Surrogate-Based Optimization for Evaluating Turbine Cooling Impacts on Aero-Engine Performance

by

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OPTIMISATION BASÉE SUR DES MODÈLES SUBSTITUTS POUR L'ÉVALUATION DES IMPACTS DU REFROIDISSEMENT DES TURBINES SUR LES PERFORMANCES DES MOTEURS AÉRONAUTIQUES

Mohamed A.K.I. AHMED

RÉSUMÉ

Traditionnellement, les moteurs à turbine à gaz (GTE) sont optimisés au niveau des composants, avec un accent principal sur la maximisation de l'efficacité individuelle afin d'assurer la fonctionnalité et la fiabilité. Cependant, cette approche ne conduit pas toujours à des moteurs à faible consommation spécifique de carburant (SFC). Compte tenu de l'augmentation des coûts du carburant et des initiatives mondiales visant la neutralité carbone d'ici 2050, il devient de plus en plus essentiel de concevoir des moteurs avec une consommation de carburant réduite au niveau système.

Cette recherche présente le développement d'un outil d'optimisation intégré qui déplace l'objectif de l'efficacité des composants vers la minimisation de la SFC au niveau moteur. Les travaux portent principalement sur la conception de la turbine, avec un accent particulier sur le refroidissement des profils aérodynamiques, qui représente la plus grande contribution à la demande de refroidissement de la turbine et qui a un impact direct sur la SFC. Bien que le refroidissement soit indispensable pour la durabilité, un excès de refroidissement réduit les performances du moteur en raison de l'extraction de l'air de prélèvement au compresseur et des pertes de mélange qui dégradent le travail utile de la turbine.

L'outil développé intègre plusieurs plateformes internes de Pratt & Whitney Canada (P&WC): le Turbine Aerodynamic Meanline (TAML) pour les calculs de ligne moyenne, le Cooling Flow Prediction Tool (CFPT) pour l'estimation des besoins en refroidissement des profils, et le Framework for Design Exploration (FDE) pour l'exécution de l'optimisation. Les flux de travail combinent Design of Experiments (DOE) et Surrogate-Assisted Optimization (SAO) afin d'explorer efficacement l'espace de conception et d'accélérer la convergence. Des facteurs d'échange de SFC et des facteurs de sensibilité sont intégrés pour estimer l'impact du refroidissement sur l'efficacité de la turbine et la SFC pendant la phase de conception préliminaire, où des estimations rapides mais fiables sont nécessaires.

Deux cas d'étude représentant des configurations de moteurs turbopropulseurs ont été analysés, explorant les variations du nombre de profils, de la corde axiale et du rayon de pointe à l'entrée de la turbine. L'outil prend en charge des flux de travail adaptés aux moteurs turbofans et turbopropulseurs/turbomoteurs, incluant des modes où la puissance de la Power Turbine (PT) peut être fixée ou autorisée à varier afin d'offrir une plus grande flexibilité de conception. Les résultats ont été validés par comparaison avec des configurations optimisées manuellement et des analyses computationnelles de l'ensemble du moteur, démontrant une forte concordance. Les analyses de sensibilité ont identifié la corde axiale et le rayon de pointe comme des paramètres clés influençant la SFC par leurs effets sur la demande de refroidissement et la performance aérodynamique.

L'outil développé offre une capacité précieuse pour la conception préliminaire des turbines, en réduisant le temps d'optimisation, en améliorant la précision et en limitant les itérations manuelles entre les équipes d'ingénierie. Son application soutient les efforts de P&WC pour proposer des moteurs performants, économes en carburant et respectueux de l'environnement.

Afin de préserver l'avantage concurrentiel de Pratt & Whitney Canada, certaines données techniques propriétaires ont été volontairement omises.

Mots-clés: Optimisation du SFC; refroidissement de la turbine; optimisation des moteurs à turbine à gaz; aéromoteurs

SURROGATE-BASED OPTIMIZATION FOR EVALUATING TURBINE COOLING IMPACTS ON AERO-ENGINE PERFORMANCE

Mohamed A.K.I. AHMED

ABSTRACT

Traditionally, Gas Turbine Engines (GTEs) have been optimized at the component level, with a primary focus on maximizing individual efficiencies to ensure functionality and reliability. However, this approach does not always result in engines with low Specific Fuel Consumption (SFC). Given rising fuel costs and global initiatives targeting net-zero carbon dioxide (CO_2) emissions by 2050, it is increasingly critical to design engines with minimized fuel consumption at the system level.

This research presents the development of an integrated optimization tool that shifts the focus from maximizing component efficiency toward minimizing engine-level SFC. The work concentrates on turbine design, with particular emphasis on airfoil cooling, which represents the largest contributor to turbine cooling demand and has a direct impact on SFC. While cooling is essential for durability, excessive cooling reduces engine performance due to the extraction of compressor bleed air and mixing losses that degrade turbine work output.

The developed tool integrates several in-house platforms from Pratt & Whitney Canada (P&WC): the Turbine Aerodynamic Meanline (TAML) solver for meanline calculation, the Cooling Flow Prediction Tool (CFPT) for estimating airfoil cooling requirements, and the Framework for Design Exploration (FDE) for optimization execution. The workflows combine Design of Experiments (DOE) and Surrogate-Assisted Optimization (SAO) to efficiently explore the design space and accelerate convergence. SFC exchange factors and sensitivity factors are incorporated to estimate the impact of cooling on turbine efficiency and SFC during the preliminary design phase, where rapid but reliable estimates are required.

Two test cases representing turboprop engine configurations were analyzed, exploring variations in airfoil count, axial chord, and turbine inlet tip radius. The tool supports workflows for both turbofan and turboprop/turboshaft engines, including modes where the power of the Power Turbine (PT) may be fixed or allowed to vary for more design flexibility. Results were validated against manually optimized configurations and full-engine computational analyses, demonstrating strong agreement. Sensitivity analyses identified axial chord and tip radius as key drivers influencing SFC through their effects on cooling demand and aerodynamic performance.

The developed tool provides a valuable capability for preliminary turbine design, reducing optimization time, improving accuracy, and minimizing manual iteration between engineering groups. Its application supports P&WC's efforts to deliver high-performance, fuel-efficient, and environmentally sustainable engines.

In order to provide Pratt & Whitney Canada with a competitive advantage, certain proprietary technical data have been withheld.

Keywords: Specific Fuel Consumption (SFC); Turbine Cooling; Gas Turbine Engines Optimization; Aeroengines; Multi-Disciplinary Optimization (MDO)

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LIST OF ABREVIATIONS

CFD	Computational Fluid Dynamics
CFPT	Cooling Flow Prediction Tool
CO2	Carbon Dioxide
DOE	Design of Experiment
ÉTS	École de technologie supérieure
FEA	Finite Elements Analysis
GTE	Gas Turbine Engine
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LHS	Latin-Hypercube Sampling
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MDO	Multi-Disciplinary Optimization
NOx	Nitrogen Oxides
P&WC	Pratt & Whitney Canada
PDDS	Pre-Detailed Design System
SAF	Sustainable Aviation Fuel
SAO	Surrogate Assisted Optimization
TAML	Turbine Aerodynamic Meanline
TBC	Thermal Barrier Coating
TGO	Thermally Grown Oxide

TIT	Turbine Inlet Temperature

INTRODUCTION

Context

Gas Turbine Engines (GTEs) are one of the most powerful engines invented up to this day. Though the main use of GTEs is in the aviation sector to supply propulsion for aircraft, different applications of GTEs also exist. They are used in the marine sector to provide propulsion for the ships, in the gas and oil sector to drive compressors and pumps to help with petroleum extraction, in the industrial sector to generate power, and many other sectors. The reasons GTEs are used in different sectors are thanks to their efficiency, reliability, and ability to generate high power.

Specific Fuel Consumption (SFC) is a vital performance parameter of GTEs. Measuring the amount of fuel consumed per unit of thrust or power generated, SFC is considered one of the key figures of merit that evaluate the performance and efficiency of a GTE. SFC is a major influence on both customers, such as airlines, and the environment. Being the primary contributor to the total operating costs of an aircraft, SFC is considered the main performance factor that attracts customers and influence their decision to have an agreement with the engine manufacturer for engine utilization (Moustapha, Zelesky, Balnes, & Japikse, 2003). Reduction in SFC not only reduces the operating costs of an aircraft, but it also reduces the engine price and the weight of the aircraft as it means the fuel mass is reduced. A study found that a reduction of 1.5% of an engine's SFC is approximately equivalent to a reduction in the aircraft direct operational costs by 1%, engine price by 8%, and engine weight by 5% (Lyantsev, Breikin, Kulikov, & Arkov, 2003). Lyantsev et al. emphasized that a reduction of 4% of the engine's SFC due to the new technologies used could be a vital reason to design a new engine (Lyantsev et al., 2003).

The effects of SFC on the environment are also crucial. Those effects include carbon emission, air quality reduction, and noise pollution. When using jet fuels in GTEs, emission of gases such as Carbon Dioxide (CO2) and Nitrogen Oxides (NOx) into the atmosphere occurs. These gases contribute to the climate change and reduce the quality of the air, especially in densely populated areas such as airports. Additionally, when more fuel is burned, such as during aircraft take-off, noise due to the higher velocity of air exiting the engine increase, which contributes to the noise pollution particularly around airports.

With the growth in air travel, it is estimated that by 2050, around 10 billion passengers will be flying yearly, requiring over 620 Mega tonnes of fuel which will result in emission of approximately 2,800 million tonnes of CO2 (Air Transport Aviation Group, 2021). For that, global organizations and governments are setting new requirements for the aviation market to ensure more sustainable and environment friendly GTEs. An existing goal is to eliminate carbon dioxide emission by 2050 using new technologies and Sustainable Aviation Fuel (SAF) (Air Transport Aviation Group, 2021). Figure 0.1 shows the trend of zero-carbon emissions by improving the technologies used in aircraft, the operations and infrastructures needed to obtain SAF, and the use of SAF by 2050 (Air Transport Aviation Group, 2021).

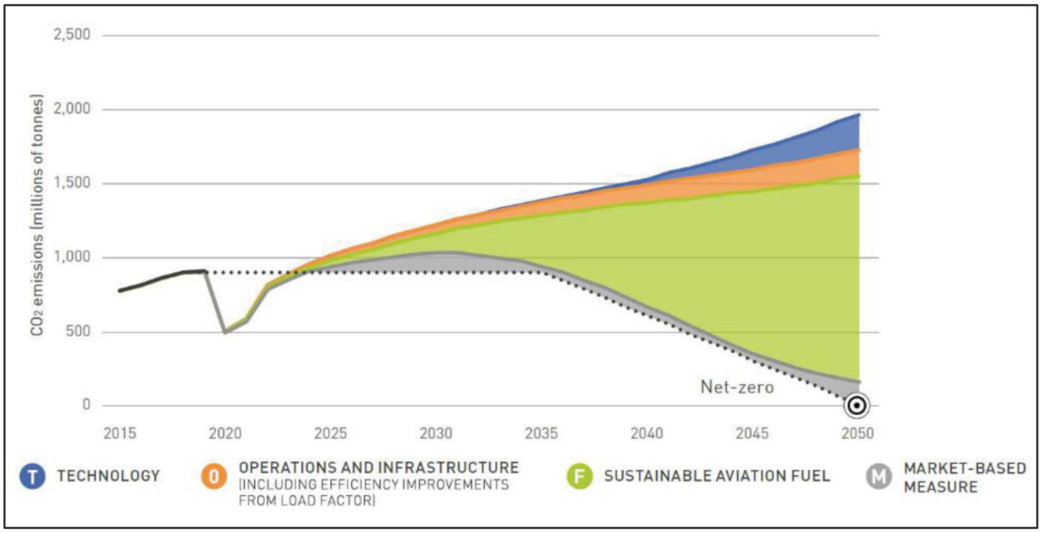

Figure 0.1 Sustainable Aviation Fuel Trend[1]

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[1] Figure taken from Air Transport Aviation Group (2021)

SAF is an alternative aviation fuel that uses sustainable fuel such as biomass, coal, hydrogen and natural gases (TechSci Research, 2023). With the increasing demands from the governments to use biofuels such as SAF, the market for global sustainable aviation fuel is expanding (TechSci Research, 2023). For example, in March 2023, JetBlue airline and Shell Aviation established an agreement to bring SAF to Los Angeles International Airport, which will provide JetBlue with million gallons of SAF (TechSci Research, 2023).

Although GTEs are expected to replace the current jet fuel with SAF in the future, and with hydrogen and hybrid-electric engines in the long-term, it is imperative that, in the interim, a concerted effort is made to minimize fuel consumption. Doing so, not only contributes to immediate environmental benefits but also ensures efficient and sustainable usage of future engines.

With the effects of fuel burn on the customers and the environment, it becomes evident that GTEs manufacturers should aim to reduce SFC on their engines. Therefore, engine optimization should be based on achieving minimum SFC and not necessarily maximum components' efficiencies. Although high components' efficiencies could lead to lower SFC, this is not always the case. Hence, it is sometimes better to sacrifice slightly on the components' efficiencies in order to have an engine that consumes less fuel.

Different factors affect SFC; one of these factors is the amount of flow extracted from the compressor. Known as "compressor bleed", this extracted flow serves various purposes, such as de-icing aircraft surfaces and pressurizing the cabin. One of the main roles of the bleed flow is to cool turbine components in order to allow the materials to withstand high temperatures and ensure their durability. However, bleed flow affects engine performance negatively. Zhao et al. conducted a study to investigate the effects of compressor bleed on engine performance, whereas Yuhas and Ray conducted a ground test on the F404-GE-400 engine to study these effects (Yuhas & Ray, 1992 ; Zhao, Li, Li, & Zhou, 2011). It was noted that as the compressor bleed increases, thrust decreases and SFC increases. Another research by Esgar and Ziemer showed that for turbojets and turboprops, turbine cooling results in high reduction in thrust and power generation, and high increase in SFC, with turboprops experiencing higher effect than turbojets (Esgar & Ziemer, 1955). Therefore, although turbine cooling is essential, the amount of cooling should be calculated wisely to ensure better SFC of the engine. This will be validated throughout this thesis.

Given that (1) Engine optimization should be based on minimum SFC, and (2) Cooling flow negatively affects engine performance, this thesis focuses on optimizing the turbine of GTEs by minimizing its effects on SFC through effective management of the amount of cooling required for the turbine's airfoils. Although the negative impact of cooling flow on engine performance is well-established from previous studies, this thesis emphasizes that optimizing turbines to consume less turbine cooling may lead to minimizing SFC, even at the expense of lower turbine efficiency. These represent the primary arguments of this thesis, particularly countering previous studies that advocated against compromising turbine efficiency to achieve lower SFC.

For this, a tool is developed that uses Surrogate Assisted Optimization (SAO) and Design of Experiments (DOE) optimization algorithms to suggest the turbine design and its cooling requirements that results in minimum SFC of the engine. This tool will be used during the conceptual/preliminary design phase, where freedom of design choices is high. Key assumptions were made during the tool's development, notably that the designs of the compressor and combustion chamber remain fixed and unchanged compressor pressure ratio. While the pressure ratio of the compressor is influenced by the cooling flow, this study exclusively focuses on turbine optimization within the constraints set by other components.

This research is part of a collaborative project between Pratt & Whitney Canada (P&WC) and École de technologie supérieure (ÉTS), titled Multidisciplinary Design Optimization for Advanced and Sustainable Propulsion. The objective of this research chair is to develop tools that support and automate the design process of GTEs across various disciplines, with a strong emphasis on next-generation propulsion systems.

Previously, the chair focused on the development of a Pre-Detailed Design System (PDDS), which primarily addressed the structural aspects of component design. The PDDS was conceived to bridge the gap between the preliminary and detailed design phases by integrating optimization algorithms, Computational Fluid Dynamics (CFD), and Finite Element Analysis (FEA). Notably, PDDS is expected to reduce the duration of the preliminary turbine design phase by a factor of ten (Twahir, 2021). Figure 0-2 illustrates some of the projects encompassed within PDDS. For further details on PDDS and the architecture of the turbine rotor system optimizer, readers are encouraged to consult the work of Twahir (Twahir, 2021).

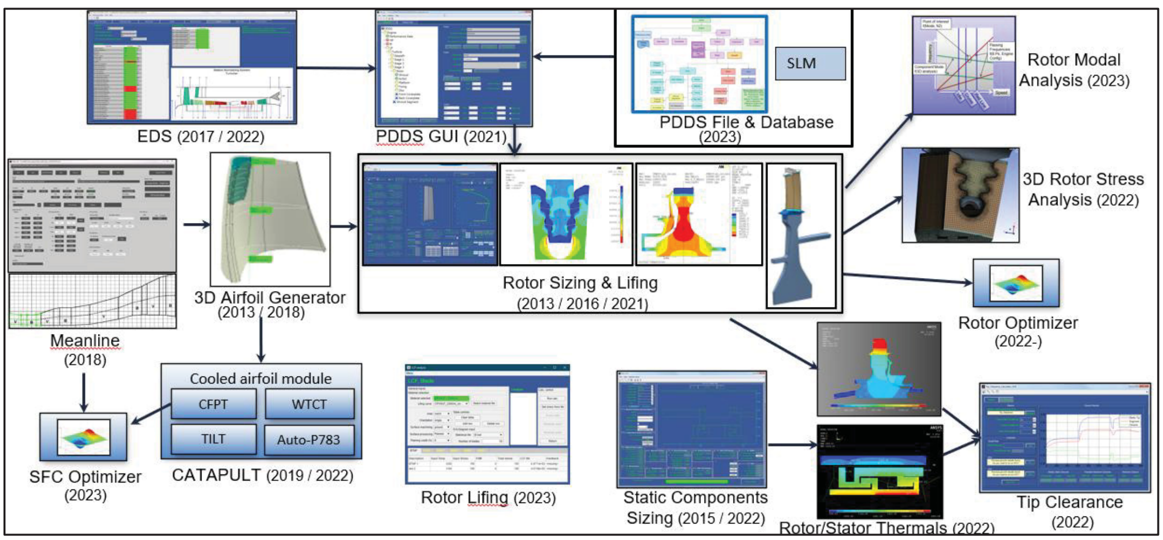

Figure 0.2 PDDS Projects

Main Objective

The main objective of this research is to develop a comprehensive tool that facilitate the design of the turbine using optimization algorithms with the focus on achieving the design that results in minimum SFC. This tool will consider the effects of turbine cooling to reduce its negative impact on turbine efficiency and engine performance. Therefore, the optimal turbine design will be the one that achieves the minimal effect on SFC while effectively managing turbine cooling. The tool aims to reduce time and human error associated with manual optimization processes and facilitate collaboration between different departments involved in turbine design.

It is worth noting that this tool does not serve as a substitute for the intricate and comprehensive analyses involved in calculating SFC of an engine. Instead, it provides an estimated value of the changes in SFC during the preliminary design phase, enabling designers to make more informed and improved design choices.

Secondary Objectives

In addition to the main objective, this research includes the following secondary objectives,

- Integrate the existing tool for estimating airfoil cooling flow requirements into the optimization framework to ensure accurate predictions of cooling needed for turbine airfoils.
- Develop an optimization framework that considers the trade-off between cooling flow reduction and turbine efficiency, prioritizing SFC reduction while considering the impact on other performance parameters.
- Incorporate sensitivity factors into the analysis to estimate the impact of mixing losses resulting from mixing the cooling flow with the main flow.
- Incorporate SFC exchange factors into the analysis to estimate the impact of cooling flow and turbine efficiency changes on SFC.

Thesis Hypothesis

The hypothesis underlying this research is that by optimizing the design of the turbine section of GTEs to minimize cooling flow while maintaining necessary cooling effectiveness, a notable reduction in SFC can be achieved without compromising the safety and durability of the turbine components. It is further hypothesized that the integration of an airfoil cooling estimation tool, a turbine meanline information tool, optimization algorithm, and the incorporation of sensitivity factors and SFC exchange factors will enable informed decision-making and result in more fuel-efficient engine based on the optimized turbine designs. This will improve GTEs performance in terms of fuel efficiency and environmental sustainability. Through various testing and validation, this research aims to support and validate the hypothesis.

Thesis Assumptions

By considering the assumptions below throughout the research process, it is expected to develop a reliable and practical framework,

- The existing airfoil cooling estimation tool used in this research accurately predicts the cooling flow requirements for turbine airfoils, ensuring their structural integrity and preventing thermal damage,
- The existing turbine meanline information tool provides accurate data of the meanline with the consideration of loss models,
- The developed optimization algorithm effectively explores the design space and identifies optimal turbine parameters that minimize cooling flow requirements and reduce SFC without compromising safety and durability,
- The sensitivity factors considered in the analysis provide reliable estimation of the impact of mixing losses resulting from different cooling flow configurations mixing with the main flow,
- The SFC exchange factors utilized in the research accurately quantify the relationship between cooling flow reduction and its effect on SFC, as well as the impact of changes in turbine efficiency on SFC,
- The developed tool aligns with P&WC practices and requirements, providing practical and feasible turbine designs that meet performance and safety criteria,
- The assumptions made in the research are based on the available data, models, and tools, and they aim to represent a realistic approximation of the gas turbine engine

system. However, it is acknowledged that certain simplifications and generalizations may be present due to practical constraints and limitations.

Thesis Organization

To ensure a coherent flow of information and facilitate the reader's understanding, the thesis is structured in the following manner:

- **Chapter 1:** Literature review covering fundamentals of turbine meanline design, the importance of turbine cooling and its calculations, and the negative effects of turbine cooling on engine performance,
- **Chapter 2:** Research methodology, including the structure of the developed tool, the integration of various tools, the optimization methods employed, and an explanation of the different workflows available,
- **Chapter 3:** Overview of the test cases and test scenarios covered in this thesis along with the validation process of the results,
- **Chapter 4:** Results obtained from the test cases and test scenarios. The findings are thoroughly discussed and interpreted, along with a comparison of two different modes for the workflow designed for turboprop and turboshaft engines,
- **Chapter 5:** Sensitivity analysis of the results, aiming to identify the geometric factors that have the most significant impact on turbine cooling, turbine efficiency, and SFC.

Finally, the thesis concludes with a summary of the key findings and recommendations for future research.

CHAPTER 1

LITERATURE REVIEW

This chapter covers some of the important literature information that is necessary to know for the reader before going through the upcoming chapters of the thesis. The chapter is divided into sections discussing the Fundamentals of Turbine Design discussing the design process during the preliminary design phase, the Fundamentals of Airfoil Cooling, and the Effects of Turbine Cooling on Engine Performance.

1.1 Fundamentals of Turbine Design

1.1.1 Gas Turbine Engine Concept

A typical Gas Turbine Engine (GTE) consists of five main components as shown in Figure 1.1. First, the inlet ingests the air, directing it to the compressor where the air is slowed down while increasing its pressure and temperature before entering the combustion chamber. When the air enters the combustion chamber, it is mixed with fuel and the mixture is burned. The high temperature mixture then enters the turbine, where it expands, rotating the blades of its stages to generate energy to power the compressor. The turbine is often divided into two or three sections: the High Pressure Turbine (HPT), the Low Pressure Turbine (LPT) and, the Power Turbine (PT) where the power generated are used to drive the compressor and a fan for turbofan engines, a propellor for turboprop engines or a shaft for turboshaft engines. After leaving the turbine, the gas enters the nozzle where the flow is accelerated, leaving with a velocity higher than that at the inlet to generate propulsion for the case of aeroengines.

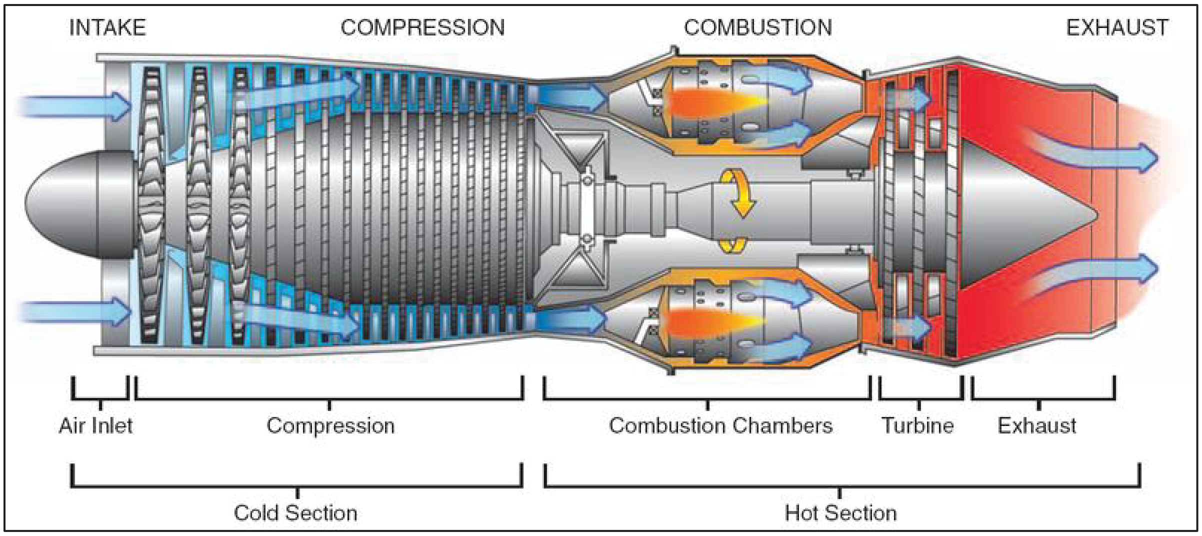

Figure 1.1 Gas Turbine Engine Sections[2]

The design process of a new GTE begins with conducting market research to define the specifications needed to design a competitive engine (Moustapha et al., 2003 ; Saravanamuttoo, Rogers, & Cohen, 2009). These new engines proposals could also arise from the engine manufacturer offering a new or upgraded design that could attract customers and increase profitability with better cycle and performance (El-Sayed, 2016). The specifications, however, face many challenges. For example, the new design must ensure that the proposed performance targets can be met with available manufacturing capabilities and materials. The selection of materials must balance high-temperature performance, durability, weight, and cost, while also aligning with supplier capabilities and production scalability (Benini, 2011 ; Srinivas, Raghunandana, & Satish Shenoy, 2018). Moreover, tight tolerances, advanced cooling techniques, and complex geometries, especially in the turbine, can impose significant manufacturing constraints (Moustapha et al., 2003). Coordination with suppliers early in the design phase is crucial to confirm that the required components can be reliably produced using existing and economically adaptable technologies. Furthermore, recent advancements in materials science have contributed to the development of high-performance materials for

[2] Figure taken from FAA-8083-3A (2004)

aerospace applications. These advances are particularly relevant in the context of emerging sustainable engine technologies, including those designed to operate on SAF and hydrogen. Comprehensive reviews by Parveez et al. (2022) and Srinivas et al. (2018) highlight recent progress in high-temperature alloys, lightweight composites, and environmentally resilient materials that support the performance demands of next-generation propulsion systems (Parveez et al., 2022 ; Srinivas et al., 2018).

Numerous additional challenges exist, including structural aspects (e.g., shaft vibrations, stress analysis, and component lifing), aerodynamic phenomena (e.g., flow separation, surge, and stall), and acoustic requirements (e.g., noise reduction). These multidisciplinary constraints make the overall engine design process both lengthy and highly complex (El-Sayed, 2016).

1.1.2 Turbine Meanline Design

With the specifications of the new engine design defined and the optimal performance map and cycle are chosen, the turbine design process begins. During the preliminary design phase, turbine design begins with meanline analysis, a one-dimensional (1D) approach used to estimate flow path geometry and key performance parameters such as pressure ratio, efficiency, and blade loading while accounting for aerodynamic loss models. This method assumes a representative mean streamline passing through the turbine, where flow properties (e.g., velocity, pressure, and temperature) are averaged across the annulus to approximate the behavior of the entire stage (Moustapha et al., 2003 ; Saravanamuttoo et al., 2009). These calculations are often implemented in parametric models or in-house codes to allow rapid results and evaluation of performance metrics such as efficiency, work output, and main stream velocity with the consideration of loss models such as those proposed by (Denton, 1993 ; Kacker & Okapuu, 1982 ; Schobeiri & Abouelkheir, 1992 ; Tremblay, Sjolander, & Moustapha, 1990).

While meanline analysis provides lower-fidelity results compared to three-dimensional methods, its computational efficiency and robustness makes it key choice for initial design iteration and conceptual design analyses (Hendricks, 2016 ; Parisi & Haglind, 2023). These rapid calculations enable the conceptual/preliminary turbine design to be evaluated quickly before selecting the optimal configuration. Subsequently, higher-fidelity analyses, including CFD are performed to refine and validate the design when moving to the detailed design phase (Parisi & Haglind, 2023).

1.1.3 Meanline Results Evaluation

Evaluating the results generated by the meanline analysis is a critical step in the turbine preliminary design process that requires expertise to ensure good design choices, yet it is not always straightforward. As mentioned earlier, the meanline output provides both geometric and aerodynamic parameters that define the structure and expected performance of each stage. Several key factors must be examined to determine whether the proposed design is viable including stage efficiency, loading coefficient, Zweifel coefficient, tip-clearance-to-span ratio, and the effective throat area. These metrics help determine how effectively the flow passes through the turbine and whether the design can meet aerodynamic and mechanical expectations under the selected design choices.

As an example, a high stage loading may indicate that too much energy is being extracted in a single stage, potentially leading to excessive aerodynamic losses or structural stress on the blades. This may suggest the need to redistribute the work over additional stages to achieve more balanced loading. Similarly, the Zweifel coefficient, which relates to blade spacing and turning angle, can reveal whether the chosen blade count provides adequate flow guidance without excessive losses due to separation or secondary flows (Farokhi, 2014 ; Moustapha et al., 2003)

Geometric considerations also play a crucial role. A stage with a large number of airfoils or long axial chords will present a larger wetted area. While this can improve flow control and increase the capacity for work generation, it also raises the surface exposed to hot gases, thereby increasing the need for cooling. This, in turn, imposes additional thermal management challenges and can lower overall efficiency if not carefully addressed while also causing a challenge for the material, manufacturing, and structure of the blades (Saravanamuttoo et al., 2009). Additionally, the tip clearance-to-span ratio is vital in determining leakage losses and is especially important in high-speed turbines where leakage can significantly impact performance.

Moreover, choosing a specific meanline design accounts for the losses occurring within the turbine. In an ideal scenario, zero losses would maximize efficiency and performance, but this is not feasible in practice. Therefore, the objective becomes minimizing these losses as much as possible. As mentioned earlier, various loss models exist, some publicly available in literature, others proprietary and used within industry. The primary losses in a turbine stage are profile losses, secondary flow losses, tip clearance losses, and trailing edge losses, as shown in Figure 1.2.

Profile losses stem from boundary layer effects over the airfoil surface due to friction and potential separation (Denton, 1993 ; Farokhi, 2014 ; Kacker & Okapuu, 1982 ; Moustapha et al., 2003 ; Saravanamuttoo et al., 2009). Secondary losses arise from complex three-dimensional flow phenomena, especially near endwalls. Tip leakage losses occur in unshrouded blades when high-pressure flow leaks over the blade tip, while trailing edge losses are caused by wake mixing downstream of the blade. These losses directly impact efficiency and are often estimated using empirical or semi-empirical correlations (Denton, 1993 ; Farokhi, 2014 ; Kacker & Okapuu, 1982 ; Moustapha et al., 2003 ; Saravanamuttoo et al., 2009). There also exist mixing losses due to the use of cooling. As the cooling flow mixes with the main flow, it introduces additional losses. This topic will be discussed in more detail later.

Therefore, a good meanline design seeks to minimize these losses through appropriate stage loading, airfoil shape, and tip clearance management (Fielding, 2000). Finally, with the aerodynamic results selected, further assessments are conducted to ensure that stress, acoustics, durability, and weight are within acceptable limits.

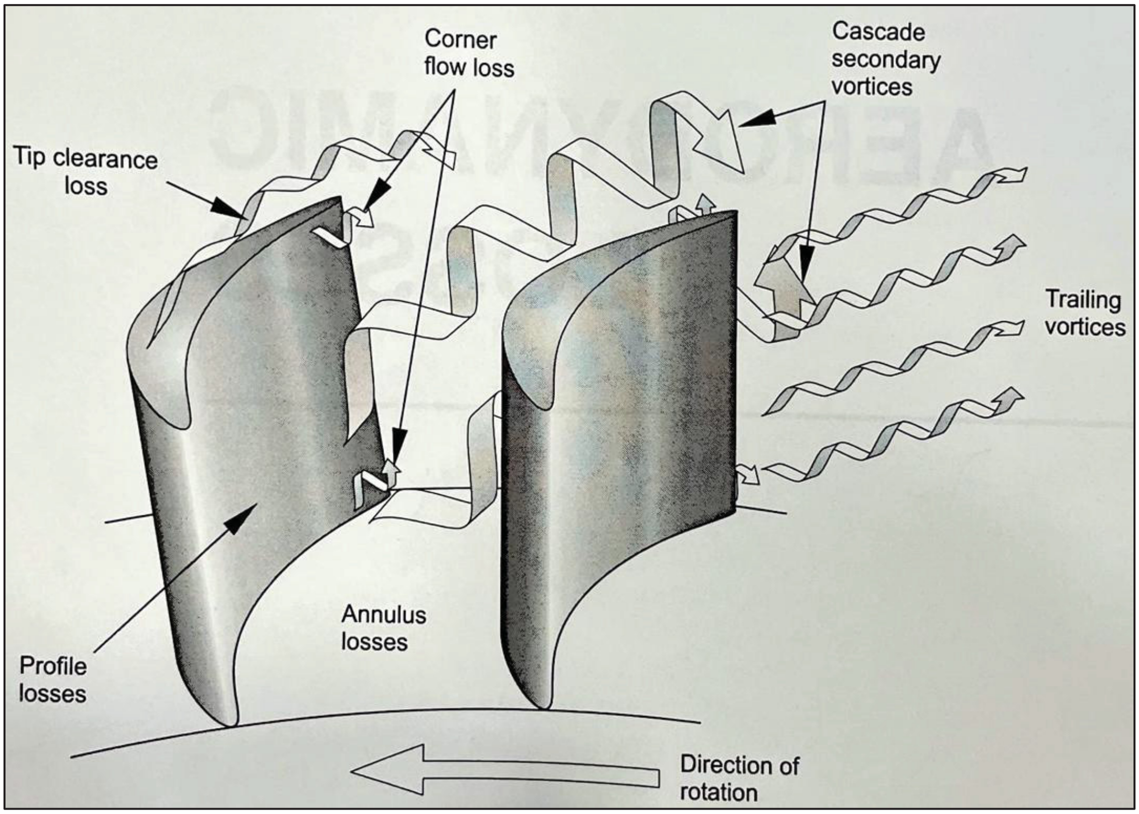

Figure 1.2 Turbine Airfoil Losses[3]

1.1.4 Meanline Automation and Optimization

Traditionally, the evaluation of turbine meanline results is a manual and iterative process, where engineers would adjust design parameters based on experience and intuition to meet performance targets and design constraints (Twahir, 2021). While this approach can be effective in the hands of experienced designers, it is time-consuming and may overlook optimal configurations due to the high dimensionality and complexity of the design space (Doran,

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[3] Figure taken from Moustapha et al. (2003)

Vlasic, Guèvremont, & Moustapha, 2018 ; Twahir, 2021). To overcome these limitations, modern gas turbine design increasingly relies on optimization frameworks that automate the exploration of the design space. Emerging advancements in optimization techniques and Machine Learning (ML) offer the potential to further reduce manual effort, automate the process, and ensure the selection of optimal designs.

An example can be taken from Doran et al., where a Framework for Design Exploration (FDE) was connected to a meanline solver at Pratt & Whitney Canada (P&WC) to create a surrogate model for solving the meanline and optimizing specific factors (Doran et al., 2018). FDE employs Design of Experiments (DOE) and Surrogate Assisted Optimization (SAO) that allows the design space to be explored effectively (Doran et al., 2018). Doran et al. highlighted one of the main drawbacks of traditional DOE methods, such as Latin-Hypercube Sampling (LHS), which is their inability to fully capture the physical relevance of all design points, often leading to non-physical or irrelevant design combinations (Doran et al., 2018). They emphasized that SAO addresses this by narrowing the focus to local optima, progressively refining the search area until an optimal solution is found.

The optimization process at P&WC follows a structured workflow (Doran et al., 2018). As shown in Figure 1.3, the first step is reading the user's settings, which define the number of learning points to be analyzed in each optimization cycle until convergence is reached. These settings also include input parameters (factors) and constraints on the output parameters (responses). After reading the settings, the surrogate model is built for each constraint and objective, and the optimum is identified. Following this, 1000 points are used as samples for the next optimization cycle, with the best points selected based on a function of interest. This function explores the design space and ensures that convergence occurs as quickly as possible to a physically approved solution. The best points are then analyzed by the optimization tool. Convergence is checked using a user-defined criterion. When the optimum remains constant after a set number of optimization cycles, the optimization is assumed to have converged. To reduce optimization time, the system is parametrized, which helps limit the design space without excluding potential optimal solutions. Parameters such as hub radius and flare angles are carefully defined to simplify the optimization process, ensuring a focus on physical, feasible solutions (Doran et al., 2018).

Doran et al. applied this methodology to optimize the gaspath of a multi-stage turbine (2018). The study aimed to improve turbine efficiency by optimizing factors such as stage efficiency, flare angles, and Zweifel coefficients. A key finding for one of their test cases was that the optimization led to a 4.45% improvement in the first spool efficiency and a 1.42% improvement in the second spool efficiency. These enhancements resulted in an overall efficiency increase of 2.79%. This example demonstrates the effectiveness of optimization frameworks in improving turbine performance while ensuring physical constraints are met.

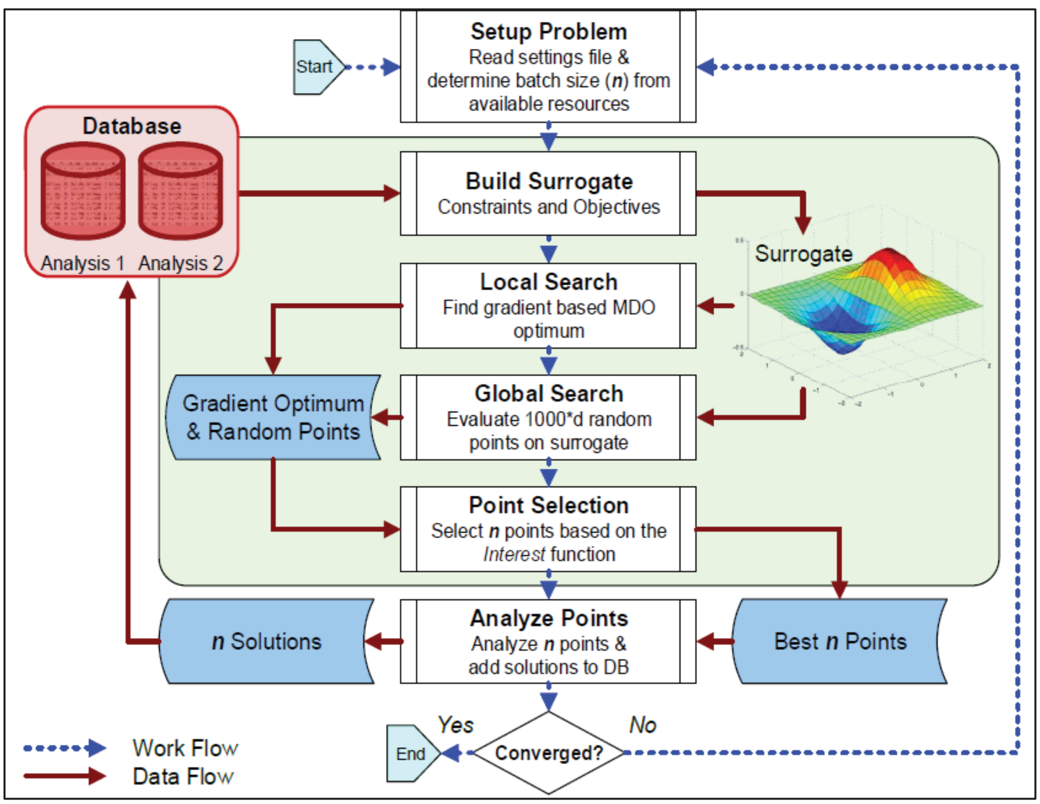

Figure 1.3 P&WC SAO Workflow[4]

[4] Figure taken from Doran et al (2018)

1.2 Fundamentals of Airfoil Cooling

1.2.1 The Importance of Cooling

As mentioned earlier, airfoil cooling is essential to ensure the durability of the turbine components. Since most competitive engines aim to have higher Turbine Inlet Temperature (TIT), mainly to increase the thermal efficiency and the power output of the engine, this will result in more heat transfer to the turbine airfoils which creates a difficult environment for them, affecting their durability and useful life (Han, Dutta, & Ekkad, 2012). Cooling air helps maintain the temperature of the turbine airfoils to a level where they can function and last longer.

Currently, research in tackling thermal issues in gas turbine engines focus on three approaches: (1) advanced materials and their ability to withheld extreme temperature, (2) developments in cooling technologies, and (3) improvements in coatings used (Chyu, 2012). Thanks to the advanced research in materials and airfoil cooling, the impact of TIT on turbine airfoils durability and useful life reduced (Moustapha et al., 2003). Figure 1.4**Error! Reference source not found.** illustrates the relationship between increased TIT and the improved lifespan of turbine components, highlighting the effectiveness of cooling technologies and advanced materials. The availability of these advancements allows airfoils to operate at or near stoichiometric limits, providing opportunities for future utilization of non-metallic materials (Moustapha et al., 2003).

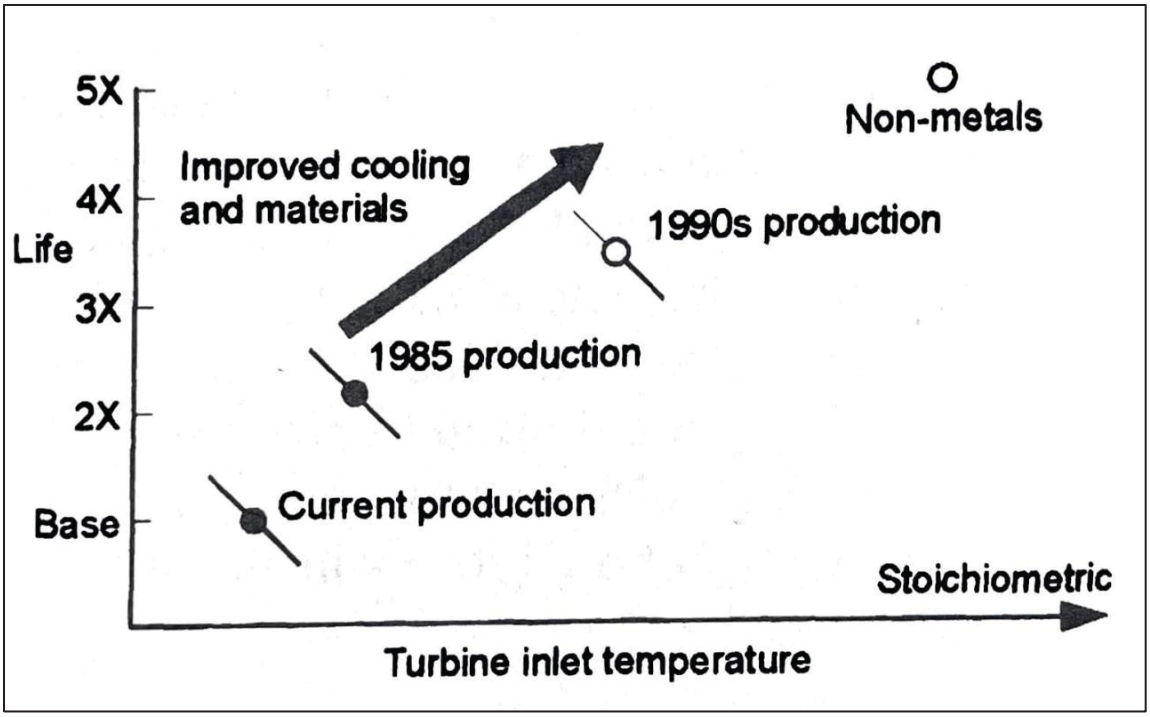

Figure 1.4 TIT vs Airfoil Life Through Cooling Improvements[5]

1.2.2 Turbine Airfoil Cooling Design

The cooling design of a turbine airfoil is a complex process that considers the geometry and the thermal load characteristics of the airfoil (Chyu & Siw, 2013). The optimal design for a turbine airfoil is to be very thin to reduce the amount of materials used and hence, the overall weight of the stages, while achieving better aerodynamic characteristics (Moustapha et al., 2003). However, the cooling system requires the airfoil shape to be thicker to accommodate internal cooling passages. Therefore, the final design is a compromise between these two requirements, often involving multiple design iterations to achieve the optimal result while ensuring manufacturability (Moustapha et al., 2003).

[5] Figure taken from Moustapha et al. (2003)

Airfoil cooling can be categorized into internal and external cooling. For the internal cooling, the cooled air extracted from the High Pressure Compressor (HPC) enters the blade from the hub section and the vane from either the hub or tip sections (Chyu, 2012). It then circulates around the interior section of the airfoil through passages of various configurations to cool it by convection before leaving the airfoil from the small holes made at the trailing edge, meeting the hot gaspath around the airfoil (Chyu, 2012). Part of the internal cooling flow is bled out the airfoil to create a blanket of cooled air around the airfoil known as film cooling, this technique contributes significantly to the external cooling of the airfoils (Moustapha et al., 2003).

Some blades, especially those in the first stages use Thermal Barrier Coating (TBC). TBC is utilized to extend the working life of the blade by reducing metal temperatures. It consists of a layered structure, including a ceramic thermal barrier, a metallic bond coat, a Thermally Grown Oxide (TGO) layer between the topcoat and bond coat, and a substrate (Xu, Guo, & Gong, 2008). The ceramic thermal barrier layer protects underlying materials and acts as a shield against erosion and corrosion (Xu et al., 2008). The metallic bond coat safeguards the superalloy substrate from oxidation, balances thermal mismatches, and prevents interdiffusion between the topcoat and substrate (Xu et al., 2008).

The combined effect of internal cooling and TBC enables a reduction of around 300°K in the airfoil's surface temperature, allowing the engine to operate above the airfoil's melting point, thereby enhancing energy efficiency and overall engine performance (Xu et al., 2008).

1.2.3 Amount of Cooling Needed

Effective cooling in turbine design requires careful consideration by designers to balance the amount of cooling. It is crucial to ensure that the maximum temperatures of the blade surface and the temperature gradients align with the maximum thermal stress of the blade for optimal durability (Han et al., 2012). Insufficient cooling can lead to higher blade temperatures and reduced lifespan, while excessive cooling can negatively impact the engine performance (Han et al., 2012). Therefore, the cooling amount should be chosen to minimize the use of compressor bleed air, maximize the benefits of high TIT, extend blade life, and minimize performance losses (Han et al., 2012).

For the cooled turbine design, two important aspects are taken into considerations (Saravanamuttoo et al., 2009). The first is to choose a good aerodynamic design which results in the least amount of cooling air for given performance of cooling, and the second is by considering the effect on the cycle efficiency due to the losses caused by the cooling process (Saravanamuttoo et al., 2009). Saravanamuttoo et al. explain those sources of loss as the following:

1. Direct loss of turbine work due to a reduction in turbine mass flow,
2. Negative reheat effect in the remaining stages as the expansion is no longer adiabatic,
3. Pressure loss and enthalpy reduction due to mixing of cooled air with the mainstream,
4. As the cooling air takes its way through the cooling passages, some ‘pumping’ work is done by the blade on the cooling flow,
5. If a heat-exchanger is used, the reduced temperature of the gas leaving the turbine will be less effective for the heat-exchanger.

Adjusting losses 1 and 5 can be done through cycle calculations. However, losses 2, 3, and 4 require a reduction in turbine efficiency (Saravanamuttoo et al., 2009). Therefore, it is important to raise the question as if it is advantageous to sacrifice some aerodynamic efficiency to reduce those losses (Saravanamuttoo et al., 2009).

1.2.4 Airfoil Cooling Sections

So far, discussions of the importance of cooling, how the cooling design is implemented and the importance of selecting the right amount of cooling were done. In this section, the cooled sections of the airfoils are discussed. Chyu classifies the turbine airfoil into five sections with accordance to the thermal load and flow conditions as the showerhead (or leading edge), the airfoil (or main body), the trailing edge, the platform, and the blade tip. These are illustrated in Figure 1.5. Each of these sections have their own techniques for cooling and cooling requirements with some of the techniques could be implemented in other turbine components such as the disks and combustor liners (Chyu, 2012). Although different cooling techniques exist, a summary of the standing techniques used is written below as covered by Chyu,

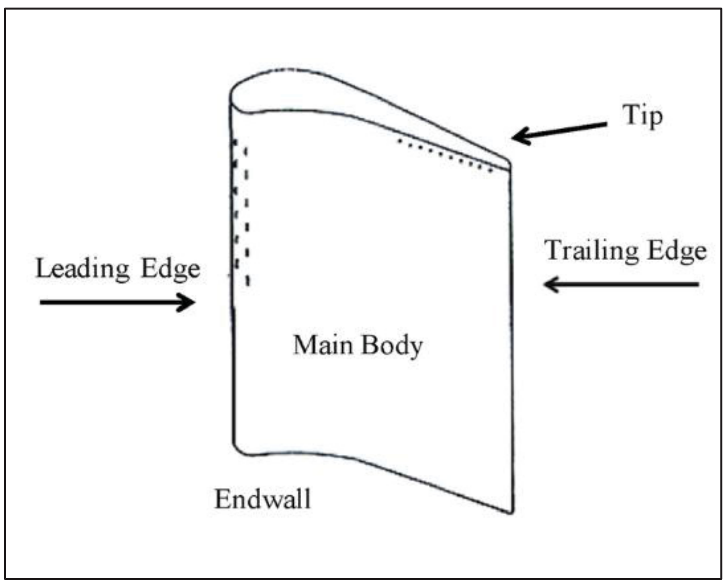

Figure 1.5 Airfoil Cooling Sections[6]

[6] Figure taken from Chyu (2012)

- **Showerhead Film Cooling:** Showerhead film cooling (at the leading edge) is most used to provide effective thermal protection of the external section of the leading edge. As the cooling flow passes internally within the airfoil, it exits through a two or more rows of film cooling holes, creating a protective film cooling around the blade, hence the name "showerhead", reducing the heat transfer to the airfoil. Despite the manufacturing challenges posed by the need to create small holes around the tight curvature of the blade's leading edge, facilitating the orientation of the cooling flow's axes along the radial direction of the airfoil with a shallow angle to the surface, utilizing this technique in the first turbine stage is preferable due to the elevated temperatures experienced in this stage.
- **Main Airfoil Cooling:** The use of internal convection is usually done for the airfoil. This is usually supplied by serpentine passages as shown in Figure 1.6. As the cooling flow circulates through the serpentine passages, internal temperature is reduced due to heat convection. The main airfoil is also cooled by the film cooling created from the showerhead cooling, which helps in reducing the external surface's temperature.
- **Trailing Edge Cooling:** Many factors make trailing edge cooling a challenge. (1) Since having a good aerodynamic shape of the airfoil requires the trailing edge to be thin, this restricts the internal space available to provide cooling. (2) The film cooling created from the leading edge becomes quite weak when it reaches the trailing edge, especially on the airfoil's convex side. (3) Since the end of the trailing edge is an extended surface, this results in the internal cooling flow to be heated before arriving. From these three points, the trailing edge cooling is usually done by using the approach of passive heat transfer enhancement. This is done by the use of pin-fin arrays (also called pedestals), especially for the vanes. Pedestals have another advantage as they serve as a structural support to bridge the suction and pressure surfaces of the airfoil.

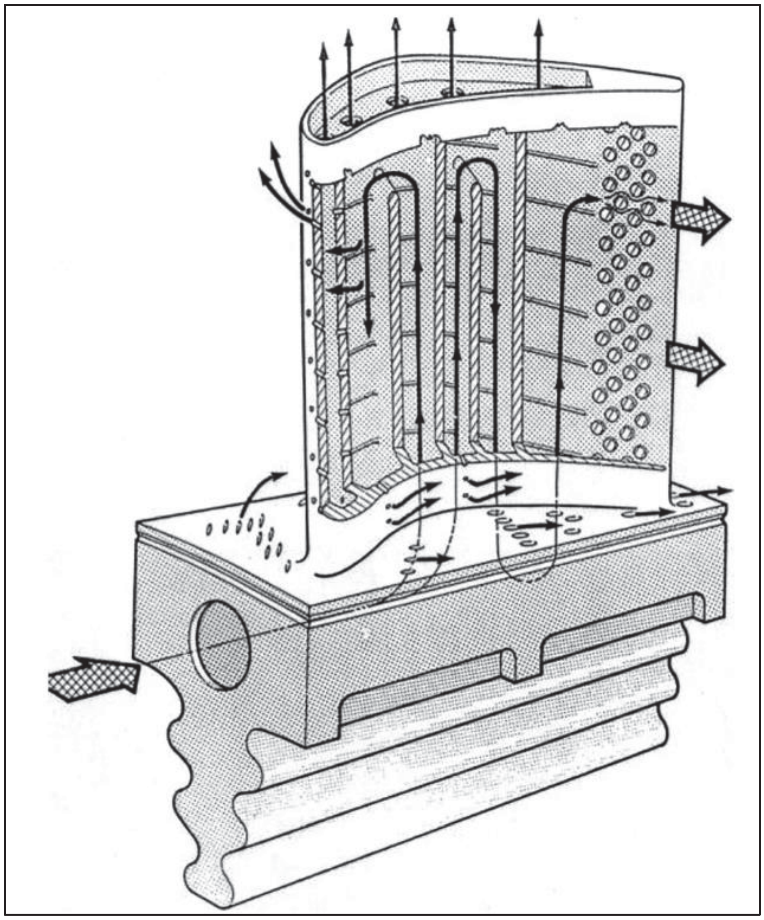

Figure 1.6 Serpentine Passages for Internal Cooling[7]

1.2.5 Cooling Scheme Analysis

With all the information mentioned taken into consideration, it can be established that designing an airfoil cooling scheme is a rather complex process. However, After selecting the cooling scheme, classical heat exchanger analyses is done to test how effective the cooling scheme is in reducing the airfoil's metal temperature (Moustapha et al., 2003). These analysis determine how the external boundary layers, internal cooling flow effectiveness, metal

[7] Figure taken from Chyu (2012)

conduction and stress analysis are successful (Moustapha et al., 2003). The results of these analyses allow the designer to estimate the life of the airfoil. Throughout these analyses, errors should be avoided as they could lead to significant changes in the predicted life of the airfoil (Moustapha et al., 2003). Furthermore, airfoils that have reached the end of their lifespan are often discovered during scheduled maintenance, exhibiting small cracks, providing feedback on the effectiveness of the cooling scheme and aiding the designer in improving their research to develop an enhanced cooling scheme. (Moustapha et al., 2003). Heat transfer analysis are also conducted on the airfoils by treating them as simple heat exchangers (Moustapha et al., 2003). Moustapha et al. provide definitions for several crucial heat transfer parameters, which are summarized below. The corresponding equations can be found in Table 1.1.

- **Heat Load Parameter:** A measure of the amount of cooling flow required for an airfoil. For better engine performance, the amount of cooling for all the airfoils should be minimized.
- **Cooling Effectiveness:** A measure of the airfoil metal temperature. Cooling effectiveness is also a measure of the airfoil life. A small cooling effectiveness will mean that the airfoil is experiencing high temperature from the mainstream, which for a very close cooling effectiveness value, could be close to the mainstream gas temperature. Theoretical maximum cooling effectiveness occurs when the metal temperature is equal to the coolant inlet temperature.
- **Convective Efficiency:** A measure of internal heat transfer process between the airfoil material and the cooling flow. It is enhanced by using internal ribs and fins.
- **Film Effectiveness:** A parameter that assesses the effectiveness of cooling between the coolant film surrounding the external surface of the airfoil and the temperature at which the cooling flow is ejected. The film effectiveness is closely related to the convective efficiency, as the temperature at which the cooling flow is ejected depends on the heat absorbed by the cooling flow as it passes through the internal passages of the airfoil. This temperature determines the theoretical minimum temperature that the coolant film should have.

- **Resistance Ratio:** A measure of the ratio of heat conduction through the airfoil material to the convection from the mainstream gas. It is a function of the convective heat transfer coefficient and the airfoil material conductivity.

Table 1.1 Airfoil Heat Transfer Parameters[8]

Parameter	Definition
Heat Load Parameter	$\beta = \frac{m_c C_p}{h_g A_g}$
Cooling Effectiveness	$\phi = \frac{T_g - T_m}{T_g - T_{c,in}}$
Convective Efficiency	$\eta_c = \frac{T_{c,out} - T_{c,in}}{T_m - T_{c,in}}$
Film Effectiveness	$\eta = \frac{T_g - T_f}{T_g - T_{c,out}}$
Resistance Ratio	$\psi = \frac{h_g A_g L}{kA}$
$\boldsymbol{m_c}$= Coolant Mass Flow Rate, $\boldsymbol{C_p}$= Heat Capacity, $\boldsymbol{h_g}$= Convective Heat Transfer Coefficient, $\boldsymbol{A_g}$=Surface Area Exposed to the Hot Gas, $\boldsymbol{T_g}$=Hot Gas Temperature, $\boldsymbol{T_{me}}$=Airfoil External Surface Temperature, $\boldsymbol{T_{c,in}}$=Coolant Temperature Entering, $\boldsymbol{T_{c,out}}$=Coolant Temperature Exiting, $\boldsymbol{T_f}$=Film Temperature, $\boldsymbol{k}$ =Thermal Conductivity Constant	

1.3 Effects of Turbine Cooling on Engine Performance

As discussed earlier, turbine cooling affects the engine performance, this section discusses the effect on the thermodynamic cycle of the engine, turbine efficiency and SFC.

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[8] Equations taken from Moustapha et al. (2003)

1.3.1 Turbine Cooling and Thermodynamic Cycle

Turbine cooling has a significant impact on the thermodynamic cycle of a GTE. The work of Denton touches more details into how cooling mechanisms influence the thermodynamic cycle and could be sought for detailed analyses (Denton, 1993). This section aims to explore the fundamental effects of turbine cooling on the thermodynamic cycle, complementing Denton's comprehensive analyses.

When extracting high-pressure air from the compressor to cool the turbine section, this flow changes some performance parameters of the turbine. One of those performance parameters is the work output of the turbine as it reduces with the introduction of cooling. This is primarily due to the diversion of high-pressure air from the compressor to facilitate turbine cooling, thereby reducing the effective power generation of the turbine (Denton, 1993).

The turbine work output is a measure of the enthalpy drop of the working fluid across the turbine. To observe the effect of cooling flow on the turbine work output, Figure 1.7 shows the thermodynamic cycle of a simple ideal GTE. The non-chargeable cooling flow, which contributes to the work output, is introduced after station 4, specifically at the blades' inlet (between stations 4 and 4.5). The remaining chargeable flows are added at the exit of station 4.5. Station 4.5 takes into account all the cooling flows in the gas generator (showerhead, trailing edge, etc.) that do not do work.

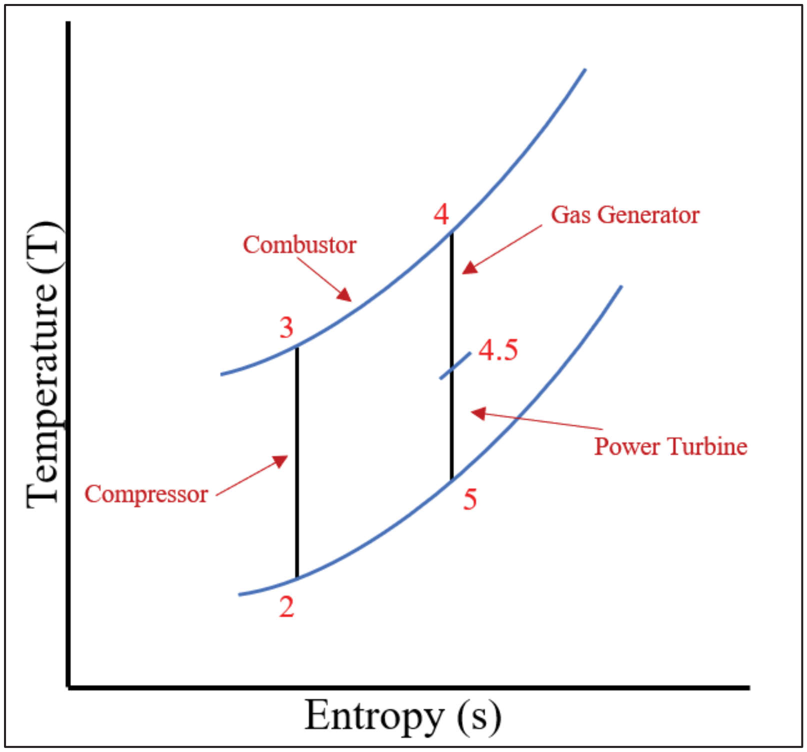

Figure 1.7 Gas Turbine Engine Ideal Thermodynamic Cycle

When considering the ideal work output of the gas generator without cooling, this could be written as follows,

$$W_{GG_{without\ Cooling}} = \dot{m}_{gas}(h_4 - h_{4.5}) \tag{1.1}$$

Where:

- h_4 , $h_{4.5}$: Specific enthalpy at the gas generator inlet and exit,
- $\dot{m}_{gas}$: Gas mass flow rate (air and fuel).

However, when cooling is added, the total enthalpy change drops due to the reduction in the mass flow rate. Therefore, the new work output with the consideration of the cooling flow will be as follows with $\dot{m}_{coolant}$ being the coolant mass flow rate,

$$W_{GG_{With\ Cooling}} = \left(\dot{m}_{gas} - \dot{m}_{coolant}\right)(h_4 - h_{4.5}) \tag{1.2}$$

And hence, the reduction in the work output due to turbine cooling becomes,

$$\Delta W_{GG} = W_{GG_{without\ cooling}} - W_{GG_{with\ cooling}} \tag{1.3}$$

Equation 1.3 shows that the work output reduction is directly proportional to the mass flow rate of the cooling flow. This implies that at constant TIT and compressor pressure ratio, when the cooling flow increases, the work output of the turbine decreases and vice versa (Esgar & Ziemer, 1955).

To achieve the desired work output (and hence, the power output) in a GTE, increase in TIT is needed. This increase in TIT results in a higher enthalpy change across the gas generator, which helps offset the impact of the cooling flow. However, raising TIT also leads to an increase in SFC since higher temperatures require more fuel to achieve the elevated TIT. Thus, one can establish that SFC is directly correlated with the cooling flow.

1.3.2 Turbine Cooling and Turbine Efficiency

Cooling flow could have a negative, neutral or even positive impact on turbine efficiency (Esgar & Ziemer, 1955 ; Whitney, 1969). This depends on the careful consideration of the amount of cooling used, the cooling technique and the location where bleed occurs (to obtain better properties of the cooling flow). When cooling flow is introduced in the turbine, it disrupts aerodynamic profiles, leading to increased losses from viscous effects and heat transfer (Denton, 1993). These losses reduce the overall efficiency of the turbine by reducing the effective power output for a given input.

If the cooling technique is done properly such that the stagnation pressure and temperature of the coolant are high, the efficiency of the turbine could increase due to reduction in mixing losses and the increase in the capacity of the coolant flow to produce useful work output (Denton, 1993 ; Whitney, 1969).

However, it is important to notice that turbine efficiency significantly affects SFC. Turbine efficiency reflects how effectively the turbine converts the energy of the working fluid into useful work output. Higher turbine efficiency typically results in lower SFC, as more of the energy from the fuel is efficiently converted into useful work output. Esgar and Ziemer (Esgar & Ziemer, 1955) emphasize that turbine efficiency should not be compromised, due to its strong influence on SFC. However, this thesis presents a contrasting argument. Specifically, it argues that in certain design scenarios, compromising turbine efficiency may be necessary to achieve better SFC. This study demonstrates that in some cases, an increase in turbine efficiency can unexpectedly lead to a higher SFC. This occurs when the negative impact of cooling flow outweighs the positive effects of improved turbine efficiency, resulting in an overall increase in SFC. Discussion of this effect will be covered in the results chapters.

1.3.3 SFC Impact of The Engine’s Thermal Efficiency

Thermal efficiency of the engine cycle is defined as the rate of production of kinetic energy to the heat release of the fuel as shown in Equation 1.4. It serves as an indicator of the engine's efficiency. The higher the thermal efficiency of the engine, the lower the fuel required, and hence, SFC. On the other hand, in the case where increased air is required for turbine cooling, and this additional flow is not contributing to turbine work, this will negatively impact the thermodynamic efficiency due to increased cycle secondary airflow consumption and its repercussion on turbine efficiency. Therefore, more fuel is required to maintain the engine output power. The reverse argument is also applicable (i.e. with reduced cooling flow).

$$\eta_{th} = \frac{\frac{1}{2}\dot{m}_0(V_9^2 - V_0^2)}{\dot{m}_f * LHV} \tag{1.4}$$

Where,

- $\dot{m}_0$: Engine's inlet mass flow rate,
- $\dot{m}_0$: Fuel mass flow rate,
- V_0, V_9: Gas velocity at inlet and exit of the engine respectively,
- LHV: Lower Heating Value.

1.4 Chapter Conclusion

This chapter provided a comprehensive literature review covering the design of turbine meanlines, the challenges encountered in this process, and how optimization techniques can help address these challenges and enhance the design process. It also presented the fundamentals of turbine cooling and its influence on overall engine performance. The literature review was structured to provide the reader with the necessary background to understand the subsequent chapters. For a deeper exploration of the topics discussed, readers are encouraged to consult the referenced sources

CHAPTER 2

RESEARCH METHODOLOGY

This chapter outlines the methodological framework, including the requirements for the developed tool, the data collection methods, the integrated tools, and the estimation approach of the Specific Fuel Consumption (SFC).

2.1 Tool Development Requirements

Table 2.1 below presents the requirements set for the development of the tool. The table provides an overview of the key requirements, including the user experience with the tool, the tools needed to be integrated, development of the tool, post-processing of the results, and the functionality of the tool.

Table 2.1 Developed Tool Requirements

Requirement Criteria	#	**Requirement**
Main Objectives	1.	The tool should optimize the turbine based on minimum SFC.
	2.	The tool should automate the previous manual processes, effectively reducing the time required for optimization.
	3.	The tool should use sensitivity factors to estimate the mixing losses due to the interaction between the main flow and the cooling flow.
	4.	Incorporate exchange factors for SFC in the tool to estimate the change in SFC resulting from variations in the thermodynamic cycle and turbine efficiency.
User Experience	1.	Develop a user-friendly tool with a simple interface, enabling users to easily input required data.
	2.	The tool should have minimal command requirements, making it easily accessible for non-experienced engineers in programming.
	3.	The tool should be designed in a way that training new users becomes effortless and straightforward.
Tools Integrated	1.	Integrate airfoil cooling flow prediction tool for required cooling estimation.

Requirement Criteria	#	Requirement
	2.	Integrate meanline calculation tool for turbine meanline information.
	3.	Integrate the optimization framework developed at Pratt & Whitney Canada (P&WC) to allow optimization analyses.
Tool Functionality	1.	The tool should take into account all cooled stages, including their vanes and blades.
	2.	The tool should apply the same work-split used in the baseline meanline for spools with multiple stages (i.e., enthalpy variation per spool must remain constant along the optimization process).
	3.	Maintain the gas generator power with respect to the baseline configuration to ensure the power required by the compressor is achievable.
	4.	Automatically recalculate the mass flow rates, the fuel-to-air ratio, and cooling flow fractions in the meanline after incorporating airfoil cooling.
	5.	Optimization should be done based on ΔSFC (relative to initial SFC of the baseline) to ensure rapid analysis for the preliminary design phase.

Requirement Criteria	#	Requirement
Post-Processing of The Results	1.	The optimization results should be added to the existing data and analytics management tool developed at P&WC.
	2.	The design points resulting from the optimization process should be visually presented, allowing for easy visualization, and aiding the designer in selecting the optimal design point through intuitive plotting.
	3.	The plot of the baseline and new gaspaths from the meanline should be obtained in order to visually illustrate the differences for the user's analysis.
	4.	All design points considered during the optimization process should be organized in a way that allows the user to navigate between different analysis easily.

2.2 Integration of Tools

The developed tool involves the integration of a couple of specialized tools developed at P&WC. These tools are the Turbine Aerodynamic Meanline (TAML) and Cooling Flow Prediction Tool (CFPT). Each tool is described briefly in the next subsections.

2.2.1 Turbine Aerodynamic Meanline (TAML)

Turbine Aerodynamic Meanline (TAML) is a powerful software application that iterates and solves the one-dimensional governing equations to determine the meanline design of the turbine based on provided input parameters (factors). TAML encompasses both design-point and off-design point calculations, incorporating loss models for accurate performance evaluation.

As a meanline solver, TAML provides critical turbine performance metrics, such as stage loading, flow angles, velocity triangles, and thermodynamic properties across each stage. It is designed in a way that ensures robustness and computational efficiency, enabling rapid calculations that facilitate iterative optimization processes. Furthermore, TAML encompasses both design-point and off-design point calculations, integrating the validated aerodynamic loss modules utilized at P&WC to ensure that the predicted performance aligns closely with real-world operational scenarios.

2.2.2 Cooling Flow Prediction Tool (CFPT)

The Cooling Flow Prediction Tool (CFPT) is a specialized software used for estimating the cooling requirements of each airfoil within the turbine section. It incorporates various cooling modules and techniques, covering diverse airfoil geometries, cooling schemes, and material types. In the aerospace sector, empirical results are commonly employed during the preliminary design phase to create new designs. CFPT enhances this conventional approach by systematically comparing a proposed design against a reference design that has similar performance characteristics.

When provided with such a reference design, CFPT leverages input data including the airfoil material properties, turbine meanline and aerodynamic performance data, as well as target average metal temperatures to determine the necessary cooling flow per airfoil. This process is conducted both with and without Thermal Barrier Coating (TBC) considerations, allowing designers to assess potential thermal management improvements clearly.

2.3 Integration of Estimation Data

As little information is available during the conceptual/preliminary design phase, it is time consuming and computationally expensive to evaluate the SFC impact for every design iteration amongst the various disciplines. Therefore, sensitivity factors are utilized in this tool to account for losses occurring due to mixing of the cooling flows with the mainstream flow, their impact on turbine efficiency and consequently convert that impact to SFC.

2.3.1 SFC Exchange Factors

Two distinct SFC exchange factors are employed in the developed tool. The first factor establishes a relationship between SFC and turbine efficiency. This relationship quantifies the percentage decrease in SFC for a given percentage increase in turbine efficiency. Additionally, it considers the interaction between aero-cooling flow and turbine efficiency losses during the mixing process.

To account for the engine thermodynamic cycle impact due to the amount of cooling flow extracted, a second exchange factor is used. This factor establishes the relationship between SFC and the thermodynamic impact of cooling flow consumption. Moreover, this factor is crucial as it is the one that could show that a design has high turbine efficiency but also high/worse SFC. Therefore, the total effect on SFC is the summation of both impacts, as expressed in Equation 2.1.

$$\Delta SFC_{total} = \Delta SFC_{Eff.\ Impact} + \Delta SFC_{Cycle\ Impact} \tag{2.1}$$

It is important to note that each of these exchange factors assumes a linear relationship between SFC and turbine efficiency, as well as between SFC and the thermodynamic cycle impact. While this assumption may not perfectly capture the true relationship, it is reasonable within a limited range of perturbation. Utilizing linear relationships facilitates initial estimations of SFC during the conceptual/preliminary design phase of the turbine. This approach provides designers with a “trend” to identify optimized designs that minimize SFC, expediting the overall design process.

The optimal design obtained from the optimization process using these exchange factors can later be further analyzed computationally to obtain the actual values of SFC, without relying on the assumed linear relationships. This approach significantly reduces the number of computational analyses required, potentially saving considerable time and computational resources.

Due to considerations of data confidentiality, the specific methodologies used to generate these exchange factors are not disclosed.

2.4 Optimization Techniques

Design exploration is done with an in-house Framework for Design Exploration (FDE) at P&WC. This FDE consists of various types of Design of Experiments (DOE) and Surrogate Assisted Optimization (SAO) workflows. This section will discuss the specific SAO and DOE methods employed in this research, as well as the reason behind their selection.

2.4.1 Design of Experiments (DOE)

There are several DOE types available in FDE including full factored, part factored, Box-Behnken and composite DOEs. Although the user will have the freedom to choose any of these types when running their analysis, the default type used in the developed tool is set to Latin-Hypercube Sampling (LHS). LHS is chosen for its ability to generate a well-distributed and representative sample of the design space, ensuring comprehensive coverage of the parameter ranges.

LHS offers advantages over other DOE types by reducing biases and providing a more balanced representation of the design space. It divides the range of each input parameter into equally probable intervals and ensures that only one sample is taken from each interval. This approach allows for a more thorough exploration of the design space while maintaining diversity and reducing potential correlations between input variables.

Despite its strengths, it is important to acknowledge that LHS has certain limitations. The finite number of samples used in LHS may restrict the resolution of the design space and potentially overlook intricate design configurations that could be beneficial. Additionally, the implementation of LHS requires computational resources, as generating and evaluating samples can be computationally intensive. Careful consideration of the number of samples and computational capabilities is necessary to strike a balance between exploration and computational efficiency.

Furthermore, encountering non-physical solutions could occur. Due to the random nature of the sampling process, there is a small chance of generating samples that do not correspond to physically feasible turbine configurations. These non-physical solutions can arise when the sampled values of the input variables do not satisfy certain constraints or dependencies inherent in the turbine design. It is therefore essential to incorporate appropriate constraints within the optimization framework to ensure that only physically valid solutions are considered.

2.4.2 Surrogate Assisted Optimization (SAO)

SAO involves constructing computationally efficient surrogate models to approximate and optimize the behavior of complex systems to reduce the computational effort required. While SAO is often employed in large-scale computational problems such as Computational Fluid Dynamics (CFD), integrating it into the developed tool will allow the optimization process, to have faster evaluations and more efficient exploration of the design space.

The primary advantage of SAO is its ability to substantially reduce the computational burden associated with direct evaluations of complex objective functions. By replacing expensive computations with quicker surrogate predictions, a greater number of design iterations can be performed within a shorter timeframe. Additionally, surrogate models effectively capture nonlinear relationships and complex interactions among design variables, which allows optimization algorithms to explore the design space more thoroughly and uncover optimal solutions that might be challenging to identify using conventional optimization methods.

Nevertheless, it is crucial to acknowledge certain limitations of SAO. The accuracy and effectiveness of the surrogate model are heavily dependent on the quality, quantity, and representativeness of the training data used during model construction. Insufficient, incomplete, or biased datasets can lead to inaccuracies and reduced confidence in optimization results. Therefore, careful selection and validation of training data are essential to ensure the reliability and robustness of the SAO-driven optimization process.

2.4.3 DOE and SAO Combined

By combining DOE and SAO, the optimization process overcomes limitations associated with each approach, resulting in a robust and efficient turbine optimization process.

DOE, specifically Latin Hypercube Sampling (LHS), facilitates a systematic and comprehensive exploration of the design space by dividing parameter ranges into equally probable intervals. This approach ensures uniform distribution of samples across the entire design space, significantly reducing biases and correlations among input variables. However, as discussed earlier, due to its finite sampling strategy, DOE alone may have limited resolution, potentially missing intricate but beneficial configurations within the design space.

To overcome these limitations, SAO is incorporated. SAO utilizes surrogate models, which accurately approximate the complex relationship between input parameters and the objective function. These surrogate models capture underlying trends and nonlinear interactions efficiently, enabling rapid evaluation and targeted exploration of promising regions. By predicting areas of high performance, SAO will enhance the design space resolution, guiding the search process toward optimal configurations that could be overlooked by a purely sampling-based approach.

The full process of FDE is mentioned briefly in Chapter 1 covering the work of Doran et. al (Doran et al., 2018).

2.5 Tool Modeling and Workflow

This section covers the operation of the developed tool, workflows, and modes of operation.

2.5.1 Developed Tool Modes of Operation

The developed tool operates under the assumption that the compressor and combustion chamber designs remain fixed, including the location of compressor bleeds, thereby maintaining a constant compressor pressure ratio. This assumption enables the tool to specifically target turbine optimization with the consideration of the constraints imposed by other engine components. Future integration with these components is discussed further in the recommendations section.

The tool provides two distinct workflows based on engine type, with the main goal to optimize the turbine to achieve the minimum SFC of the engine. For turbofan engines, the workflow optimizes the turbine designs to improve their efficiency while ensuring that the power produced by the High Pressure Turbine (HPT) and Low Pressure Turbine (LPT) remains consistent with the baseline. This consistency is necessary to guarantee sufficient power delivery to the compressor and fan. To achieve this, if the new design choices suggested by the optimizer and the integration in the cooling flow affected the power of a spool, adjusting the specific enthalpy of the spool will allow the power to be maintained. Moreover, the temperature at the exit of the turbine must also be maintained. This is to ensure that the mixing of the core engine is aligned with what the cycle needs in order to achieve the required thrust.

For turboprop and turboshaft engines, the tool offers two modes of operation. The first mode ensures that the power delivered by the turbines (HPT, LPT, and Power Turbine (PT)) remains aligned with baseline levels to maintain the power distribution required by the compressor and the propeller or shaft. Similar to the turbofan workflow, turbine stage power is adjusted through modifications of specific enthalpy. This is required given the mass flow rate within the turbine is re-calculated with the consideration of the mass flow of the cooling flow. Furthermore, the turbine exit pressure is maintained at the baseline condition to allow matching with the atmospheric pressure.

The second mode matches only the gas generator power and turbine exit pressure to the baseline, allowing the PT power output to vary. This approach provides greater flexibility, enabling broader design adjustments, performance enhancements, or change in material choice of the PT that results in a less heavy engine. Hence, depending on how PT power changes, subsequent modifications can be accommodated during the detailed design phase with fewer constraints.

Table 2.2 summarizes the functionalities of the modes of operation for both decreased and increased cooling requirements (scenarios 1 and 2 respectively). Scenario 1 represents cases where factors provided by the optimizer suggest reduction in the airfoil cooling flow. The aim of this scenario is to maximize the reduction in SFC. On the other hand, Scenario 2 explores factors that may lead to higher airfoil cooling flow requirement, with the focus being on minimizing SFC damage caused by the increase in the cooling flow.

Table 2.2 Developed Tool Operating Modes

	Scenario 1 Decrease in A/F Cooling Flow		**Scenario 2 Increase in A/F Cooling Flow**	
	Mode 1	**Mode 2**	**Mode 1**	**Mode 2**
Gas Generator Turbine Power	Constant	Constant	Constant	Constant
Power Turbine	Constant	Increase	Constant	Decrease
Temperature Impact	T_{GGE} Increase	TIT Increase	T_{GGE} Decrease	TIT Decrease
Optimization Objective	Maximize SFC Improvement		Minimize SFC Damage	

2.5.2 Workflow Modes Descriptions

The optimization process begins by running TAML to obtain the meanline information of the turbine. This information is passed to CFPT where calculations are conducted based on the component type (vane or blade), accounting for various factors such as material considerations, mission requirements, and the chosen cooling scheme. CFPT then provides updated cooling requirements per airfoil, which are subsequently returned to TAML. Prior to re-running TAML, total mass flow calculations are updated to account for the revised cooling flow, fuel-to-air ratio adjustments are made to preserve the targeted turbine inlet temperature, and specific cooling fractions are defined separately for vanes and blades.

With the updated meanline results, the tool verifies the gas generator power output. If deviations from the baseline power occur, adjustments to the specific enthalpy are performed to align the gas generator power with the baseline design. Depending on the engine type (turbofan, turboprop, or turboshaft) and selected operational mode, the corresponding optimization workflow is then followed. Additional constraints are applied to ensure consistency of the gas generator power and the preservation of the baseline work-split across turbine stages.

Next, by using the mixing losses sensitivity factors, the efficiency of the turbine is adjusted to accommodate the mixing losses with the main flow. Moreover, using SFC exchange factors, the value of ΔSFC (change in SFC with respect to the baseline design) is calculated.

The resulting performance data is then transferred to FDE, where the surrogate model is constructed and the optimization process is conducted, as previously shown in Figure 1.3 in Chapter 2. After obtaining the updated design parameters (factors), the optimization workflow iteratively repeats until convergence criteria are satisfied. A simplified visualization of this optimization workflow is presented in Figure 2.1. Due to confidentiality restrictions, detailed aspects of the workflow are not included.

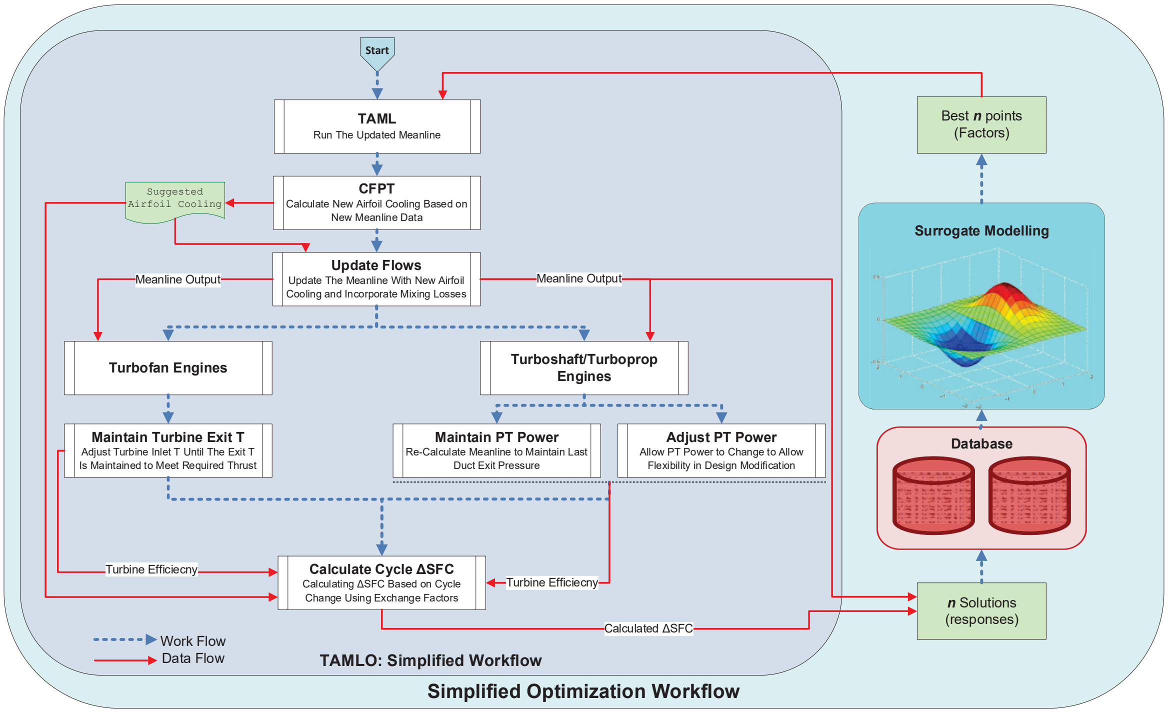

Figure 2.1 Simplified Workflow of The Developed Tool

2.6 Chapter Conclusion

This chapter outlined the methodological framework developed to optimize turbine design with a focus on minimizing SFC. It described the integration of key tools, including the TAML, CFPT, and FDE, and detailed the optimization workflow applied within the tool. Furthermore, the chapter presented the different workflows implemented to accommodate various engine types, highlighting its flexibility and applicability across multiple propulsion systems.

CHAPTER 3

EVALUATION OF THE DEVELOPED TOOL: TEST CASES

3.1 Introduction

This chapter summarizes the test cases covered in this thesis. The results and assessments of these test cases will be discussed in the next chapters.

3.2 Test Cases Configurations

Two test cases are presented in this thesis, both employing a turboprop engine with 3-spool configuration comprising of High Pressure Turbine (HPT), Low Pressure Turbine (LPT), and Power Turbine (PT) modules. The engine's gas generator turbine (HPT) and LPT stages are actively cooled and, therefore, these components were optimized to achieve the turbine configuration leading to minimum Specific Fuel Consumption (SFC) with the consideration of airfoil cooling. For simplicity and consistency, only analyses from the first operational mode; where the power of all turbine stages and the turbine exit pressure remain aligned with the baseline design; are discussed in these test cases.

In the first test case, the optimization focused on variations in airfoil count and axial chord length, aiming to understand their influence on turbine cooling requirements, turbine efficiency, and SFC. During this analysis, the gaspath geometry was held constant relative to the baseline configuration to isolate the effects of these specific geometric parameters.

The second test case expanded the scope by introducing variations to the gaspath geometry, specifically adjusting the turbine inlet tip radius, in addition to the previously studied parameters (airfoil count and axial chord). The objective of this broader analysis was to quantify and understand the impact of gaspath modifications on cooling flow demands, turbine performance metrics, and ultimately, SFC.

In both test cases, realistic design constraints based on Zweifel coefficients and stage reaction were applied to ensure feasible and practical turbine blade loading conditions. A comparative analysis of these two test cases provides insight into the relative importance of various geometric factors on cooling requirements, turbine efficiency, and SFC. Table 3.1 summarizes the optimization settings and key parameters employed in each test case.

Table 3.1 Test Cases Optimization Settings

	Test Case 1	**Test Case 2**
Factors	- Airfoil Count - Axial Chord	- Airfoil Count - Axial Chord - Gaspath
Constraints	- Zweifel	- Zweifel
Objective	Minimize SFC	Minimize SFC

Although different test cases were studied, covering different engines, the two cases presented in this thesis serve to show the “trend” in SFC when different geometrical factors are changed.

3.3 Validation and Verifications of The Results

The validation of the results obtained from the optimization process is a crucial step in ensuring the reliability and accuracy of the developed tool. Since the developed tool integrates CFPT, TAML, FDE and these tools were already validated, the validations needed for the developed tool is for ΔSFC values (change in SFC with respect to the original value). To achieve this, two validation approaches were considered.

The first validation approach involved a direct comparison between the minimum ΔSFC value predicted by the developed tool and the results obtained from a manually conducted preliminary design process for a new engine. This manual process, traditionally characterized by iterative exchanges among multidisciplinary groups, provided a reliable reference to assess the performance of the automated tool. By performing this comparative analysis, it was possible to evaluate the capability of the tool to rapidly and robustly identify either equivalent or better turbine designs. Furthermore, this approach demonstrated the tool's efficiency in reducing the overall duration of the preliminary design phase by minimizing manual iterations.

The second approach involved performing a comprehensive computational analysis of the entire engine using the optimized turbine configuration proposed by the tool. The resulting SFC from this analysis served as a high-fidelity benchmark to assess the accuracy of the ΔSFC predicted by the developed tool. Unlike the tool, which primarily focuses on turbine optimization alone, the computational analysis accounts for interactions between the optimized turbine and other engine components, thereby providing a more accurate representation of the engine performance. Consequently, some discrepancies, such as the error margin, were anticipated, hence the acceptability of the developed tool was determined by evaluating its magnitude. A sufficiently small error margin indicated that the tool provided a reliable estimation of ΔSFC by the developed tool. This confirmed that the developed optimization methodology could be effectively employed during the preliminary design phase to accelerate the design process and identify the optimal turbine configurations, which could subsequently be refined further during the detailed design stage.

3.4 Chapter Conclusion

This chapter presents the two test cases that will be covered in the next chapters and the factors and constraints used during the optimization process. The validation strategy followed in evaluating the developed tool results was also introduced. The following chapters will discuss the outcomes of these test cases and provide detailed analysis of the optimization results.

CHAPTER 4
ANALYSIS AND INTERPRETATION: TEST CASES RESULTS

4.1 Introduction

In the previous two chapters, the methodology of the developed tool was discussed as well as the test cases considered to validate and test the tool. This chapter focuses on discussing the results obtained by using the factors, constraints and the test scenarios explained in Chapter 3.

To maintain confidentiality and protect sensitive information, the results will be presented in normalized plots.

4.2 Test Case 1: Effect of Airfoils Wetted Area on SFC and Turbine Efficiency

4.2.1 Scenario Overview

In this scenario, the focus was on varying the axial chord and airfoil number while keeping all other parameters constant. Specifically, the optimization process considered only the axial chord and airfoil number of the blades and vanes of the cooled stages as the varying factor. By focusing only on this particular design parameter, we aim to evaluate the impact of geometry on the cooling flow distribution, Specific Fuel Consumption (SFC), and turbine performance.

4.2.2 Airfoils Wetted Area Approximation

A simple and practical way to approximate the wetted area of turbine airfoils is by focusing on the dominant geometric parameters that strongly influence it. These include the number of airfoils, the true chord, and the span. Combined, these factors account for the majority of the surface area and are thus considered the primary contributors to the total wetted area. The wetted area refers to the external surface of the airfoil that is exposed to the hot gas flow and requires cooling to ensure thermal protection and structural integrity. By using this approximation, the airfoil surface can be represented as a rectangular geometry, as illustrated in Figure 0.1. This simplification is especially useful during the preliminary design phase, where a fast and reasonable estimate of cooling requirements is often necessary. Similar approximations are well-established and widely accepted in the field of heat transfer (Bergman & Incropera, 2011 ; Han et al., 2012). Since the product of true chord and span represents the surface area of a single side of a single blade, multiplying this area by 2 accounts for both the pressure and suction surfaces, and further multiplying by the number of blades yields the total wetted area of the stage vanes or blades. This leads to the expression shown in Equation 4.1, which provides an approximation of the total wetted area of a single stage vanes or blades.

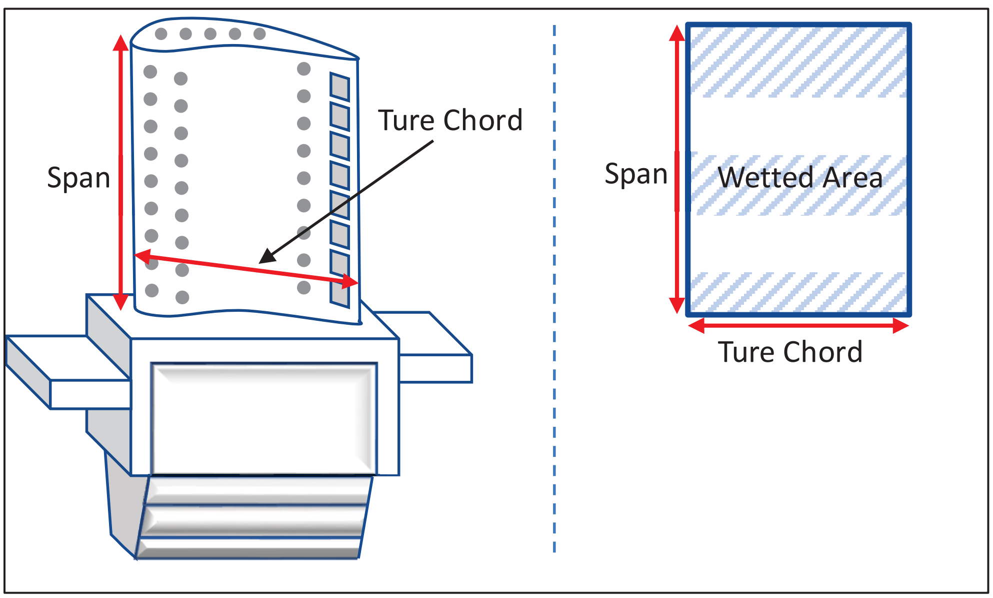

Figure 4.1 Airfoil Wetter Area Approximation

$$A_{wetted} = 2 * N_{airfoils} * C * S \tag{4.1}$$

Where:

$A_{wetted} = Airfoil\ Wetted\ Area,$

$N_{airfoils} = Number\ of\ Airfoils,$

$C = Airfoil's\ True\ Chord,$

$S = Airfoil's\ Span$

4.2.3 Airfoils Wetted Area, SFC and Turbine Efficiency Trends

As presented in Equation 4.1, the wetted area of the turbine airfoils has a proportional effect with the true chord, span, and the number of blades. When one of these parameters is changed while the others are held constant, the change in wetted area is linear. However, when two or more parameters vary simultaneously, the interaction between them introduces a non-linear dependency. Physically, an increase in wetted area implies a larger heat-exposed surface, which in turn demands more cooling to ensure structural integrity (i.e., durability) and sustained performance of the blades. Since the cooling requirement is directly linked to the wetted surface area, this relationship becomes essential in estimating airfoil thermal loads early in the design phase.

An increase in the required cooling flow has a direct consequence on the SFC of the engine. To maintain a targeted Turbine Inlet Temperature (TIT), which is critical for engine performance and competitiveness, more cooling air must be extracted from the compressor, reducing the amount of air available for combustion. To offset this reduction in core mass flow and achieve the desired TIT, additional fuel must be injected, thereby increasing the SFC.

Figure 4.2 highlights the relationship between variations in the High Pressure Turbine (HPT) blades wetted area and its impact on both SFC and turbine efficiency. These trends represent the design points derived from the optimization results while applying constraints for Zweifel coefficient and stage reaction. The data is presented as deltas relative to the baseline in order to reduce the computational cost associated with calculating actual SFC values, as previously discussed. Given the high dimensionality of the design space and the time required for surrogate model convergence, a third-degree polynomial regression is used in this section to approximate and visualize the observed trends. This approach is considered appropriate, as the objective here is to illustrate the general influence of cooling on turbine efficiency and engine performance. Detailed numerical data are not included due to confidentiality agreements with Pratt & Whitney Canada (P&WC).

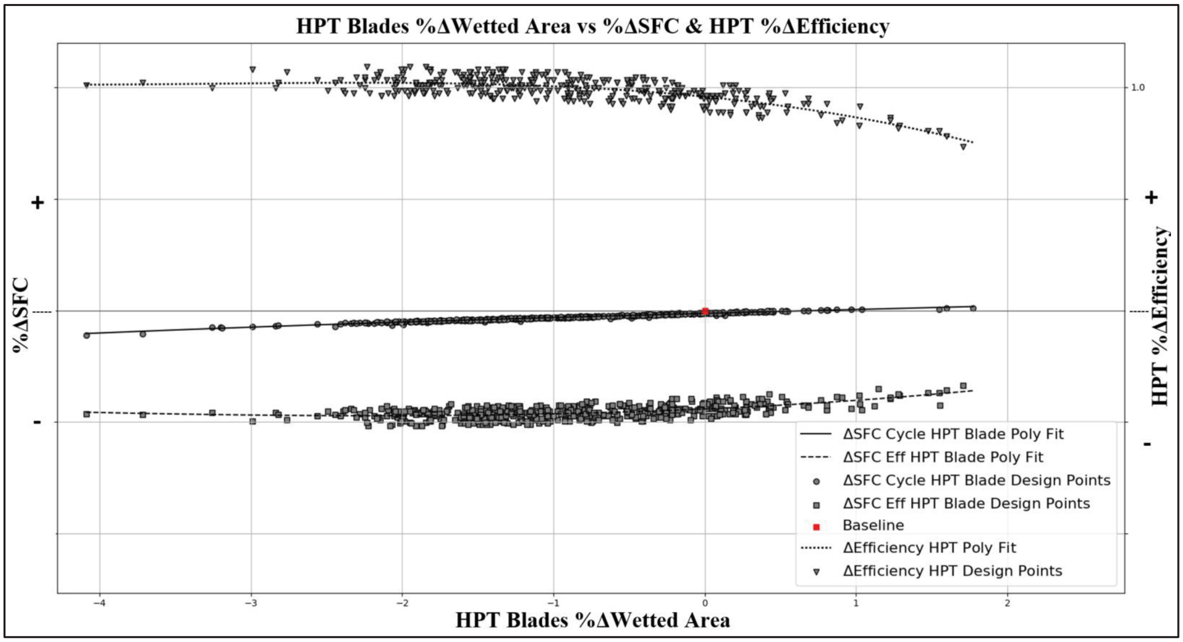

Figure 4.2 Test Case 1 HPT Blade Wetted Area vs ΔSFC & ΔEfficiency of HPT

When analyzing the influence of wetted area on SFC, a distinct correlation emerges: as the airfoil wetted area increases, SFC also increases, and vice versa. This relationship is illustrated in two subplots. The first shows the impact of wetted area variation on SFC through its effect on the engine's thermodynamic cycle. As discussed earlier, the wetted area serves as a representation for the surface exposed to thermal loads, and therefore, a key indicator of the required cooling. Changes in wetted area directly affect cooling demand, which in turn influences SFC and turbine efficiency.

As described in Chapter 3, the developed tool uses SFC exchange factors to estimate the impact of cooling requirements on SFC. This method is suitable for the preliminary design phase, where quick and reasonably accurate estimations are often more valuable than high-fidelity simulations. Consequently, the first subplot appears nearly linear illustrating that as the wetted area changes, the cooling requirement also changes, and since one of the SFC exchange factors represent the cycle-based effect of cooling on SFC for a specific component (either vanes or blades), the resulting trend appears almost as a linear polynomial fit.

Unlike the cycle-based exchange factor, the second SFC exchange factor quantifies how changes in stage efficiency influence the engine's SFC. This efficiency-based exchange factor captures the combined aerodynamic performance of both vanes and blades, as stage efficiency is not attributed to a single row of airfoils but to the entire stage. As a result, the relationship between this exchange factor and the wetted area of an individual component becomes more complex and non-linear. This non-linearity is visible in Figure 4.2, where a wider spread of design points around the regression curve appears, particularly for configurations that deviate further from the baseline.

Furthermore, an increase in cooling flow has a negative effect on turbine efficiency, primarily due to mixing losses. As discussed in the literature review chapter, when cooling air is injected into the mainstream flow, it disrupts the uniformity of the gaspath, leading to irreversible energy losses (Denton, 1993). These losses arise from the mixing of coolant with the hot gas stream, which differ in temperature, velocity, and composition, causing entropy generation and a reduction in overall efficiency.

The connection between wetted area and turbine efficiency thus becomes clearer: as the wetted area increases, more surface is exposed to the hot gaspath, requiring higher cooling flow to maintain structural integrity. This elevated cooling demand leads to increased mixing with the mainstream flow, exacerbating entropy generation and degrading efficiency. Conversely, when the wetted area is reduced, the associated cooling demand drops, minimizing mixing losses and improving aerodynamic efficiency. This inverse relationship between airfoil wetted area and stage efficiency is illustrated in the third trend of Figure 4.2.

It is important to note once again that the plotted relationship is based solely on changes in the wetted area of the HPT blades, while the efficiency metric represents the performance of the entire stage, including both vanes and blades. As such, some data points deviate from the polynomial fit line. These outliers can be attributed to the fact that blade-only geometric changes do not fully capture the total aerodynamic performance of the stage, especially in configurations where vane geometry or flow conditions also play a significant role. This discrepancy highlights the limitations of component-level simplifications when interpreting full-stage efficiency behavior.

4.2.4 Amount of Cooling Reduction and SFC

To further understand the relationship between cooling flow distribution and engine performance, two design points were selected from the results obtained from the optimization analysis and are shown Figure 4.3. These points illustrate the effect of varying cooling levels across the gas generator components on both SFC and overall HPT efficiency. While both points demonstrated a reduction in total cooling flow, the specific distribution and resulting performance differed notably.

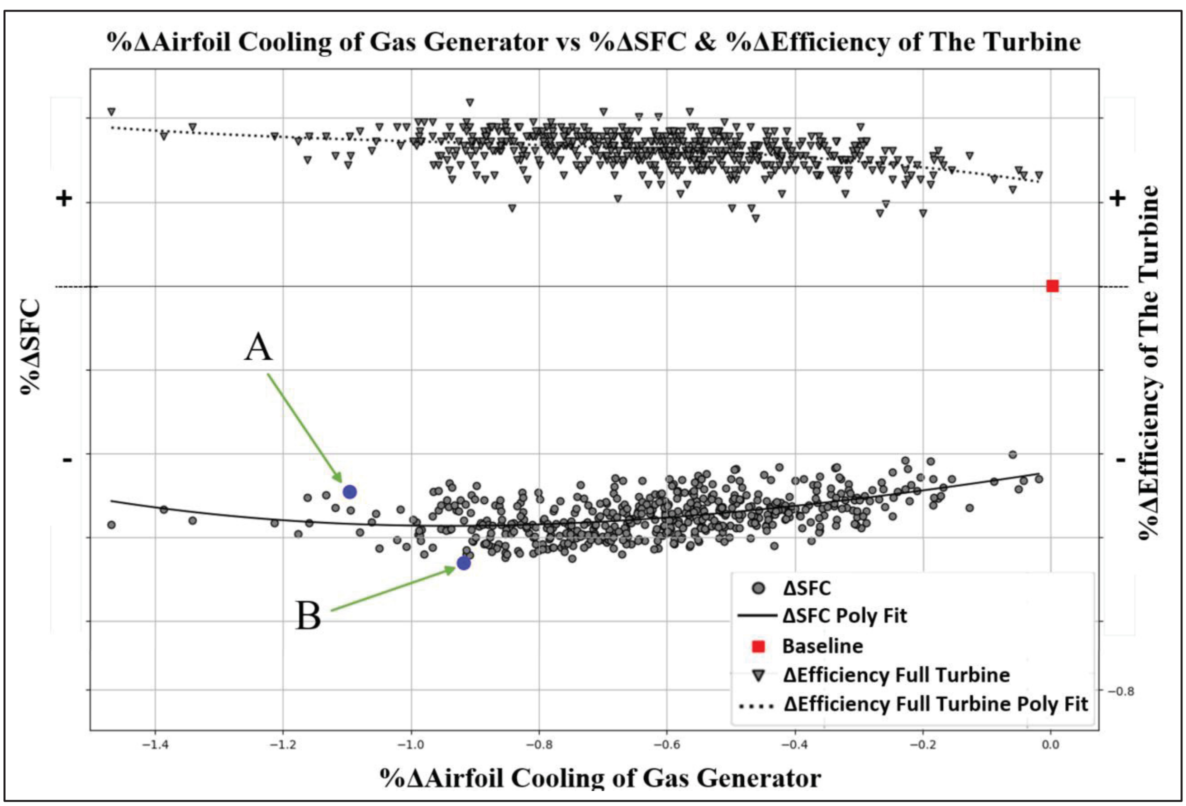

Figure 4.3 Test Case 1 Gas Generator Cooling vs SFC & Efficiency

When looking at the results, Point A exhibited a more substantial reduction in overall cooling flow when compared to Point B. However, despite this higher reduction, Point A resulted in a smaller improvement in SFC. Upon closer examination, it was observed that the majority of the cooling reduction at Point A occurred at the HPT vanes. When it comes to the flow path through the HPT, the vanes primarily function as guide components. They are responsible for shaping and accelerating the flow before it enters the rotating blades, ensuring that the incoming gas strikes the blades at the correct angle to maximize energy extraction (Farokhi, 2014 ; Moustapha et al., 2003). While their aerodynamic shaping is essential for efficient turbine operation, the vanes themselves do not contribute directly to the mechanical work output of the turbine. Instead, their role is to prepare the flow conditions such as swirl angle, velocity, and pressure distribution, so that the downstream rotor blades can extract energy more effectively.

As a result, changes in vane cooling, though impactful in terms of material temperature management and vane durability, tend to have a limited effect on the overall thermodynamic performance of the engine (Denton, 1993). A reduction in cooling flow to the vanes may reduce local thermal loads and improve aerodynamic conditions slightly, but it does not significantly alter the net energy transfer occurring in the rotating stage. More specifically, since the mass flow entering the turbine blades remains nearly unchanged by vane cooling adjustments, the amount of energy available for conversion into shaft work is unaffected. This explains why Point A, which had a higher overall cooling reduction concentrated at the vanes, showed minimal improvement in SFC despite the reduction in thermal management effort.

In contrast, Point B demonstrated a more strategically distributed cooling reduction, with a significant portion of the decrease applied to the HPT blades rather than the vanes. This shift in cooling distribution resulted in a clear performance benefit. By reducing the amount of coolant injected into the blade passage, the extent of mixing between the relatively cool air and the high-temperature mainstream flow was minimized. As covered earlier, mixing losses are a well-known source of aerodynamic inefficiency, arising from the thermal and momentum differences between the mainstream and cooling flow. Therefore, the improvement in the flow conditions contributed directly to an increase in stage efficiency. Since the rotating blades are the primary contributors to the mechanical work extraction, improving their performance has a direct effect on engine efficiency. The enhanced stage efficiency at Point B reduced the amount of fuel required to achieve the same turbine inlet temperature, leading to a measurable drop in SFC. Combined, the effects between improved HPT efficiency and blade cooling reduction, as described in Equation 2.1, contributed to a more substantial decrease in SFC.

The comparison between Points A and B demonstrates an important insight: a greater reduction in cooling flow does not always guarantee better SFC performance. While minimizing cooling losses is beneficial, the effectiveness of this strategy depends on where the cooling is reduced and whether it contributes to useful work. For example, reducing cooling in the vanes may reduce thermal load but does little to enhance work extraction, whereas reducing blade cooling, when done carefully, can improve stage efficiency and reduce fuel burn. This emphasizes the need for a balanced optimization approach, where the objective is not simply to minimize cooling flow, but to optimize it for maximum efficiency and performance gain. A marginal increase in cooling at the right component may prove more beneficial than an aggressive reduction applied indiscriminately.

Moreover, these findings reaffirm the complexity of multidisciplinary trade-offs inherent in gas turbine design. They highlight the importance of the integrated optimization approach adopted in the developed tool which enables simultaneous consideration of thermal management (i.e., durability of the airfoils) and aerodynamic performance from the early design phase. The proposed framework incorporates its impact directly within the preliminary design phase rather than treating cooling flow as a separate, post-turbine-design consideration. This allows the turbine to be optimized with realistic cooling requirements in mind, avoiding the traditional sequential approach where the turbine is first designed for peak efficiency and later adjusted for cooling, often requiring repeated design iterations.

4.3 Test Case 2: Effects of Inlet Tip Radius on SFC

4.3.1 Test Case 2 Overview

In this test case, the factors chosen for the optimization included not only variations in the number of airfoils and axial chord but also modifications to the gaspath geometry. More specifically the HPT vane inlet tip radius. The purpose of this test case is to study the effect of yet another geometric factor to allow an additional degree of freedom and assess how changes in the gaspath influence the cooling flow requirements, turbine efficiency, and SFC.

Although in practical designs the inlet tip radius is typically constrained by the exit area of the combustion chamber, this test case adopts a more flexible design approach to enable exploration of broader gaspath variations.

4.3.2 HPT Vane Inlet Tip Radius Effects on Turbine Cooling, Efficiency, and SFC

The HPT vane inlet tip radius; also known as turbine inlet tip radius; defines the radial location at the outer tip of the first vane row, immediately downstream of the combustion chamber. This geometric parameter plays a significant role in shaping the flow characteristics and aerodynamic behavior within the turbine section.

Changes in the tip radius can significantly affect the flow behavior near the airfoil tips, where complex interactions between the high-velocity gases and the airfoil surfaces occur. A larger tip radius inlet allows for smoother flow entry into the turbine, reducing flow separation and minimizing the formation of adverse pressure gradients. This can enhance the aerodynamic performance of the airfoils, resulting in improved airfoil cooling efficiency and reduced SFC.

However, since the tip radius is a geometric factor, it has a direct impact on the cooling requirements for the airfoils. As the tip radius increases, the annulus area expands, resulting in longer airfoils to maintain aerodynamic stability and stage loading. This enlargement leads to a proportional increase in wetted surface area, raising the cooling demand to ensure durability of the airfoils. Consequently, higher cooling flow is extracted from the compressor, which reduces the air mass available for combustion. This additional bleed flow contributes to increased SFC, unless sufficiently compensated by substantial aerodynamic efficiency gains.

While a larger tip radius can sometimes improve local flow conditions such as reducing tip leakage or improved incidence angles, these benefits can be outweighed by geometric penalties. The increased blade length introduces more surface area subject to mixing losses due to an increase in cooling, thermal gradients, and tip-region pressure drag. These effects are especially pronounced near the blade tips, where secondary flow interactions are more intense (Denton, 1993 ; Moustapha et al., 2003).

Therefore, optimizing the gaspath of the turbine is challenging but essential. The optimum design must minimize aerodynamic losses and cooling demands, while also considering material usage, structural stresses, and overall system weight and cost. This will result in a design that can provide the work required efficiently while having the least negative impact on SFC.

4.3.3 Test Case 2 Results

By varying the number of airfoils, axial chord, and HPT vane inlet tip radius while constraining Zweifel and stage reaction, the results revealed that the optimization led to significant reductions in SFC when compared to Test Case 1, primarily driven by improvements in gas generator efficiency. Compared to Test Case 1, which focused solely on airfoil geometry, this case enabled a broader exploration of the design space given an extra degree of freedom included. By allowing the gaspath itself to vary, the optimizer was able to identify more favorable configurations that contributed to further reductions in fuel consumption.

A detailed inspection of the optimized meanline revealed that the gains in SFC were mainly attributed to improvement in stage efficiency within the gas generator. As discussed earlier, although the reduction in HPT vane cooling has no direct impact on SFC, this reduction allowed more hot gas to flow through the turbine, thereby reducing the need for secondary airflow extraction. This in turn reduced the mixing losses and contributed to an improvement in HPT efficiency. Additionally, reductions in cooling flow for both the HPT blades and Low Pressure Turbine (LPT) vanes have direct impact on SFC improvement, which also allowed the efficiency of the gas generator to improve given less mixing losses which also improved SFC. With all of these combined, the design experienced a notable reduction in SFC.

Moreover, the optimized configuration also exhibited a shift in the vane design, specifically an increase in the vane aspect ratio. This change helped reduce both profile and secondary losses, thereby improving flow uniformity and aerodynamic behavior within the gas generator. As a result, the stage operated more efficiently, supporting further improvements in SFC.

To better visualize the trade-offs between turbine efficiency and SFC, Figure 4.4 plots the reduction in SFC against the increase in HPT efficiency for the optimized design points. As discussed earlier, turbine efficiency and SFC are directly correlated. Improvement in the efficiency means less losses occurring within the turbine, with the flow able to perform and extract the work required. This results in less fuel consumption need and have an overall improvement on the engine performance. This trend can be seen in the figure.

Moreover, as mentioned earlier, sometimes, higher turbine efficiency does not always lead to better SFC of the engine. To show this, two design points, labeled Points C and D, were selected in Figure 4.4 for closer analysis to compare a turbine design point that results in higher SFC reduction but lower efficiency vs one that results in lower SFC reduction but higher efficiency their distinct performance characteristics.

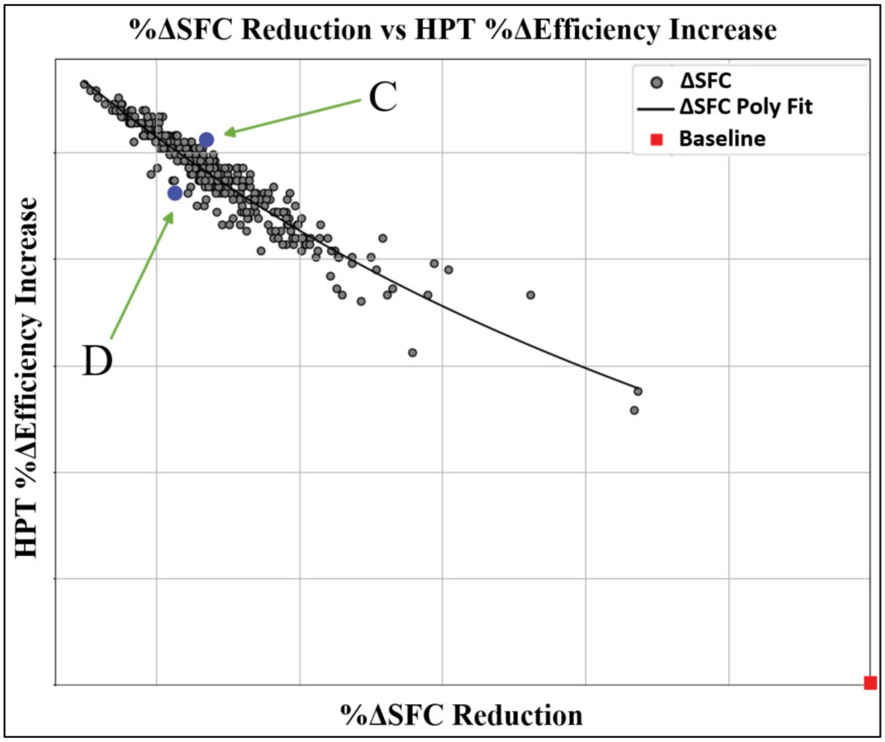

Figure 4.4 Test Case 2 HPT ΔSFC Reduction vs HPT ΔEfficiency

After analysing the meanline for each point, the following observations were made:

a) HPT Vanes: Point C had almost double the amount of reduction in the cooling flow compared to Point D.
b) HPT Blades: Point C had no reduction in cooling while Point D experienced reduction.

(a) explains that the HPT efficiency of Point C will be higher than that of Point D since the double reduction in the amount of cooling results in less mixing losses within the HPT. This improvement in HPT efficiency of Point C will have higher impact on SFC reduction. Referring to Equation 2.1, and considering only the HPT vanes, the impact on SFC will be due to the impact of the improved HPT efficiency resulting from the reduction in mixing losses.

(b) elaborates that the reduction in HPT blades cooling of Point D allowed the HPT to produce more work, and have less mixing losses when compared to Point C. This helped raise the HPT efficiency. Moreover, since the cooling flow of the blades influences the engine's thermodynamic cycle (as the blades extract work), the overall reduction in SFC due to the HPT blades encompasses the combined effects of HPT efficiency and engine thermodynamic cycle impacts. Consequently, the reduction in HPT blades cooling at Point D led to an additional decrease in SFC relative to point C.

When considering the effects of both the vanes and blades, Point D showed more reduction in SFC compared to Point C, while Point C had higher HPT efficiency due to the higher reduction in the cooling flow of the HPT vanes.

This comparison shows that although Point C had better HPT efficiency, this did not result in lower SFC. Referring to what was discussed earlier, and by considering Equation 2.1, the impact of the cooling flow on SFC must be considered. Cooling flow affects both SFC and turbine efficiency, and since turbine efficiency affects SFC, cooling flow is said to have an impact on SFC twice. Therefore, a design could sacrifice a small increase in turbine efficiency to obtain lower/better SFC.

4.4 Test Case 1 vs Test Case 2

When comparing the results of the two test cases investigated in this thesis, Figure 4.5 emerges as a crucial reference. It reveals that the SFC reduction trend in the second test case is nearly double that of the first. This substantial improvement can be attributed to the introduction of an additional optimization factor during the process. By increasing the degrees of freedom in the optimization, a broader exploration of design possibilities was facilitated, leading to a more comprehensive reduction in SFC. Moreover, the changes in the gaspath design significantly enhanced flow aerodynamics, minimized losses, and increased the efficiency of the gas generator, contributing to the notable reduction in SFC.

Another significant observation from the figure is that even with an increase in cooling flow, Test Case 2 still exhibited a reduction in SFC. Referring to Equation 2.1, it becomes apparent that this reduction in SFC is primarily due to the enhanced efficiency of the gas generator rather than improvements in the engine's thermodynamic cycle.

Furthermore, the increase in cooling flow for Test Case 2 resulted in a better meanline design compared to the baseline design. However, it is crucial to emphasize the importance of an optimized algorithm and problem setup that adequately cover the design space. Without the correct definition of factors limits, and constraints in the optimization process, the best design points shown on the left side of the figure, indicating reduced cooling flow, might not have been identified. Therefore, designers must adopt a holistic approach that considers various design points to determine the most advantageous impact on SFC.

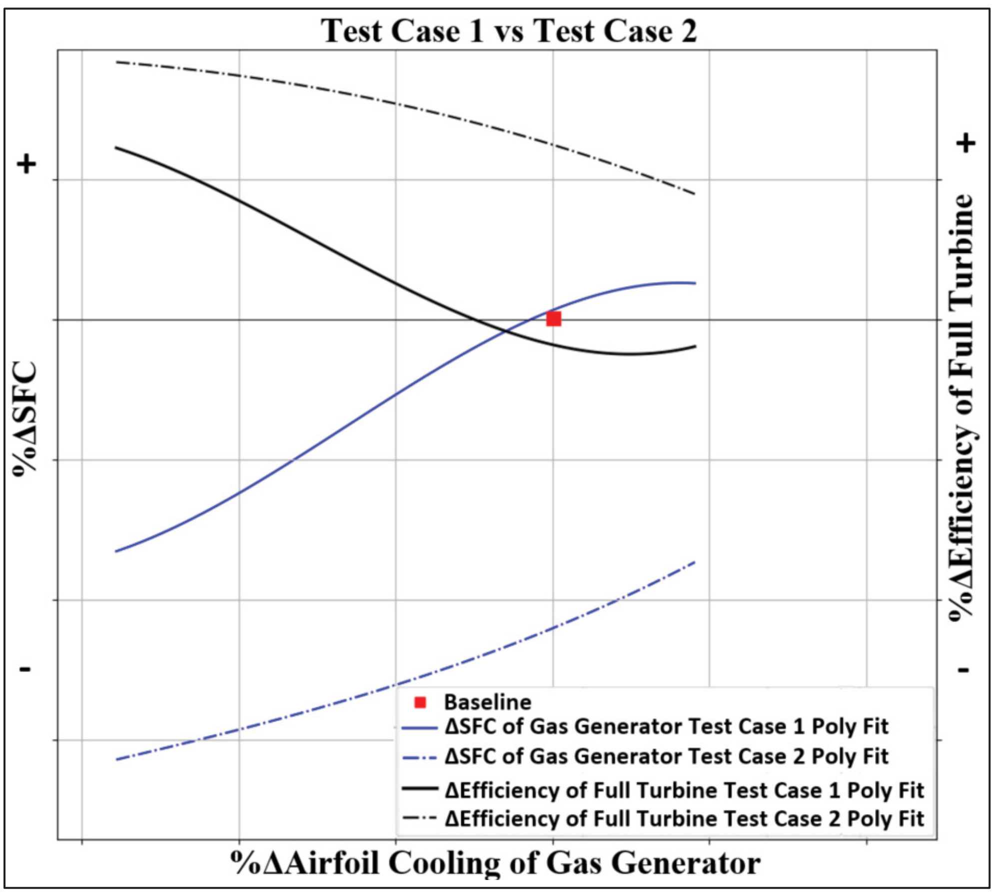

Figure 4.5 Test Case 1 vs Test Case 2

4.5 Results Validation

As mentioned in Chapter 3, two different validation processes were followed. The first involved comparing the optimum design suggested by the developed tool with the optimum design obtained by the manual calculations that combines iterations between the Turbine Aerodynamics, Hot Section Durability, and Advanced Performance groups. The second validation involved running the computational analysis of the test cases with the consideration of the whole engine and not only with the focus on the turbine. This validation was crucial as it verified the accuracy of the SFC exchange factors utilized by the tool, approximating changes in SFC due to variations in turbine efficiency and cooling flow. The SFC obtained from the tool closely matched the values from the computational analysis, leading to the conclusion that the SFC exchange factors are adequate for optimizing the turbine based on minimum SFC of the engine during the preliminary design phase.

4.6 Chapter Conclusion

In this chapter, two test cases were considered, one optimized the turbine of a gas generator with the consideration of only changing airfoil count and axial chords, and the other considered changes in airfoil count, axial chord and the gaspath. It was evident that optimizing the turbine with the consideration of the gaspath could lead to more reduction in SFC due to an increase in the degree of freedom.

The selected test cases emphasized that focusing solely on reducing cooling flow or improving turbine efficiency does not guarantee improved SFC reduction. Instead, a holistic approach considering both factors is essential

CHAPTER 5

OPTIMIZATION RESULTS: SENSITIVITY ANALYSES

5.1 Introduction

In this chapter, sensitivity analyses will be conducted to further explore the effects and relationships of the factors considered during the optimization process of Test Case 1 and Test Case 2. The sensitivity analyses aim to investigate how changes in specific variables, such as axial chord, number of airfoils, flow Mach number, and total temperature influence the resulting changes in Specific Fuel Consumption (SFC), airfoil cooling, and turbine efficiency. By systematically varying these factors and examining their impact on the optimization results, valuable insights can be gained into the sensitivity of the turbine and engine performance to different design parameters.

5.2 Sensitivity Analyses: Test Case 1

As mentioned in Chapter 3, the test cases carried out in this thesis considered a turboshaft engine consisting of a High Pressure Turbine (HPT) and Low Pressure Turbine (LPT) to drive the compressors, and Power Turbine (PT) to drive the propellor. The HPT and LPT are cooled, and PT is shrouded and uncooled. Therefore, the sensitivity analysis carried out considered the HPT and LPT.

5.2.1 Test Case 1: High Pressure Turbine Results

The results of the sensitivity analysis, as depicted in Figure 5.1, Figure 5.2, and Figure 5.3, reveal important insights regarding the influence of different factors on HPT airfoil cooling, SFC, and HPT efficiency. Specifically, when examining the axial chord of the vanes and blades, it becomes apparent that these factors exhibit a higher level of sensitivity compared to the number of airfoils.

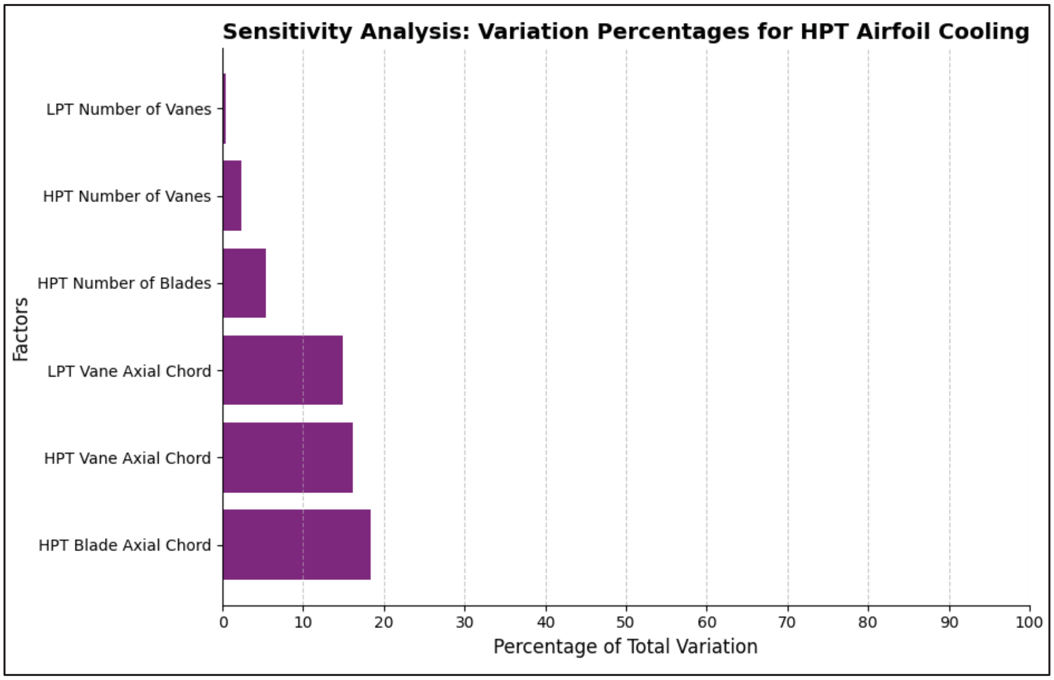

Figure 5.1 Test Case 1 Sensitivity Analysis of HPT Airfoil Cooling

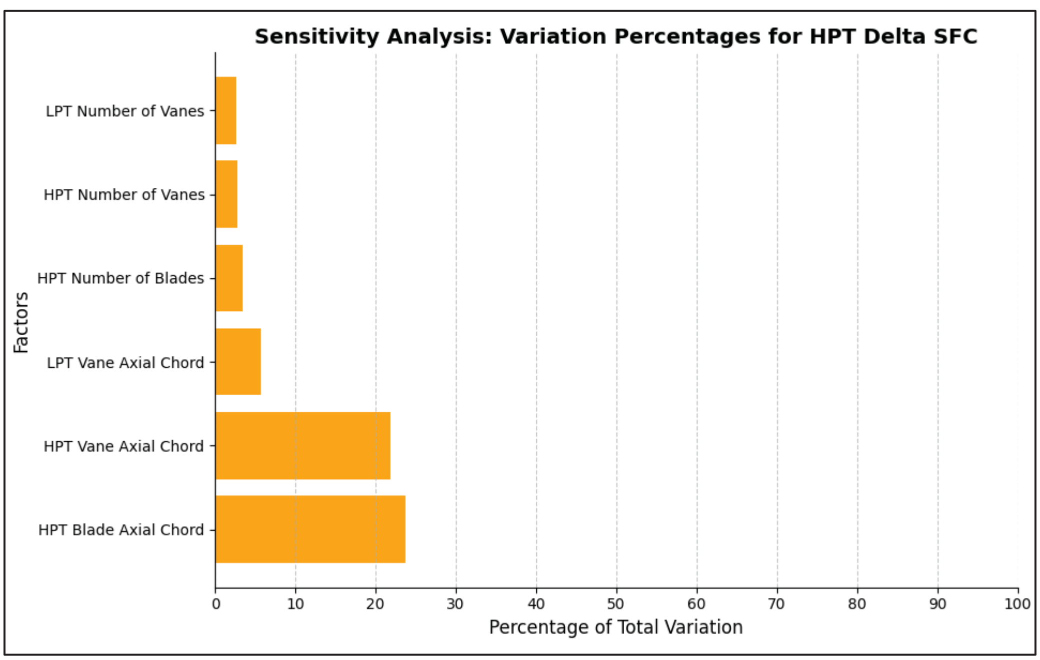

Figure 5.2 Test Case 1 Sensitivity Analysis of HPT ΔSFC

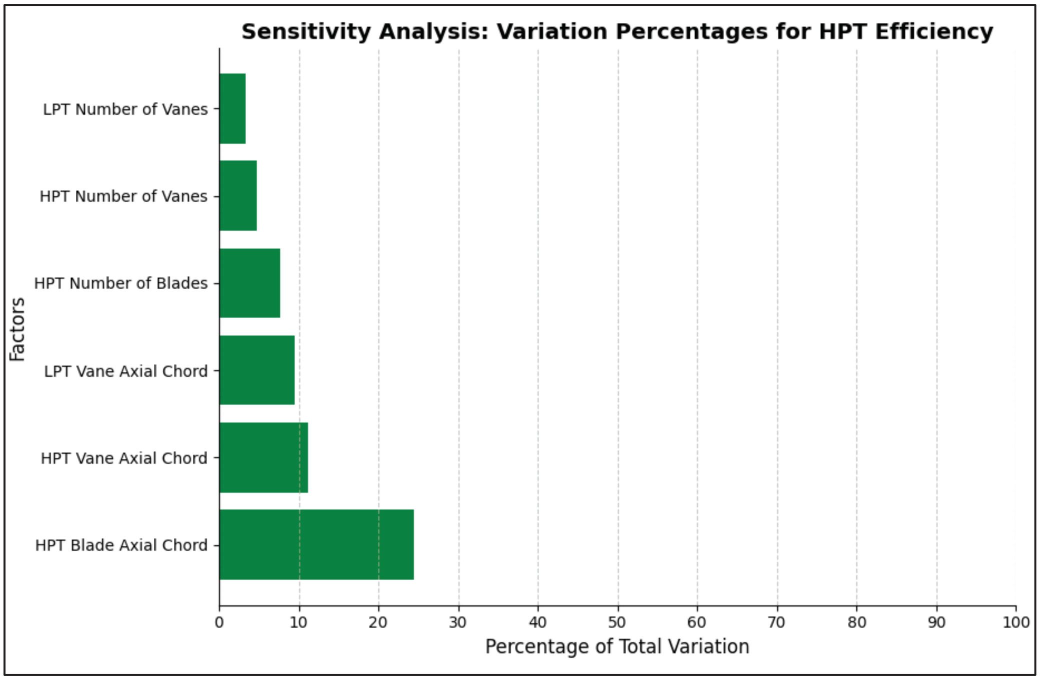

Figure 5.3 Test Case 1 Sensitivity Analysis of HPT Efficiency

As discussed in the previous chapter, both the chord and the number of airfoils contribute directly to the wetted area, as expressed in Equation 4.1. However, the axial chord has a more direct and continuous effect on the wetted area per airfoil, while the number of airfoils influences the repetition of a fixed geometry around the annulus. In other words, increasing the axial chord increases the wetted area of each individual airfoil, which substantially affects the heat transfer surface exposed to the hot gaspath. This will directly impact the cooling flow required for each airfoil and thus, has a more immediate influence on thermal loads, mixing losses, and bleed flow, which affect SFC.

Moreover, increasing axial chord can also influence aerodynamic performance beyond wetted area. Longer chords tend to lower surface curvature and reduce profile losses, but also increase heat transfer surface area, creating a tighter coupling between thermal and aerodynamic effects. This coupling makes the axial chord a more sensitive parameter in terms of both efficiency and cooling.

On the other hand, while increasing the number of airfoils does increase the total wetted area, it also leads to aerodynamic interactions such as narrower passages and increased blockage. These effects are partially caused by stage design constraints such as maintaining mass flow capacity and Mach number limits which means the overall impact on cooling and SFC may not be as significant in this particular configuration.

An important observation from the figures above is that the HPT blades exhibit greater sensitivity in relation to SFC, HPT efficiency, and overall cooling requirements of the HPT airfoils when compared to the vanes. A simple explanation for this trend can be drawn from the discussion in the previous chapter. Being the components responsible for energy extraction, the blades play a direct role in determining the aerodynamic and thermodynamic performance of the turbine. Therefore, variations in blade geometry, in this case the axial chord, affect critical flow characteristics such as flow turning, blade loading, and loss mechanisms including profile and secondary losses. Consequently, increasing the blade axial chord alters the aerodynamic surface area, which impacts boundary layer development, local incidence angles, and mixing behavior, all of which directly influence stage efficiency (Moustapha et al., 2003).

In contrast, while the HPT vanes have a significant aerodynamic impact, their primary function is to direct the flow toward the blades at the correct angle. Changes in the vane axial chord affect the uniformity and turning of the flow before the rotor, but since vanes do not extract work, their direct influence on efficiency is more limited. Therefore, although the impact of vane geometry changes on HPT efficiency is present, it is less significant than that of the blades.

Interestingly, the sensitivity analysis on the HPT efficiency and total cooling requirement also reveals a measurable effect from the LPT vane axial chord. This finding can be considered as a reflection of the aerodynamic coupling between adjacent turbine stages. Modifications in the LPT vane geometry can influence the exit pressure distributions and the downstream backpressure conditions, which in turn may propagate upstream and affect the aerodynamic environment in which the HPT operates. Although these inter-stage effects are indirect, they can cause noticeable changes in HPT performance. This further emphasizes the importance of adopting an integrated design approach that considers stage-to-stage aerodynamic interactions rather than treating each component in isolation.

5.2.2 Test Case 1: Low Pressure Turbine Results

Similar to the HPT, the sensitivity analysis for the LPT reveals that the axial chord is the most influential factor, as shown in Figure 5.4 and Figure 5.5. Interestingly, the analysis shows that the axial chords of the HPT blades and vanes have a stronger effect on LPT performance metrics than the axial chord of the LPT vanes. While this may raise questions, it reflects the inherent thermodynamic and aerodynamic coupling between the HPT and LPT stages.

In a multi-stage turbine, the performance of the downstream LPT is strongly influenced by the flow and thermodynamic conditions established by the upstream HPT. Geometric changes in the HPT, particularly those that affect cooling flow and stage efficiency, can significantly alter the temperature, pressure, and velocity distribution at the LPT inlet. For example, reducing HPT blade cooling flow decreases compressor bleed, allowing more mass flow through the combustor. This increases the TIT, which in turn changes the expansion ratio across the turbine and alters LPT stage loading. As a result, upstream HPT parameters that impact flow quality and thermal conditions are captured as dominant drivers in the sensitivity analysis, even when evaluating LPT performance.

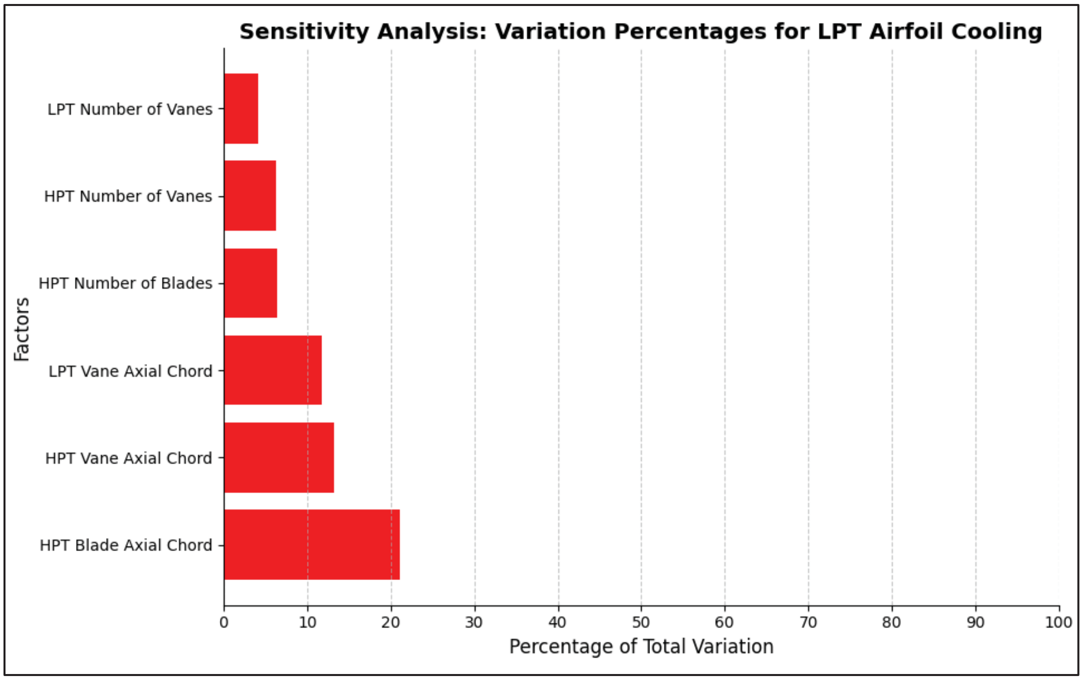

Figure 5.4 Test Case 1 Sensitivity Analysis of LPT Airfoil Cooling

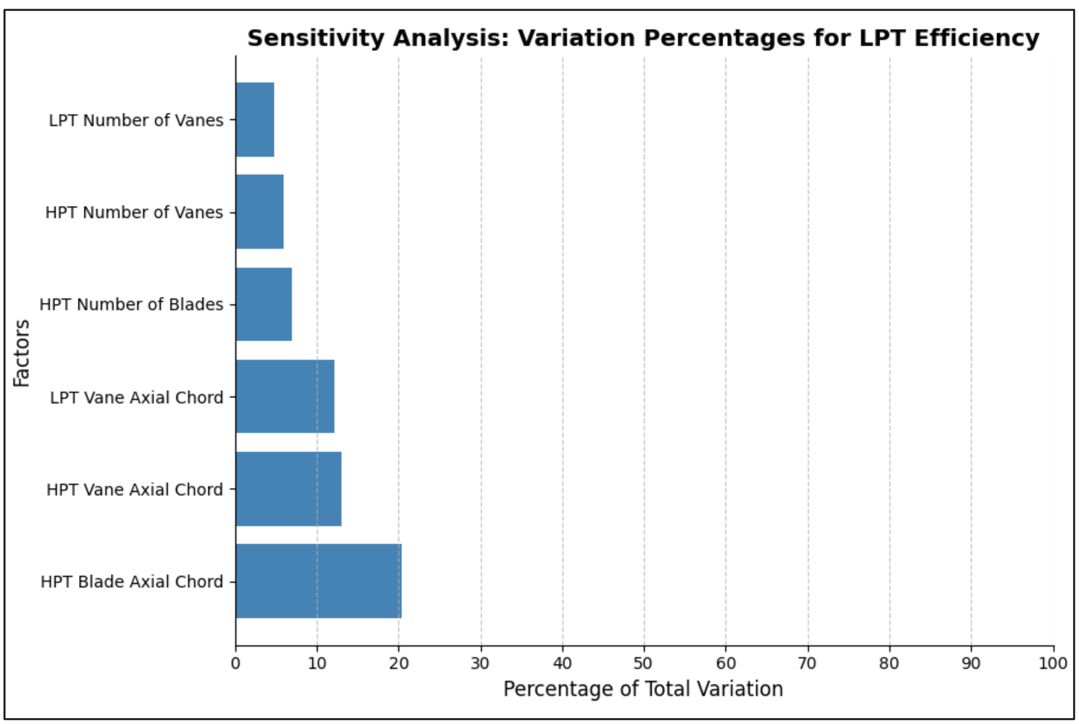

Figure 5.5 Test Case 1 Sensitivity Analysis of LPT Efficiency

5.3 Sensitivity Analyses: Test Case 2

Similar to Test Case 1, the axial chord and number of airfoils for the blades and vanes of the cooled stages are considered during these analyses as well as the tip radius inlet to the HPT to see how another geometric factor affects the cooling requirement, SFC and stage efficiency.

As observed in Figure 5.6, Figure 5.7, and Figure 5.8, the axial chord of both HPT and LPT airfoils continues to demonstrate a strong influence on airfoil cooling, turbine efficiency, and SFC when compared to the number of airfoils. However, the tip radius at the inlet to the HPT emerges as the most dominant factor. This result aligns with the expectations and discussion carried out in the previous chapter.

The tip radius not only represents a geometric change but also carries thermodynamic consequences. As discussed in the previous chapter, increasing the tip radius at the HPT inlet affects the annulus area and blade height, directly influencing the flow cross-sectional area, wetted surface, and therefore the cooling requirement. Furthermore, changes in this radius alter the flow path geometry at the turbine entry, impacting velocity profiles and expansion characteristics throughout the turbine stages, resulting in changes in the aerodynamic performance and affecting the cooling demand.

Following the tip radius, the same trend is visible where the axial chords have stronger effect when compared to the number of blades, with the HPT axial chord having the strongest effect among them due to its direct impact on the airfoil surface area and loss mechanisms such as secondary and profile losses.

Interestingly, when examining the sensitivity of the number of airfoils we can see that both the HPT and LPT number of vanes exhibit minimal sensitivity, with the LPT vanes showing nearly zero contribution. This is not indicative that these factors have negligible effect on the turbine and engine performance nor represent a modeling error, but rather an expected outcome of the correlation-based sensitivity method used, where variables with weak linear relationships to the objectives are assigned negligible influence due to normalization. When a low-impact factor is excluded from the analysis, the remaining factors redistribute the total contribution to maintain a 100% total. This highlights the importance of choosing input variables that have distinct and measurable influence within the studied design space. In this case, it may be beneficial to exclude such low-impact variables from future optimization to reduce problem dimensionality and improve solver efficiency.

Finally, the results from this test case reinforce the importance of gaspath parameters as factors during the optimization process as they serve as the primary drivers of turbine performance and cooling requirements.

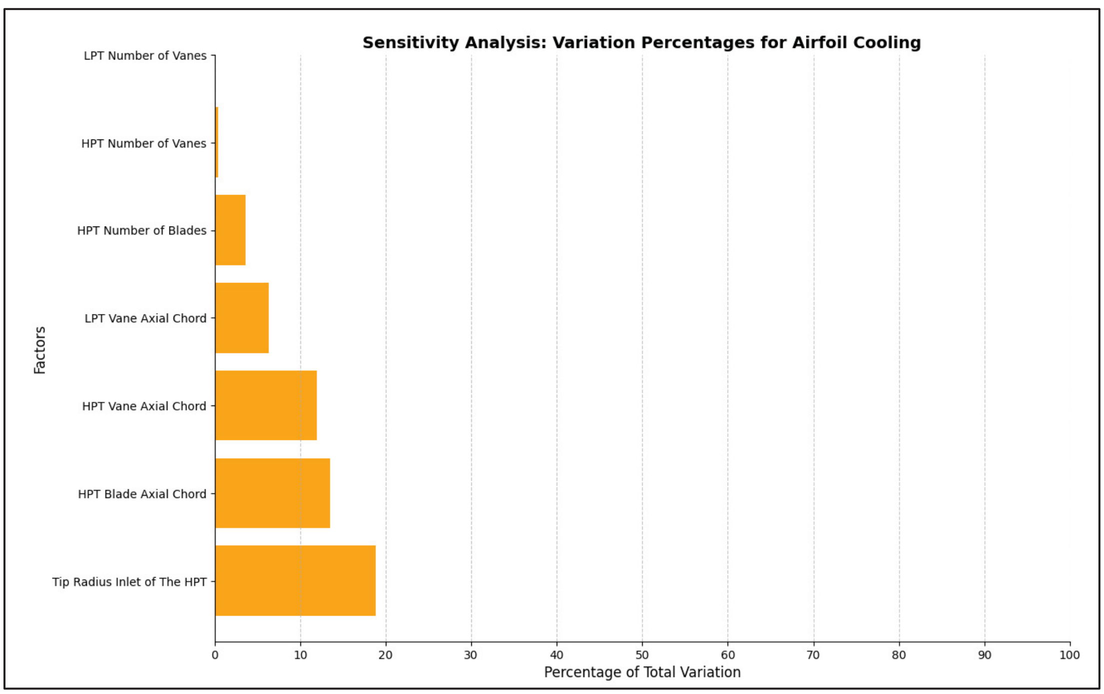

Figure 5.6 Test Case 2 Sensitivity Analysis for Overall Airfoil Cooling

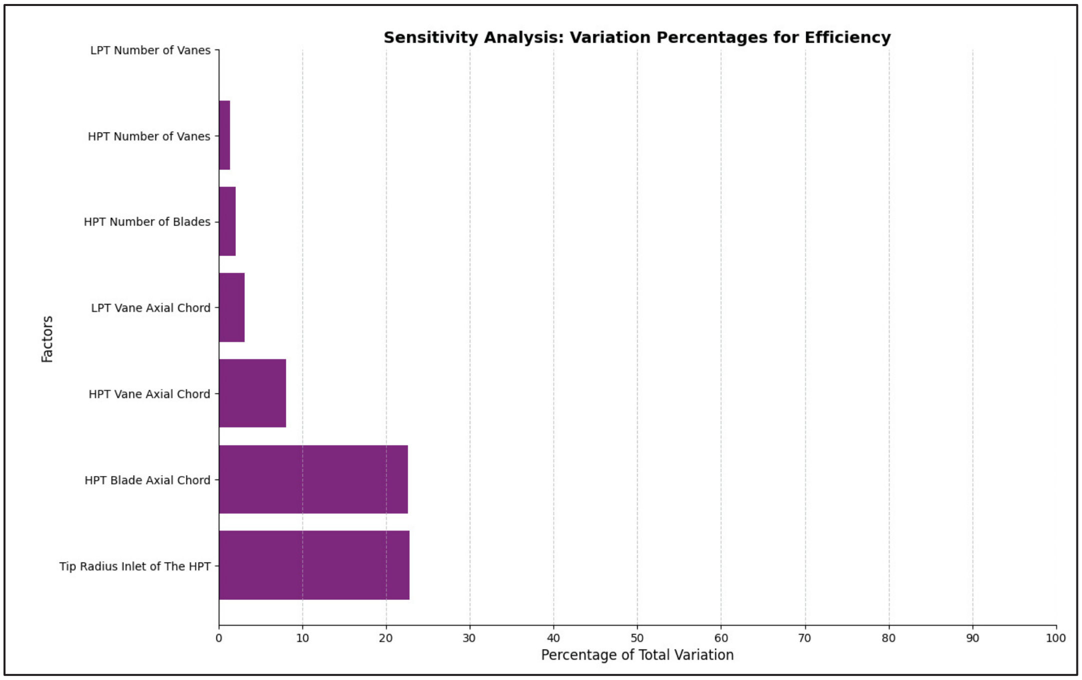

Figure 5.7 Test Case 2 Sensitivity Analysis for HPT Efficiency

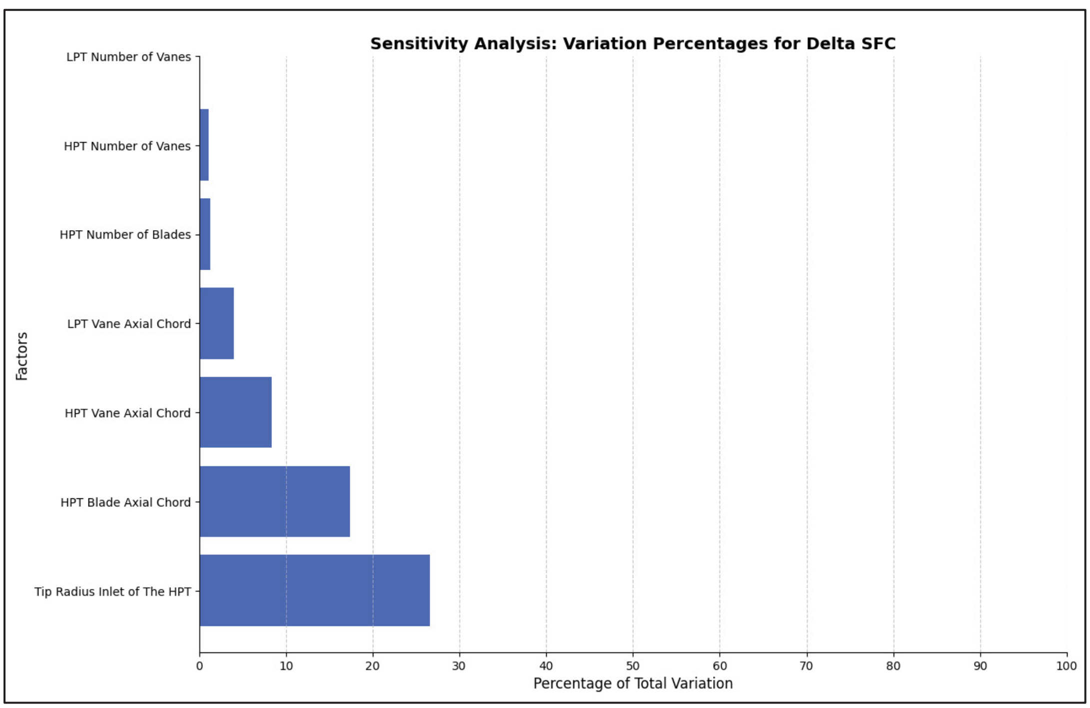

Figure 5.8 Test Case 2 Sensitivity Analysis for ΔSFC

5.4 Chapter Conclusion

In this chapter, sensitivity analyses were performed on the geometric design variables (i.e., the factors) used in the optimization test cases to evaluate their influence on SFC, turbine efficiency, and airfoil cooling requirements. The results showed that the inlet tip radius and axial chord length are the most sensitive parameters. This was explained to be the result of their strong correlation with the wetted area and aerodynamic performance. Additionally, the analyses revealed significant interdependence between the geometric parameters of different turbine spools. For instance, variations in HPT geometry were shown to influence LPT performance, emphasizing the need for an integrated and system-level approach to turbine design optimization.

CONCLUSION

To conclude, this thesis presented the development and validation of a tool aimed at optimizing Gas Turbine Engines (GTEs) based on minimizing Specific Fuel Consumption (SFC), with a particular focus on turbine airfoil cooling. Traditional optimization approaches often focus on "component-level" efficiency, which, while important, do not necessarily lead to "global" fuel efficiency improvements. Given current industry demands to reduce fuel burn and meet environmental regulations, SFC-focused optimization has become increasingly critical.

The methodology centered on minimizing airfoil cooling requirements while ensuring adequate turbine performance. Excessive cooling flow, drawn from compressor bleed, reduces combustor mass flow and raises fuel requirements to maintain the desired TIT, thereby increasing SFC. Consequently, this work emphasized the importance of optimizing cooling flow distribution without compromising thermal protection to ensure durability of the components.

A dedicated optimization tool was developed, integrating three key modules: the Cooling Flow Prediction Tool (CFPT) for airfoil cooling estimation, the Turbine Aerodynamic Meanline (TAML) solver for thermodynamic and aerodynamic performance assessment, and the Framework for Design Exploration (FDE) for optimization. The optimization strategy combined Design of Experiments (DOE) with Surrogate-Assisted Optimization (SAO) to explore the design space efficiently and reduce computational cost.

Two representative test cases based on actual Pratt & Whitney Canada (P&WC) turboprop engines were analyzed. These test cases varied in geometric parameters such as airfoil count, axial chord, and turbine inlet tip radius. Sensitivity analyses were conducted to assess the impact of these parameters on cooling flow, turbine efficiency, and SFC. The results demonstrated that geometric parameters exerted the strongest influence on SFC, highlighting the importance of careful geometric and aerodynamic shaping in the early design phase.

The developed tool was validated through comparison against prior manually optimized engine configurations, and full engine computational analysis. While the tool provides ΔSFC estimates rather than absolute SFC values, it showed acceptable agreement with more detailed simulations, supporting its use in the preliminary design phase to guide early design decisions.

Lastly, the sensitivity analysis revealed strong interdependence between components, particularly between different turbine spools. This underscores the importance of a holistic, system-level optimization approach that considers inter-stage aerodynamic and thermal interactions.

In summary, the presented tool offers a robust and efficient approach to preliminary turbine design optimization, balancing cooling requirements and performance objectives to support the development of fuel-efficient and environmentally sustainable engines.

RECOMMENDATIONS

This research focused on optimizing turbine design based on Specific Fuel Consumption (SFC) with particular emphasis on airfoil cooling. Although airfoil cooling is the dominant contributor to turbine cooling requirements and it represents a major portion of the total cooling flow and offers significant potential for SFC reduction, future work should consider extending the developed tool to include other cooled components such as disks, platforms, and shrouds. This will improve the accuracy of the cooling flow estimation and enable more holistic turbine optimization.

Beyond the turbine, the optimization methodology should be expanded to include upstream and downstream components of the engine. Creating an integrated framework that allows various engine modules (e.g., compressor, combustor, fan, secondary air system) to "communicate" through shared performance metrics would enable true engine-level Multi-Disciplinary Optimization (MDO). This not only provides more realistic boundary conditions for each component but also allows for dynamic trade-off decisions that reflect real engine interactions.

Such an integrated, system-level approach would significantly enhance the applicability of the developed tool in early-stage design. It aligns with the broader goals of future propulsion system development, supporting the move toward high-efficiency, low-emission engines through coordinated component interaction and system-wide performance enhancement.

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