in fact to evaluate the dependance of each of the output variable from the input parameters,

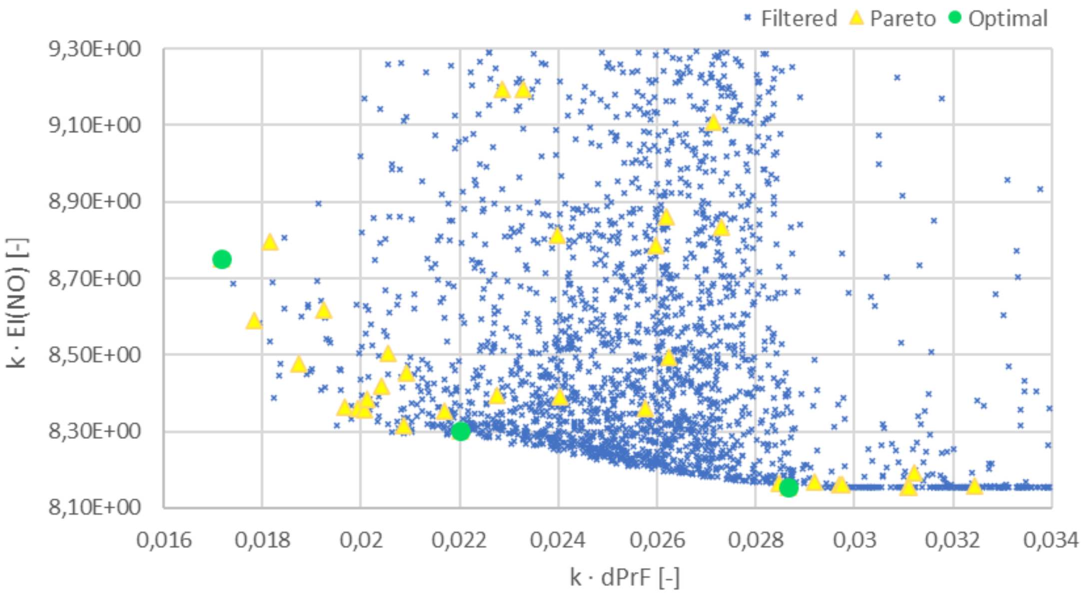


Figure 4.11 - Pareto front with evidence of the optimum design candidates (in green)

in terms of percentual variation. It can be here noticed that emission indexes are the most impacted by DOFs variation and, following the sensitivity hierarchy already highlighted, a predominant influence is given by dS and $TgInn$. Nevertheless, also in this case it is verified the inverse relationship between the NO and the CO emission indexes. All of the consideration reported have been obtained by exploiting by exploiting the capabilities of Ansys DesignXplorer, an Ansys Workbench application dedicated to the metamodeling of simulated systems [85].

In order to retrieve the combustor configurations to be considered as optimal candidates for the LEM-RQL design, 3 different sets of weights have been specified to initiate the strategy presented in the previous chapter. Such values are defining three cases aiming at conflicting performance purposes. The first one is considering the parameters related to temperature profile and pattern as predominant, whilst in the last one the emission quantities are preferred. Is case 2, instead, the relevance of the different drivers has been considered equivalent by providing an identical weighting. In the same table are reported the DOF values for the three cases which have been elected from the Pareto dataset, together with the corresponding OF quantities predicted by the ANN. For the sake of clarity, they can be observed in Figure 4.11 as the green dots laying on the Pareto front.

The cases have been processed through the DSI tools for CAD generation and CFD simulation in order to analyze their performance and to mutually highlight the behaviors. A comparison between the baseline design and the optimum candidates is presented in Figure 4.12 and Figure 4.14, in which are reported the developments of the most relevant quantities onto the meridional plane. From the velocity contour maps it can be noticed the effect of the different quenching specifications on the development of the chamber's flow field. For cases 1 and 2 the fluid structures of the dilution jets can notice at inner liner since the dilution pattern results in in a staggered configuration. The case 3, instead, presents a much more similar behavior to the baseline configuration, given that the dilution pattern has only a minimum in tangential direction with respect to the initial design.

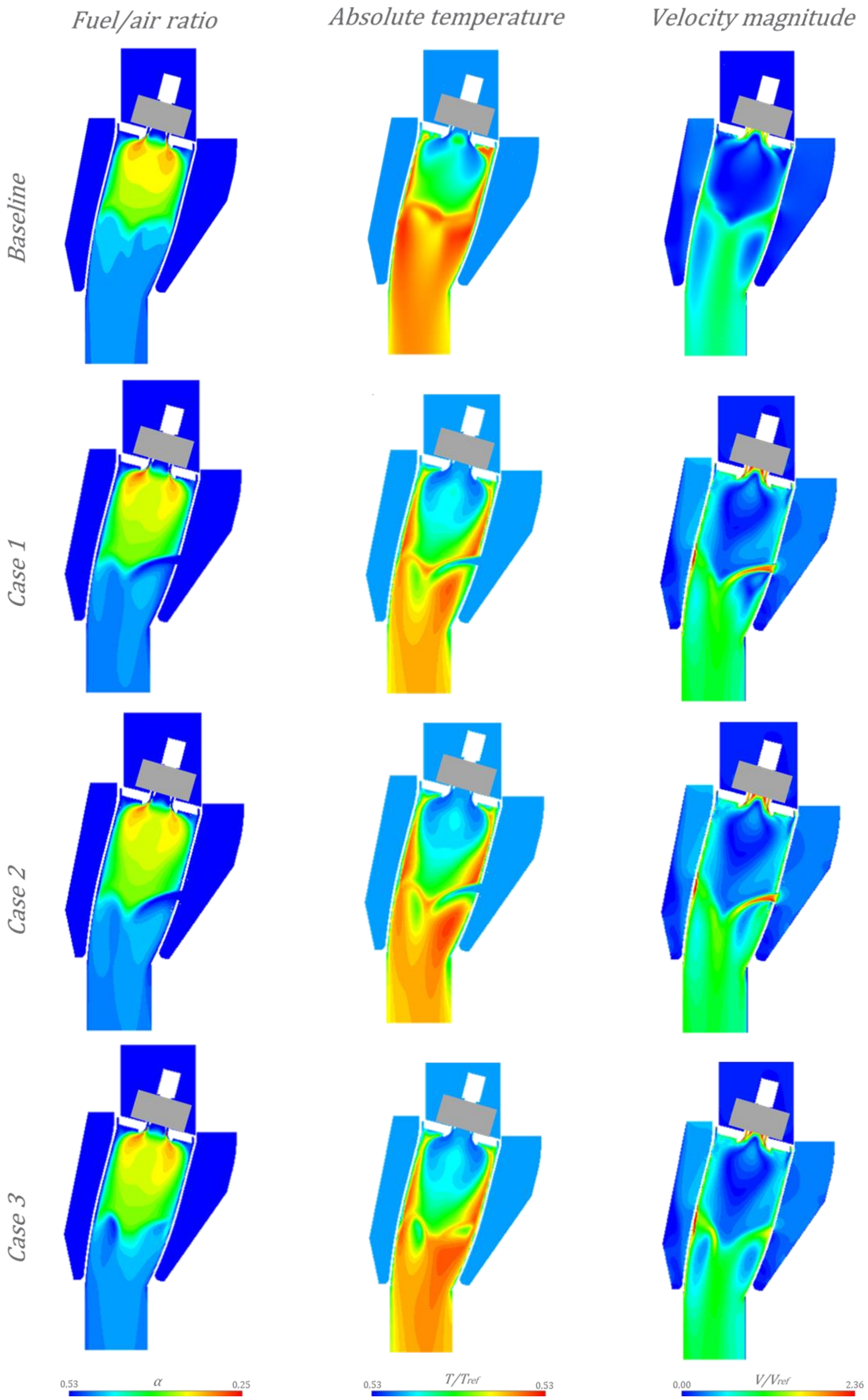


Figure 4.12 - Comparison between baseline and optimized, map of quantities – Part 1

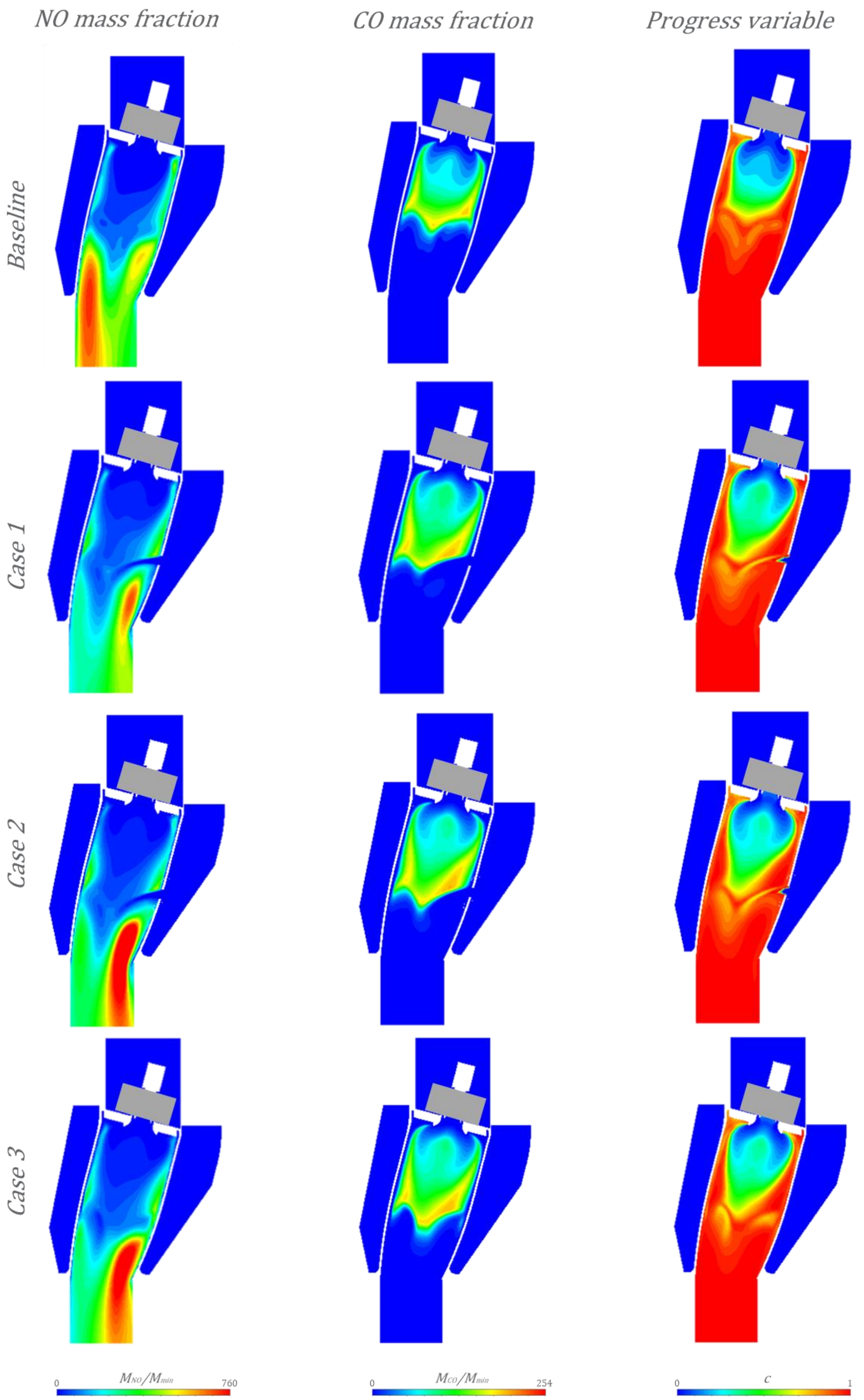


Figure 4.13 - Comparison between baseline and optimized, map of quantities – Part 2

By considering the maps of absolute temperatures, the axial shifting of the quenching module leads to a wider primary zone for the three cases, which appears to be helpful for the development of the flame, which is progressing with less volume constrictions. Because of the interaction of the jets and the reduction in the exit region volume, the downstream temperature field results to be less uniform than the baseline. Anyway, in general, the maximum temperature values appear to be minor than this last. This behavior can be also traced back from the FAR distribution, where the effect promoted by the updated pattern of dilutions on the distribution of fuel is clear. Moreover, for cases 1 and 2 there is also the evidence of how quenching jets affects the ratio between air and fuel, locally. In any case, however, the reactive process comes to its accomplishment, as it is clear from the charts of progress variables. With reference to carbon and nitrogen oxides, the following aspects can be observed. The formation of CO il limited to the rich region and, in particular, the maximum rates are situated in the zone where swirling and quenching fluid structures are interacting. NOx production, instead, shows the maximum values downstream of the quenching region, where stoichiometric values of the mixture can be found. With respect to the baseline model, in the meridional plane it can be noticed an inversion to the location of production for this species. The core of high NO values, indeed, switches from the outer to the inner liner's area. For all of the configuration, baseline included, the higher rates can be found right after the interspace between dilution jets. Given the purposes of this study, it is essential to further the investigation on the temperature conditions at combustor's exit plane. To this end, in Figure 4.14-are presented the results of the profile and pattern factors averaged at 5 points, compared for the four configurations. Despite of the shape assumed by the optimized configurations, an aspect which might be enhanced by following different strategies to train the ANN, it can be noticed that the profiles are following the purposes of the design: the more the weighting factors related to temperature quantities increase, the more PrF and PF points tend to globally move towards 0. This condition could be also proved by taking into account the contour plots of Figure 4.14-b, in which a more uniform and reduced maximum temperature can be noticed by moving from right to left. All of them seems better than the reference.

Finally, by processing the CFD results of the optimized configurations it is possible to provide a cross-validation for the metamodel. In Table 4.8 are reported the OF quantities of the three cases, which can be compared with the values predicted by the ANN in order to evaluate the accuracy of the model. For the Profile and Pattern variations it is observed a discrepancy in the range of ±9%, with a maximum error of -9% obtained for $dPrF$ of case 3. Considering the emission quantities, the difference is comprised within ±5%, where the maximum excursion reaches +5%

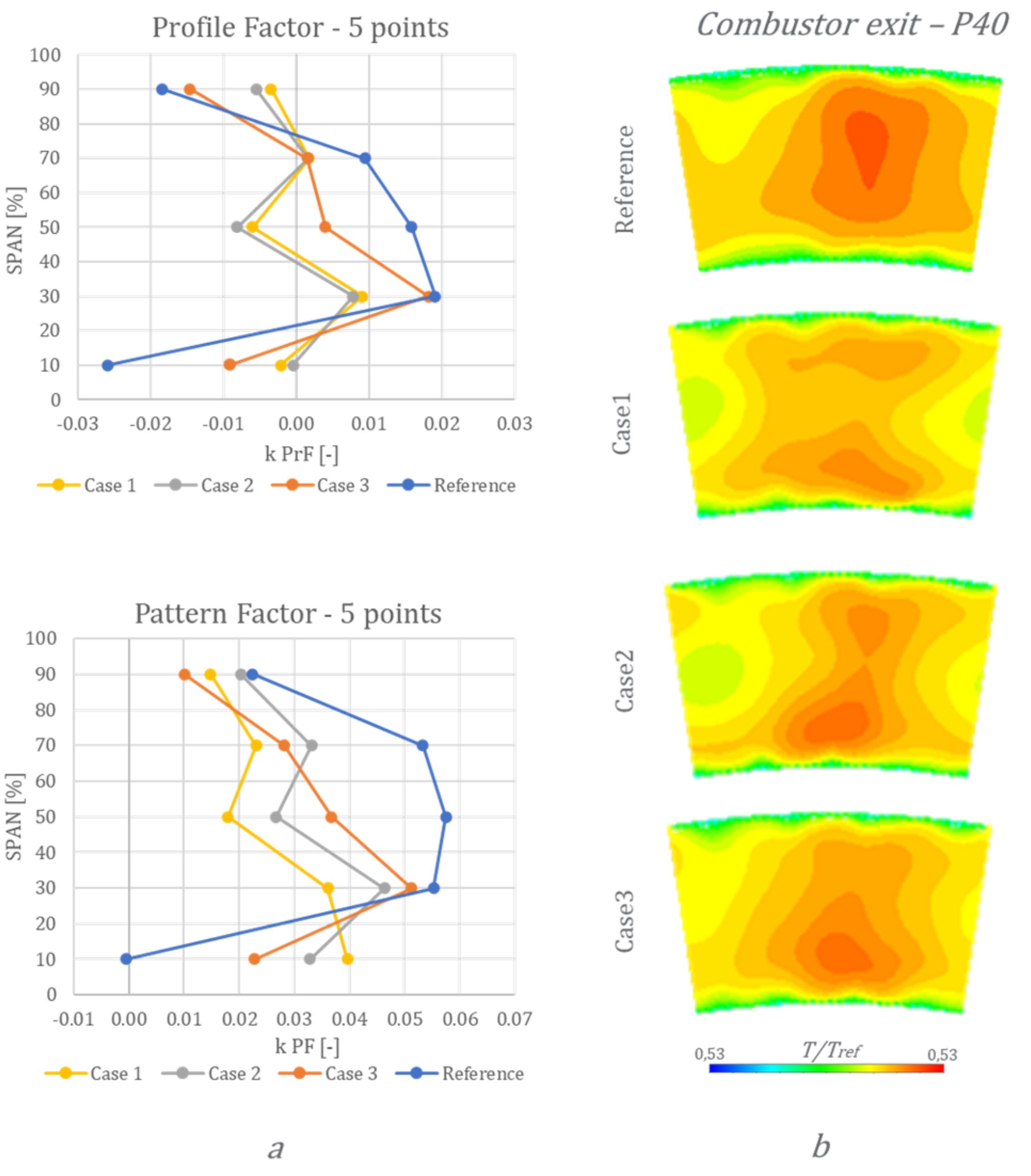


Figure 4.14 - Results of temperature at combustor's exit plane: PrF-PF (a) and contours (b)

for EI(CO) of case1. Overall, it can be noticed a good agreement between the surrogate solutions and the CFD results, since the trends of quantities selected to carry out the present design optimization are kept for all the configurations tested. It can so be stated that the optimization process implemented in the aim of this work is effective in being adopted for the multi-objective design of combustors for aero engine applications. The accuracy of the surrogate model presented in this study has been evaluated through a direct comparison of the OFs data, comparing the values predicted by the ANN with the results obtained via CFD simulation. The training dataset is composed by the 20 initial combustor configurations, while the validation dataset consists of the 3 optimized designs elected through the ANN.

	CASE 1	CASE 2	CASE 3
$dPrF$	0.057	0.059	0.135
dPF	0.100	0.113	0.184
$EI(NO)$	-9.60	-14.19	-25.91
$EI(CO)$	-5.66	-7.18	-13.38

Table 4.8 – CFD results of the system's OFs, for the optimum configurations

4.3.2 Resources

To carry out the present optimization study it has been made available a total amount of 200 CPUs, leading to an overall time to design of about 30 days. The generation of the simulation database took up to 25 days, while 5 additional days have been dedicated to process the optimal design candidates and derive the DOE and optimization results. Compared to this, the amount resources required to train and interrogate the network can be considered neglectable: once the ANN is properly defined, these processes are running in the order of seconds on a minimal quantity of computational resources. In contrast to what discussed in the straight-forward design of the NEWAC combustor, with the optimization exercise of the LEM-RQL it is not possible to have a direct application of the MBPM technique. Indeed, the process implemented through the DSI and COS procedures is providing an approach which is moderately different from trial-and-error design. Despite the gains in the management of multiple, subsequential combustor configurations it is considerable, the most relevant aspect is represented by the possibility to dispose of a surrogate model of the system. This allows the designer to initialize a wide range of optimization studies, based on the same simulation database or reinforcing it with additional one.

Conclusions

The increasingly stringent regulatory requirements that are driving the civil aviation towards a climate-neutral future are posing a major challenge to all the industry players but are also revealing significant opportunities to be seized at once. Anyway, for keep being competitive and to shrink the time-to-market, companies' development processes are required to perform effectively and efficiently, thus calling for continuous improvements aimed at rationalizing the resources and minimizing the timing. For what concerns the design phase, simulation-based approaches represent the nowadays standard in accelerating the product development times. Despite of the advantages which these techniques has been proven to provide, it cannot be assumed the resulting design workflow will perform in a robust process able to manage miscellaneous information. It is properly in this context that finds reason the Combustor Design System Integration: a platform capable of integrating and automatizing the design process of aero engine combustors. In this work, an attempt has been made in demonstrating the intrinsic complexity of the design workflow by reviewing the set of different physical aspects involved in the system's functioning, as well as the variety of requirements existing at product's level. It is denoted as a multi-disciplinary and multi-objective process which can be considered composed of three main steps: concept, preliminary and detailed. With reference to the preliminary phase, multiple product configurations are evaluated with the main purpose of seeking a design candidate that minimized profile temperatures and emission level at combustor's exit, while meeting system's feasibility requirement and verifying compliance to the thermo-structural admissible conditions for components.

Based on the design activities carried out by the Combustion System Design Team of *Avio Aero – a GE Aviation business*, it has been possible to review the operations related to the development of combustor products. The "current state" of the design workflow has been traced via a Metric-Based Process Mapping approach, thus identifying rooms for the improvement of tasks denoted by redundancy, low-value added and propensity to error. This allowed to foresee an enhanced "future state" featuring intra-tool automation and inter-tool automation concepts, which are leveraging on lean principles and digitalization fundamentals. With the specific purpose of easing and streamlining such activities, it has been proposed an analysis procedure ranging among the different physical domains: the DSI toolkit. It is composed of a set of tools capable to drastically reduce the overall lead-time for analysis while enhancing the robustness of the overall process. The resulting process is enabled by 4 Ansys Custom extensions devoted to creating the CAD model, to exploit CFD for assessing the aero-thermal and emission performance, to prepare boundary conditions for thermal evaluations and to address the stress and displacement behavior through a structural FE analysis. All of these tools are featuring a knowledge-based principle and a feature recognition-based approach, to respectively embed design practices/rules in the analysis steps and enhance the processing the models among the subsequent simulation activities. According to literature, a procedure addressing the range of analyses that have been presented, which are conducted at a full 3D level with an advance management of liners' cooling and quenching information, has not been proposed so far. The tools' baseline logic is presented in the context of its application to a real case combustor product: the NEWAC concept. By means of a direct comparison between the results of the DSI and the experimental data coming from test cell, it has been possible to provide an assessment of the proposed RANS-based methodology. Maximum deviations have been calculated for the quantities which are representative of a preliminary design step for combustors. For PrF and PF, these values amount to -0.11 $PrF\ k$ and -0.13 $PF\ k$ and are found at 95% of the span, while for emission quantities the predictions are leading the $EI(CO)$ to be underestimated and, on the contrary, $EI(NO)$ are showing a good agreement with an error under 5%. Based on these values, the level of accuracy achieved can be considered admissible for the stage of design in which the tool is intended to be adopted.

Despite the DSI toolkit results to be effective in helping the designer during the analysis and simulations steps, it is not capable of providing information for the design iteration and the configuration selection tasks. A custom optimization suite based on python/FORTRAN scripting, the COS, has been provided with the specific purpose of managing design workflows while embedding metamodeling and optimization techniques. The integration of the DSI tools within such optimization framework is the Combustor DSI platform: it implements a dedicated process for a general-purpose optimization of combustors, which potentialities are shown by its direct application to a test case specifically provided for this activity, named LEM-RQL. With the intention of addressing one of the most relevant preliminary design challenges as the dilution mixing problem is, the optimization task has been initialized. The Degrees of Freedom of the system are set as quenching module related quantities, while parameters representative for temperature profiles and emission levels are selected as Optimization Factors. Once the design space and sampling are defined, the DSI tools allow to full automate the calculation step and provide the data required for training a neural network based, dedicated surrogate model of the combustor. By means of an overall optimization function scanning the front of Pareto identified through the metamodel, three optimal designs have been elected and verified. A cross-validation process based on the optimization drivers has shown a level of accuracy of the network aligned with the intent of the design optimization, thus being able to state that the ANN is adequate for representing the system in the settled ranges of design. As an outlook for future developments, such accuracy limits might be enhanced by a more detailed definition of the OFs and/or providing a wider set of combustor configuration data to train the metamodel.

The methodology developed within the DSI design suite has demonstrated to achieve levels in the accuracy of results and in the effectiveness of time such as to be considered a powerful resource to perform the study of combustor products in the preliminary phase. The design procedure ranges indeed from the definition of a geometrical arrangement for the system, thus enabling a feasibility evaluation of the displacement of cooling system on liner components, to the verification of thermo-mechanical stresses for the combustor configuration under analysis. It has been conceived as a modular software-based procedure, so to ease future developments that may involve the substitution of tools or local modifications within the tools aimed at enhancing the methodology following the designer's possible needs. However, there is an initial limitation in extending the procedure to more advanced design stages, such as the detail design. The CFD simulation is currently implemented in the tool as a RANS approach. This is providing the criteria for the upstream process of CAD model export, which requirements are in fact based on a such a simplified strategy. A potential development of the procedure can be found in its extension to scale-resolved simulation processes, which will therefore lead to a major overhaul of the routines developed to export CAD. Furthermore, aspects related to the usability have a lot of room for improvement. Future applications of the procedure may include the adoption of the simulative platform to produce numerical database of combustors' performances, for both the development of new products and the optimization of existing ones. This latter case would potentially represent a first step into the implementation of a proper digital-twin logic, thus opening not only a novel design approach but also the starting point for an industrial digital thread.

To conclude, in this research an attempt has been made to demonstrate that advanced design platforms made of an optimization framework embedding integrated tools provide multiple benefits to the combustor's preliminary design phase. Form a process perspective, the design workflow is enhanced by an increased robustness and a reduced time-to-design. The product is indeed defined as a trade-off between the most relevant design variables, meaning the optimal design configuration is driven by the requirements of the system. Given the results of this work, the DSI procedure can be deemed an effective approach to be adopted in the technology maturation process, with potentialities in enabling not only the improvement of in-service components but also the development of next-generation combustor products.

Bibliography

[1] "New Generation Aero Combustor | IntechOpen" [Online]. Available: https://www.intechopen.com/chapters/73513. [Last accessed: 30-Jan-2022].

[2] Meher-Homji, C. B., 1998, "The Development of the Whittle Turbojet," J. Eng. Gas Turbines Power, 120(2), pp. 249–256.

[3] Kay, A., 2007, Turbojet: History and Development 1930-1960 Volume 1 - Great Britain and Germany, Crowood Press UK.

[4] Lefebvre, A. H., 1983, Gas Turbine Combustion, Hemisphere Pub. Corp.

[5] "The Postal History of ICAO" [Online]. Available: https://applications.icao.int/postalhistory/annex_16_environmental_protection.htm. [Last accessed: Jan-2022].

[6] Spalart, P. R., and Venkatakrishnan, V., 2016, "On the Role and Challenges of CFD in the Aerospace Industry," Aeronaut. J., 120(1223), pp. 209–232.

[7] Innovation and Networks Executive Agency., 2020, Towards Climate-Neutral Aviation: Contributions from Horizon 2020 Projects Implemented by INEA., Publications Office, LU.

[8] Gullapalli, S., Narayanan, V., and Sankara, K., 2014, Role of CFD in the Design & Development of Gas Turbine Combustors – Preliminary Sizing to Performance Optimization.

[9] Badin, J., Chamoret, D., Gomes, S., and Monticolo, D., 2011, "Knowledge Configuration Management For Product Design And Numerical Simulation," 68-6 Proc. 18th Int. Conf. Eng. Des. ICED 11 Impacting Soc. Eng. Des. Vol 6 Des. Inf. Knowl. LyngbyCopenhagen Den. 15-19082011, pp. 161–172 [Online]. Available: https://www.designsociety.org/publication/30623/knowledge+configuration+management+for+product+design+and+numerical+simulation. [Last accessed: 28-Nov-2020].

[10] Mellor, A. M., 1990, Design of Modern Turbine Combustors, Academic Press.

[11] Norgren, C. T., "Reverse-Flow Combustor for Small Gas Turbines with Pressure-Atomizing Fuel Injectors," p. 31.

[12] "ICAO Aircraft Engine Emissions Databank," EASA [Online]. Available: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank. [Last accessed: Jan-2022].

[13] Kaddah, K. S. M. I., 1964, "Discharge Coefficient and Jet Deflection Studies for Combustor Liner Air-Entry Holes."

[14] "Freeman: Discharge Coefficients of Combustion Chamber", Google Scholar [Online]. Available: https://scholar.google.com/scholar_lookup?hl=en&publication_year=1969&author=B.+C.+Freeman&author=E.+R.+Norster&title=Discharge+coefficient+of+combustion+chamber+dilution+holes. [Last accessed: Jan-2022].

[15] Cox, G. B., Jr., 1976, "Multiple Jet Correlations for Gas Turbine Engine Combustor Design," J. Eng. Power, 98(2), pp. 265–272.

[16] Sridhara, K., 1970, Gas Mixing in the Dilution Zone of a Combustion Chamber, NAL.

[17] Norster, E. R., 1964, Second Report on Jet Penetration and Mixing Studies, College of Aeronautics.

[18] Tangirala, V. E., Tolpadi, A. K., Danis, A. M., and Mongia, H., 2014, "Parametric Modeling Approach to Gas Turbine Combustor Design," American Society of Mechanical Engineers Digital Collection.

[19] Dawes, W. N., Dhanasekaran, P. C., Demargne, A. a. J., Kellar, W. P., and Savill, A. M., 2001, "Reducing Bottlenecks in the CAD-to-Mesh-to-Solution Cycle Time to Allow CFD to Participate in Design," J. Turbomach., 123(3), pp. 552–557.

[20] Malecki, R. E., Rhie, C. M., McKinney, R. G., Ouyang, H., Syed, S. A., Colket, M. B., and Madabhushi, R. K., 2014, "Application of an Advanced CFD-Based Analysis System to the PW6000 Combustor to Optimize Exit Temperature Distribution: Part I — Description and Validation of the Analysis Tool," American Society of Mechanical Engineers Digital Collection.

[21] Snyder, T. S., Stewart, J. F., Stoner, M. D., and McKinney, R. G., 2014, "Application of an Advanced CFD-Based Analysis System to the PW6000 Combustor to Optimize Exit Temperature Distribution: Part II — Comparison of Predictions to Full Annular Rig Test Data," American Society of Mechanical Engineers Digital Collection.

[22] Lai, M. K., Reynolds, R. S., and Armstrong, J., 2009, "CFD-Based, Parametric, Design Tool for Gas Turbine Combustors From Compressor Deswirl Exit to Turbine Inlet," American Society of Mechanical Engineers Digital Collection, pp. 545–552.

[23] Dudebout, R., Reynolds, B., and Molla-Hosseini, K., 2008, "Integrated Process for CFD Modeling and Optimization of Gas Turbine Combustors," American Society of Mechanical Engineers Digital Collection, pp. 679–686.

[24] Pegemanyfar, N., Pfitzner, M., Eggels, R., von der Bank, R., and Zedda, M., 2008, "Development of an Automated Preliminary Combustion Chamber Design Tool," American Society of Mechanical Engineers Digital Collection, pp. 327–336.

[25] Pegemanyfar, N., and Pfitzner, M., 2009, "State-of-the-Art Combustor Design Utilizing the Preliminary Combustor Design System PRECODES," American Society of Mechanical Engineers Digital Collection, pp. 465–475.

[26] Pegemanyfar, N., Pfitzner, M., and Surace, M., 2009, "Automated CFD Analysis Within the Preliminary Combustor Design System PRECODES Utilizing Improved Cooling Models," American Society of Mechanical Engineers Digital Collection, pp. 289–300.

[27] Gessel, M., Pfitzner, M., and Eggels, R., 2015, "Development of an Advanced Automated Knowledge Based Combustor Preliminary Design Process Suitable for Low NOx Combustion Systems Optimization," American Society of Mechanical Engineers Digital Collection.

[28] Toal, D., Zhang, X., Bressloff, N., Keane, A., Witham, F., Gregory, J., Stow, S., Goddard, C., Zedda, M., and Rodgers, M., 2014, "Prometheus: A Geometry-Centric Optimization System for Combustor Design."

[29] Zhang, X., Toal, D. J. J., Keane, A. J., Witham, F., Gregory, J., Ravikanti, M., Aurifeille, E., Stow, S., Rogers, M., and Zedda, M., 2016, "Isothermal Combustor Prediffuser and Fuel Injector Feed Arm Design Optimization Using the Prometheus Design System," J. Eng. Gas Turbines Power, 138(6).

[30] "The Potential of a Multi-Fidelity Approach to Gas Turbine Combustor Design Optimization | Journal of Engineering for Gas Turbines and Power | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/gasturbinespower/article-abstract/doi/10.1115/1.4048654/1087604/The-Potential-of-a-Multi-Fidelity-Approach-to-Gas?redirectedFrom=fulltext. [Last accessed: Nov-2020].

[31] Rogero, J. M., 2002, "A Genetic Algorithms Based Optimisation Tool for the Preliminary Design of Gas Turbine Combustors."

[32] Rogero, J., and Rubini, P., 2003, "Optimisation of Combustor Wall Heat Transfer and Pollutant Emissions for Preliminary Design Using Evolutionary Techniques," Proc. Inst. Mech. Eng. Part J. Power Energy, 217.

[33] Gordon, R., and Levy, Y., 2005, "Optimization of Wall Cooling in Gaas Turbine Combustor Through Three-Dimensional Numerical Simulation," J. Eng. Gas Turbines Power, 127(4), pp. 704–723.

[34] Motsamai, O. S., Snyman, J. A., and Meyer, J. P., 2010, "Optimization of Gas Turbine Combustor Mixing for Improved Exit Temperature Profile," Heat Transf. Eng., 31(5), pp. 402–418.

[35] Angersbach, A., Bestle, D., and Eggels, R., 2013, "Automated Combustor Preliminary Design Using Tools of Different Fidelity," American Society of Mechanical Engineers Digital Collection.

[36] Kenworthy, T. L., and Jensen, C. G., 2009, "CAD-Centric Dynamic Workflow Generation," Comput.-Aided Des. Appl., 6(5), pp. 673–683.

[37] Elmi, C. A., Agnolio, F., Ferraro, R., Menard, A., Reese, H., and Andreini, A., 2020, "Development of an Integrated Procedure for Combustor Aero-Thermal Preliminary Design," p. 11.

[38] Elmi, C. A., Agnolio, F., Ferraro, R., Menard, A., Reese, H., and Andreini, A., 2021, "Development of an Integrated Procedure for Combustor Aero-Thermal Preliminary Design," American Society of Mechanical Engineers Digital Collection.

[39] Eschenauer, H., Koski, J., and Osyczka, A., 2012, Multicriteria Design Optimization: Procedures and Applications, Springer Science & Business Media.

[40] Wankhede, M. J., Bressloff, N. W., and Keane, A. J., 2011, "Combustor Design Optimization Using Co-Kriging of Steady and Unsteady Turbulent Combustion," J. Eng. Gas Turbines Power, 133(12).

[41] Cox, D., and Reid, N., 2000, "The Theory of Design of Experiments."

[42] Torkzadeh, M. M., Bolourchifard, F., and Amani, E., 2016, "An Investigation of Air-Swirl Design Criteria for Gas Turbine Combustors through a Multi-Objective CFD Optimization," Fuel, 186, pp. 734–749.

[43] Saboohi, Z., Ommi, F., and Akbari, Mj., 2019, "Multi-Objective Optimization Approach toward Conceptual Design of Gas Turbine Combustor," Appl. Therm. Eng., 148, pp. 1210–1223.

[44] Park, Y., Choi, M., Kim, K., Li, X., Jung, C., Na, S., and Choi, G., 2020, "Prediction of Operating Characteristics for Industrial Gas Turbine Combustor Using an Optimized Artificial Neural Network," Energy, 213, p. 118769.

[45] Gardner, M. W., and Dorling, S. R., 1998, "Artificial Neural Networks (the Multilayer Perceptron)—a Review of Applications in the Atmospheric Sciences," Atmos. Environ., 32(14), pp. 2627–2636.

[46] Paccati, S., 2020, "Development of Advanced Numerical Tools for the Prediction of Wall Temperature and Heat Fluxes for Aeroengine Combustors," Ph.D. Thesis, University of Florence.

[47] "Survey of Multi-Objective Optimization Methods for Engineering | SpringerLink" [Online]. Available: https://link.springer.com/article/10.1007/s00158-003-0368-6. [Last accessed: Nov-2019].

[48] Andreini, A., Facchini, B., Mazzei, L., Bellocci, L., and Turrini, F., 2014, "Assessment of Aero-Thermal Design Methodology for Effusion Cooled Lean Burn Annular Combustors," American Society of Mechanical Engineers Digital Collection.

[49] Bianchini, C., Andrei, L., Andreini, A., and Facchini, B., 2013, "Numerical Benchmark of Nonconventional RANS Turbulence Models for Film and Effusion Cooling," J. Turbomach., 135(4), p. 041026.

[50] Andrei, L., Andreini, A., Bianchini, C., Facchini, B., Mazzei, L., and Turrini, F., 2014, "Investigation on the Effect of a Realistic Flow Field on the Adiabatic Effectiveness of an Effusion-Cooled Combustor," American Society of Mechanical Engineers Digital Collection.

[51] Andreini, A., Becchi, R., Facchini, B., Mazzei, L., Picchi, A., and Turrini, F., 2015, "Adiabatic Effectiveness and Flow Field Measurements in a Realistic Effusion Cooled Lean Burn Combustor," J. Eng. Gas Turbines Power, 138(3), pp. 031506-031506–11.

[52] Andreini, A., Bianchini, C., Caciolli, G., Facchini, B., Giusti, A., and Turrini, F., 2014, "Multi-Coupled Numerical Analysis of Advanced Lean Burn Injection Systems," Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers, p. V04BT04A041.

[53] Andreini, A., Da Soghe, R., Facchini, B., Mazzei, L., Colantuoni, S., and Turrini, F., 2014, "Local Source Based CFD Modeling of Effusion Cooling Holes: Validation and Application to an Actual Combustor Test Case," J. Eng. Gas Turbines Power, 136(1).

[54] Andreini, A., Facchini, B., Becchi, R., Picchi, A., and Turrini, F., 2015, "Effect of Slot Injection and Effusion Array on the Liner Heat Transfer Coefficient of a Scaled Lean-Burn Combustor With Representative Swirling Flow," J. Eng. Gas Turbines Power, 138(4), pp. 041501-041501–10.

[55] Achten, H., and Joosen, G., "The Digital Design Process," p. 6.

[56] Martin, K., and Osterling, M., 2012, Metrics-Based Process Mapping: Identifying and Eliminating Waste in Office and Service Processes, CRC Press.

[57] Locher, D. A., 2008, Value Stream Mapping for Lean Development: A How-To Guide for Streamlining Time to Market, CRC Press.

[58] "Ansys SpaceClaim | 3D CAD Modeling Software" [Online]. Available: https://www.ansys.com/it-it/products/3d-design/ansys-spaceclaim. [Last accessed: Jan-2022].

[59] Ceccherini, A., Facchini, B., Tarchi, L., Toni, L., and Coutandin, D., 2010, "Combined Effect of Slot Injection, Effusion Array and Dilution Hole on the Cooling Performance of a Real Combustor Liner," American Society of Mechanical Engineers Digital Collection, pp. 1431–1440.

[60] Andreini, A., Caciolli, G., Facchini, B., Tarchi, L., Coutandin, D., Peschiulli, A., and Taddei, S., 2013, "Density Ratio Effects on the Cooling Performances of a Combustor Liner Cooled by a Combined Slot/Effusion System," American Society of Mechanical Engineers Digital Collection, pp. 903–914.

[61] Shrager, A. C., Thole, K. A., and Mongillo, D., 2019, "Effects of Effusion Cooling Pattern Near the Dilution Hole for a Double-Walled Combustor Liner—Part 1: Overall Effectiveness Measurements," J. Eng. Gas Turbines Power, 141(1), p. 011022.

[62] Scrittore, J., 2008, "Experimental Study of the Effect of Dilution Jets on Film Cooling Flow in a Gas Turbine Combustor."

[63] "Combustor Dilution Hole Placement and Its Effect on the Turbine Inlet Flowfield | Journal of Propulsion and Power" [Online]. Available: https://arc.aiaa.org/doi/pdf/10.2514/1.B36308. [Last accessed: Dec-2021].

[64] "Ansys Workbench | Simulation Integration Platform" [Online]. Available: https://www.ansys.com/it-it/products/ansys-workbench. [Last accessed: 24-Jan-2022].

[65] "Morfo Design – Advanced Aerodynamics."

[66] Wong, T.-T., Luk, W.-S., and Heng, P.-A., 1997, "Sampling with Hammersley and Halton Points," J. Graph. Tools, 2(2), pp. 9–24.

[67] Cauwet, M.-L., Couprie, C., Dehos, J., Luc, P., Rapin, J., Riviere, M., Teytaud, F., Teytaud, O., and Usunier, N., 2020, "Fully Parallel Hyperparameter Search: Reshaped Space-Filling," Proceedings of the 37th International Conference on Machine Learning, PMLR, pp. 1338–1348.

[68] "Assessment of a Set of Numerical Tools for the Design of Aero-Engines Combustors: Study of a Tubular Test Rig | Turbo Expo: Power for Land, Sea, and Air | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2009/48838/421/344775. [Last accessed: Nov-2019].

[69] "Combined Effect of Slot Injection, Effusion Array and Dilution Hole on the Cooling Performance of a Real Combustor Liner | GT | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2009/48845/1431/338157. [Last accessed: Jan-2022].

[70] "Numerical Study of Aerodynamic Losses of Effusion Cooling Holes in Aero-Engine Combustor Liners | J. Eng. Gas Turbines Power | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/gasturbinespower/article-abstract/133/2/021901/456234/Numerical-Study-of-Aerodynamic-Losses-of-Effusion?redirectedFrom=fulltext. [Last accessed: Jan-2022].

[71] "ISO 9241-11:2018(En), Ergonomics of Human-System Interaction — Part 11: Usability: Definitions and Concepts" [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en. [Last accessed: Jun-2022].

[72] "CFD Aerodynamic and Reactive Study of an Innovative Lean Combustion System in the Frame of the NEWAC Project | Turbo Expo: Power for Land, Sea, and Air | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2010/43970/377/339198. [Last accessed: Nov-2019].

[73] Mazzei, L., Andreini, A., Facchini, B., and Bellocci, L., 2016, "A 3D Coupled Approach for the Thermal Design of Aero-Engine Combustor Liners," American Society of Mechanical Engineers Digital Collection.

[74] Colantuoni, S., Bake, S., and Badet, J. P., "Low Emissions Combustors Development for New Aero-Engines Core Applications," p. 6.

[75] "Numerical and Experimental Investigation on an Effusion-Cooled Lean Burn Aeronautical Combustor: Aerothermal Field and Metal Temperature | Turbo Expo: Power for Land, Sea, and Air | ASME Digital Collection" [Online]. Available: https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2018/V05CT17A010/273065. [Last accessed: Jan-2021].

[76] Sirjean, B., Dames, E., Sheen, D. A., and Wang, H., "Simplified Chemical Kinetic Models for High-Temperature Oxidation of C1 to C12 n-Alkanes," p. 7.

[77] Phillips, T. S., and Roy, C. J., 2014, "Richardson Extrapolation-Based Discretization Uncertainty Estimation for Computational Fluid Dynamics," J. Fluids Eng., 136(121401).

[78] “Low Emissions Core-Engine Technologies | LEMCOTEC Project | Fact Sheet | FP7 | CORDIS | European Commission” [Online]. Available: https://cordis.europa.eu/project/id/283216. [Last accessed: Dec-2021].

[79] “Numerical Investigation of Enhanced Dilution Zone Mixing in a Reverse Flow Gas Turbine Combustor | J. Eng. Gas Turbines Power | ASME Digital Collection” [Online]. Available: https://asmedigitalcollection.asme.org/gasturbinespower/article-abstract/117/2/272/408494/Numerical-Investigation-of-Enhanced-Dilution-Zone?redirectedFrom=fulltext. [Last accessed: Dec-2021].

[80] Dai, W., Zhang, Y., Lin, Y., Yang, Q., and Zhang, C., 2014, “Influence of the Arrangement of Dilution Holes for Dilution Mixing in a Three-Injector Reverse Flow Combustor,” American Society of Mechanical Engineers Digital Collection.

[81] “Preliminary Design of a Reverse Flow Annular Combustor and Experimental Investigations at Design and Off Design Operating Conditions by Deepa M S, Dr. A Arokkiaswamy :: SSRN” [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3507372. [Last accessed: Dec-2021].

[82] “A Primer in Data Reduction: An Introductory Statistics Textbook | Wiley,” Wiley.com [Online]. Available: https://www.wiley.com/en-ie/A+Primer+in+Data+Reduction%3A+An+Introductory+Statistics+Textbook-p-9780471101352. [Last accessed: Jan-2022].

[83] Rafiq, M. Y., Bugmann, G., and Easterbrook, D. J., 2001, “Neural Network Design for Engineering Applications,” Comput. Struct., 79(17), pp. 1541–1552.

[84] Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M., 2016, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, John Wiley & Sons.

[85] Ansys Inc., 2020, “Ansys Workbench - User’s Guide, Version 2019R3.”