Integration of Finite Element Analysis for Lifing in a Design and Analysis Platform for Gas Turbines

by

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Intégration de l’analyse par éléments finis pour le lifing dans une plateforme de conception et d’analyse pour les turbines à gaz

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RÉSUMÉ

La conception des turbines à gaz est un processus à multiples facettes qui nécessite l’interaction de plusieurs disciplines comme l’aérothermique, la performance, le Système d’Air Secondaire (SAS), l’analyse par éléments finis (FEA) et le lifing. Travailler dans des domaines multiexpertises exige des tâches sans valeur ajoutée comme la transmission ou la gestion des données entre les logiciels mais également des tâches fastidieuses parmi le pré-traitement, le traitement et le post-traitement notamment répétitifs et similaires ce qui demande un temps important. L'objectif de la plateforme de conception et d’analyse est de regrouper toutes les disciplines utilisant plusieurs logiciels pour les turbines à gaz et de les intégrer dans un contexte d’Optimisation et de conception Multidisciplinaire (OMD) grâce à l'automatisation.

Cette thèse porte sur l’intégration de l’outil d’analyse par éléments finis (FEA) afin d’évaluer la durée de vie des composants du moteur dans une plateforme de conception et d’analyse. Un outil automatisé a été développé intégrant le logiciel par éléments finis utilisé par Siemens, SC03, qui résout le modèle de turbine à gaz en mode structurel, thermique et thermomécanique. Cet outil est principalement conçu et testé pour les ingénieurs d’intégrité mécanique et de modélisation thermique du moteur. Ces derniers ont besoin de données différentes des analyses, pour cela, un flux de travail a été créé permettant à l’utilisateur de faire du pré-traitement, du traitement et du post-traitement. L’implémentation du flux de travail a été rendu possible grâce à l’automatisation.

L’outil créé dans la plateforme digitale inclut l’automatisation des analyses du moteur thermique. L’utilisateur peut générer une quantité importante de données d’entrée qui définissent le cycle du moteur soit *Basic Design Data* (BDD) et les résultats des analyses de simulation numérique soit *Finite Element Model* (FEM) pour différentes configurations de moteur. À la suite des analyses, une étape d’extraction a été mise en place ainsi qu’une interface utilisateur pour faciliter le post-traitement ce qui permet aux utilisateurs de choisir les quantités voulues comme les déplacements, contraintes et températures. Cette plateforme et application multidisciplinaire a pour but de réduire le temps du cycle et les coûts de conception tout en améliorant la qualité et la robustesse du procédé de conception.

Mots-clés : Automatisation, intégration, analyse par éléments finis, basic design data, gain de temps

Integration of finite element analysis for lifing in a design and analysis platform for gas turbines

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ABSTRACT

Gas turbine design is a multifaceted process that requires designing many disciplines as aerothermal, performance, Secondary Air System (SAS), Finite Element Analysis (FEA) and lifing. Working in multi-expertise fields requires non-value-added tasks such as data transmission between software or data management but also tedious tasks among pre-processing, processing and post-processing especially repetitive and similar which requires valuable time. The objective of the Design and Analysis (D&A) platform is to regroup all disciplines using multiple gas turbine software and integrated them into a Multidisciplinary Design Optimization (MDO) context through automation.

This thesis presents the integration of Finite Element Analysis (FEA) tool for lifing into a Design and Analysis (D&A) platform. An automated tool has been deployed integrating finite element software used at Siemens, SC03, that solves the structural, thermal and thermo-mechanical gas turbine model. This platform is designed and tested for Mechanical Integrity (MI) and Whole Engine Thermal Modelling (WETM) engineers. Both need different data from the FEA, so a workflow has been created that allows the user to pre-process, process and post-process FEA. Implementation of this workflow was made possible with this platform thanks to automation.

The tool created in the digital platform includes the analysis automation for the whole engine thermal model (WETM). The user can generate a huge amount of inputs of engine cycle definition, namely the Basic Design Data (BDD) and the results of numerical simulation analyses namely the Finite Element Model (FEM), for different engines configurations. After the analysis is done, a step of extraction of values will occur to facilitate the post-processing. For that, a user interface is displayed, and stakeholders can choose the quantities needed such as displacements, stresses, temperatures. This multidisciplinary application and platform aim to reduce design cycle time and cost while at the same time improving design process quality and robustness.

Keywords: Automation, integration, finite element analysis, basic design data, time saving

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LIST OF ABREVIATIONS

AGT	Aeroderivative Gas Turbine
BDD	Basic Design Data
CPU	Central Processing Unit
CSV	Comma Separated Values
D&A	Design and Analysis
DLE	Dry Low Emission
FEA	Finite Element Analysis
FEM	Finite Element Model
GUI	Graphical User Interface
HPT	High-Pressure Turbine
JSON	JavaScript Object Notation
MDO	Multidisciplinary Design Optimization
MI	Mechanical Integrity
PLM	Product Lifecycle Management
PM	Physical Model
SAS	Secondary Air System
UI	User Interface
WETM	Whole Engine Thermal Model
WEMM	Whole Engine Mechanical Model
WLE	Wet Low Emission

INTRODUCTION

Gas turbines are a proven unit for electrical power generation and mechanical drive applications. The combine of both make it an ideal candidate for the demand in oil and gas industry. Gas turbine with his robust design empowers high efficiency and excellent performances that enables it to master the dynamic energy market environment. Siemens Aeroderivative Gas Turbines (AGT) were originally developed by Rolls-Royce to be used in aviation. Today, its capacity to be flexible, compact and lightweight design enables power generation and mechanical drive for a wide range of applications. Designing AGT consists of an execution of complex workflows in order to satisfy the product requirements. It should be noted that these workflows require the involvement of multiple stakeholders. These teams use different tools and generate data in different formats that are sometimes converted to be readable by another tool. They need to collaborate to exchange data from their disciplines namely their departments. For that, a framework is developed to facilitate multidisciplinary design and analysis of the engine and components. This platform will run heterogeneous tools, with several engineering workflows and are able to perform computationally intensive tasks. A key aspect of an integration framework is model reusability along different disciplines in the design process (Ramamurthy et al., 2014). The purpose of this platform is to reduce the design cycle time and cost of the AGT while improving design quality and robustness. To connect disciplines, we need to automate engineering workflows in the D&A platform.

Automation is part of what we call today “Industry 4.0”. This concept that originated from Germany represents nowadays the transformation of industry via intelligent networking of processes and machines through information and communication technologies. It focuses mainly in interconnectivity through the Internet of Things (IoT), automation, machine learning and real-time data. The term “Industry 4.0” is often used interchangeably as the fourth industrial revolution. It aims to enable the development of a digital and automated manufacturing environment (Oesterreich et al., 2016) via various factors as illustrated in Figure 0.1. Today, industry like Siemens implements this concept to improve manufacturing efficiency, processes, boost productivity and drive growth. Digitalization will allow better collaboration and access across departments, product and people.

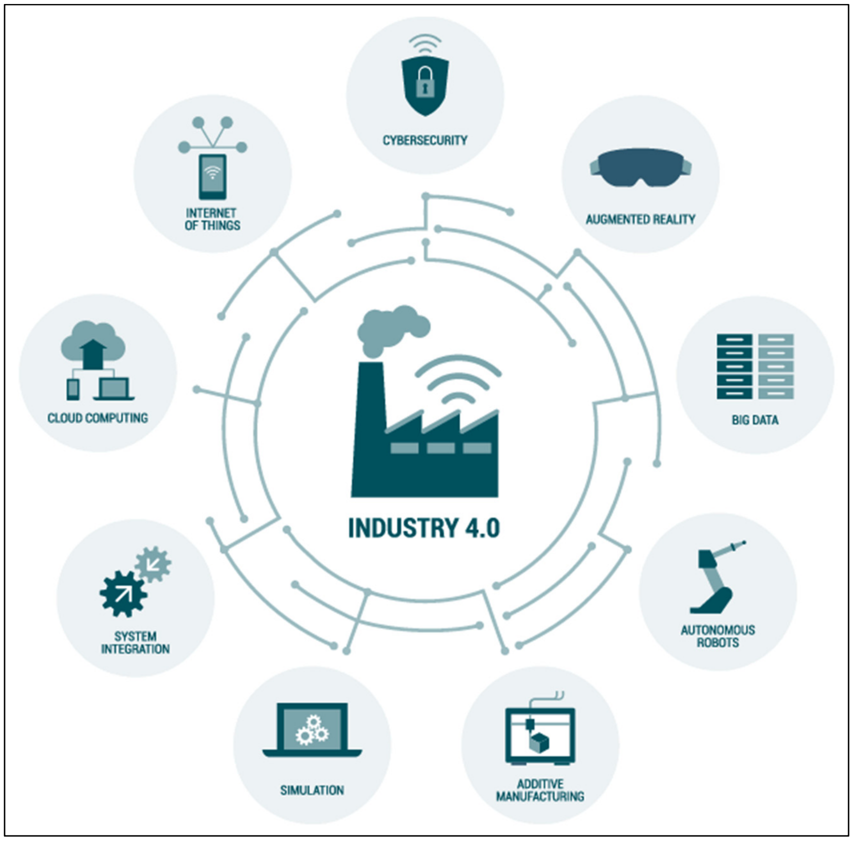

Figure 0.1 Industry 4.0 - Digital transformation

For that, a digital multidisciplinary analysis and optimization platform have been developed that permit engineers to collaborate and exchange data by reducing tasks management. This platform gathers miscellaneous disciplines in a unique platform. The framework will unify different disciplines and modules in one platform.

This project will be focused on the integration of Finite Element Analysis (FEA) tool in order to solve the engine model in the in-house FEA software, developed by Rolls Royce, SC03.

Objectives

This thesis will present the study of the integration of finite element analysis tool in a multidisciplinary platform. Integrating this discipline into the platform by way of automation will reduce a huge amount of time and will decrease the number of mistakes that human can make. The integration of this tool requires an input to solve the gas turbine model in the FEA software, called the Basic Design Data (BDD). This input file is nowadays created manually by engineers in the company by using UNIX application with limited access for users and require a lot of manual tasks that take valuable time. Indeed, time is fundamental in engineering workflows. Most of the work will be around the BDD, because this input will gather disciplines and will combine multiple data from various tools. To run a FEA, we need to retrieve outputs from different tools from different disciplines and create the BDD in order to solve the whole engine thermo-mechanical model already meshed. The purpose of this project is to use an automated FEA tool that will reduce time to pre-process the analysis and to focus more on the post-processing for stakeholders. The framework in which the tool is developed is accessible by every engineer in the company and use Windows application. Reducing the time allows engineers to spend more time on the data analysis and assess life of AGT components. FEA automated tool will generate data that will permit to have accurate predictions of components strength and life which is essential for maximizing component life, maintaining safety and reducing cost by improving the design process and quality of the product.

The first chapter will present the AGT workflow by describing the framework and the design and analysis platform. The second chapter will present the review of literature and we will be able to understand in detail the aspects of the tool that would be automated and why automation is needed. In the third chapter, the methodology will be described, in other words, the description of the automation of the FEA tool in the D&A platform. Besides, the implementation of the tool and the results will be studied in the fourth chapter. Finally, the fifth and last chapter will present what the benefits and the drawbacks of this tool are by including the user experience.

CHAPTER 1

AGT WORKFLOW AND D&A PLATFORM

1.1 Aeroderivative gas turbine workflow

Siemens empowers in the power generation market, it plays a significant role in the design of Aeroderivative Gas Turbine (AGT). Over the years, the company has acquired a huge amount of knowledge and capacity to produce efficient gas turbines. Many tools have been deployed to enhance the design, and analysis of AGT by the engineers in order to achieve high productivity.

Aeroderivative gas turbine workflow is complex, particularly because of the dependence of many disciplines. This workflow is simplified, and it is not including manufacturing and engine test bed, it is focused on the design phase. The AGT workflow is mainly composed of nine different disciplines as shown in Figure 1.1 below.

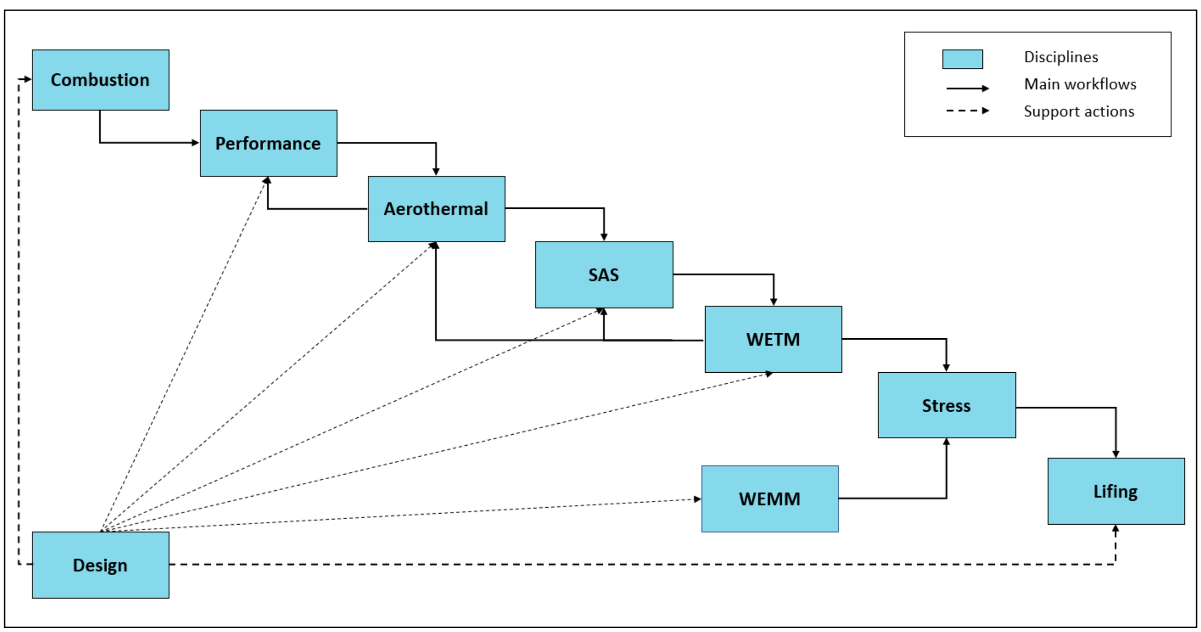

Figure 1.1 AGT main workflow

As we can see, AGT design process can be separate in nine main disciplines:

- Combustion: This discipline represents ones of the most important one because it involves the design of the combustion chamber which is a delicate part to study. It comes at the beginning of the workflow and creates an initial performance model.
- Design: The design team is focused more on Computer-Aided Design and will study the different components of the gas turbine or different parts of components that needs to be assessed in detail.
- Performance: Designing the performance model is a discipline that creates a model containing all the temperatures, pressures and mass flows among other parameters needed depending on the gas turbine configuration. This model defines these values for each section of the AGT.
- Aerothermal: Computation of flow conditions is done by aerothermal team. The aerodynamics and cooling design of the blade, compressor and turbine are provided by this discipline.
- Secondary Air System (SAS): Performances over the cooling air are calculated on blades, vanes and sealing on the gas turbine and are computed at some specific locations. SAS also calculates bearing loads and assesses them.
- Whole Engine Thermal Model (WETM): In this discipline, engineers work on creating and updating the 2D/3D thermal models by defining the boundary conditions and thereafter assess the temperatures and displacements on relevant components. The analysis is configured in thermal and thermo-mechanical modes.
- Whole Engine Mechanical Model (WEMM): Engineers of WEMM look at outside vibrations caused by earthquakes, waves on floating platforms by performing structural analysis of the engine. They study and analyze the rotor dynamic.
- Stress: Values of stress are extracted during stress analysis on the WETM and used for lifing. The Mechanical Integrity (MI) department is charged to do this analysis in structural model of gas turbine especially on critical parts like blades, discs to identify the damages.

- Lifing: Experts on lifing team predict the life of components, particularly, critical ones as mentioned above. This study could be done by analyzing stress, fatigue or creep for instance.

After each test and analysis, requirements and requests are provided by specialists of the disciplines to another level of the workflow. Observations after tests can provoke many iterations of analysis and design. In fact, we can notice a strong connectivity between disciplines by the fact that an output from a discipline represents an input from another one. The design discipline is the only one to be connected to all disciplines because it proves the mechanical design. After all tests from performance analysis to life prediction of components validated by engineers, the turbine goes to production and gets delivered to customers.

It should be noted that in the main design process, human interactions and tasks but also software tasks and management occur during the main workflow. It demands a lot of iterations in terms of design and analysis. Thus, integration of tools into a digital platform is a solution. Indeed, as product design becomes increasingly complex, competitive pressure pushes new levels of innovation such as integration of framework technology. In fact, that will enable to measure product performance efficiently and create new models (Warde et al., 2019). Nowadays, companies are making a lot of investment to deploy such a platform in order to reduce design cycle time by improving the performance of the product.

1.2 Design and analysis platform

1.2.1 Framework

In many engineering problems, it exists strong interactions between multiple phenomena to produce accurate simulation results (Chernukhin et al., 2019). Indeed, specialists of disciplines use different tools to complete their tasks. Furthermore, the design process is often executing a large number of similar simulations, so automate these methodologies allows not only the user to minimize the chance of error, it simplifies the number of tasks that has to be done.

The design and analysis platform represents a key factor for the workflow, it is an in-house framework that has been developed by engineers at Siemens. Empowering automation solutions into the framework plays a vital role in industry. In fact, the platform relies on several factors such as interoperability, that is to say, the capacity to be integrated with other disciplines and be able to exchange information. Virtualization is the capacity to create a replica of physical entity or process, also called digital twins. In addition, the traceability enables the user to track and monitor the resources in real time, in order words, to acquire the information and analyze immediately. One of the most important factors is the modularity, indeed, engineers need a flexible integration if new modules are developed or an adaptation if modifications have been done. To be modular, the framework is decomposed of independent subsystems in order to face complexity (Coito et al., 2019). The previous features mentioned are all part of the initiative of Industry 4.0.

The framework is developed in python in object-oriented environment, it has been deployed with the work done by Ramamurthy (Ramamurthy et al., 2014). Indeed, this framework represents an effective interface between tools. It includes a system engineering module allowing creation and definition of model after mapping inputs. It contains a processing module that allows the generation of results and permits reusability of models. Also, an advance visualization module has been developed to post-process the results of analyses. This platform enables the user to analyze, compare and save the results. In that way, the engineers can have access to the historic revisions at any step of the design process and can move across them. The revisions are published after the work is done to be accessible by other teams (Ramamurthy et al., 2014).

The benefits of such framework are the elimination of non-value-added tasks and it provides unique and coherent information across the disciplines and along the product life cycle. This D&A platform has developed a technology strategy that aims to support a highly integrated concurrent design process in order to improve performance and robustness of its products, maximizing thus its competitiveness while minimizing its financial risks. The purpose of this platform is to provide for engineers a tool integration platform and a solid foundation of a computational environment that integrate functional data management, model version control, analysis tools and optimization algorithms in a way that is customizable to specific workflows of different engineering disciplines by using automation.

1.2.2 Tool Integration

A tool integration framework facilitates the development of application tools. It supports developers to implement workflows by providing the ecosystem desired. By integrating various tools in the framework, artifacts which mean requirements and simulation models, become reusable and traceable across the D&A platform. Besides, it should be noted that different engineering tools mean different disciplines that produce different artifacts (Binder et al., 2019). The link between disciplines is introduced by way of automation methods in the framework.

Indeed, the main workflow of AGT is subdivided into sub-workflows for disciplines. As it is illustrated in Figure 1.2 below.

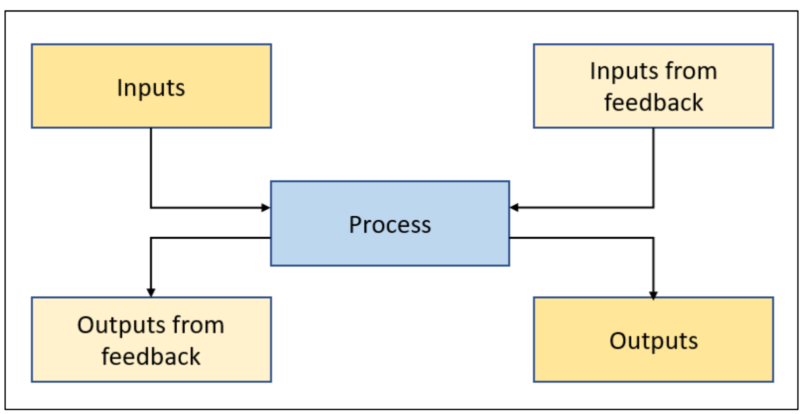

Figure 1.2 Representation of a sub-workflow

A sub-workflow of a discipline will run an analysis or a design tool, to be executable, a set of inputs must be provided in order to generate a set of outputs. In fact, there are two sorts of inputs, some of them are mandatory to run the model others are optional, those are from feedback.

Integrating the FEA simulation tool in the D&A platform is fundamental for product design and development process. It represents one of the tasks that consume so much time from configuration to post-processing of results passing by the big part of analysis. FEA workflow use different inputs from different disciplines, therefore interactions will be established. Connectivity and traceability can be applied in the numerical simulation tool, by means of automation and integration approaches. Indeed, robust and traceable simulations data are required to set up this tool. The modular in-house framework increases the reusability of the simulation tool thanks to integration. That leads teams to collaborate and manage through the framework.

This D&A platform contains specific modules and standard activities. These activities represent entities that enable design engineer to perform their everyday work. Design engineers are people who create tasks, configure and collaborate on designs. Entities will generate design and analysis data for the gas turbine. Interaction between modules is made possible through metadata description of their activities by using JavaScript Object Notation (JSON) format.
In order to achieve agility across the platform, information must flow from application to application without loss or corruption. Tool integration framework facilitates data exchange between disciplines automatically in real time by labeling them. In addition, this platform saves time and efforts for users to convert the data to be compatible in another tool. This non-value-added task is automated by the developer in order to gain time in the design process.

1.2.3 WETM discipline and activities

The FEA tool is developed in WETM discipline where simulation of the 2D whole engine can be solved. The reusability of simulation model is essential when it comes to run analyses in a design process for gas turbines. Automation of FEA workflow will permit engineers especially mechanical integrity team engineers to focus more on life assessment of components. In this module, activities will be created in order to run the tool to do the analyses and obtain the results needed for the specialists.

To be precise, the framework includes a project dashboard, activities including itself activity blocks, input blocks and output blocks and sometimes User Interface (UI) is created. An activity is assigned to a workflow of a discipline and represents typically the gas turbine version. A workflow is composed of an input block, an activity block that can also be called a "tool" block and an output block as shown in Figure 1.3. These blocks play a vital role because it makes the comprehension of the workflow easier and in general AGT design workflow. The "tool" block contains all the configurations to be able to run analyses.

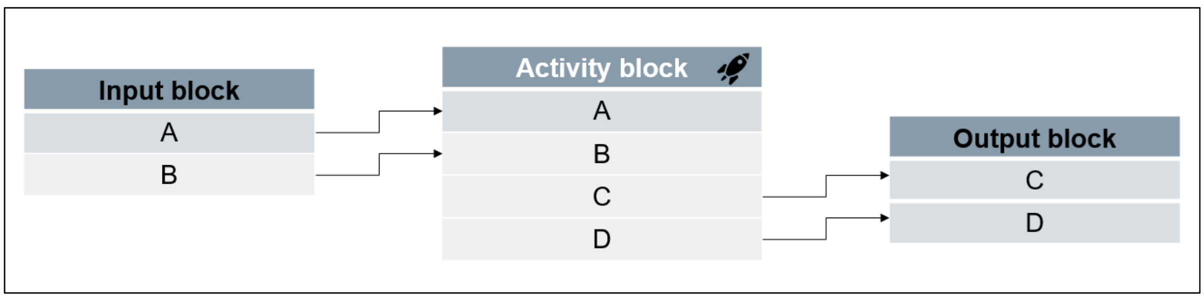

Figure 1.3 Structure of an activity

The user runs the activity by clicking on the rocket launcher in the "tool" block and executes his simulation that produces output data. This output data can be saved by creating a revision that stores the results that can be read at any time.

This activity can contain other activities, it means that a workflow can contain many workflows. That is the case for the automation of FEA tool developed, in fact, it is a multidisciplinary activity which interacts many workflows such as performance tool and secondary air system tool. The benefits of such platform are the performance of more iterations in less time and elimination of non-value-added tasks like data collecting, retrieving the correct model, for example. This obviously reduce the human factor error and increase productivity.

1.3 Conclusion

This chapter has been introduced AGT workflow by pointing out the number of interactions necessary between experts and tools. The benefits of the proposed framework are the reduction of process development time by the fact that is supported to the subject matter experts for including new processes. Also, the process standardization due to the reusability model followed by the fast and easy-to-setup technology impact evaluation. Indeed, this framework permits to trace the changes in the design over the various phases. In addition, the introduction of the FEA tool by the means of WETM discipline is presented through the activity describing the workflow.

Thus, Industry 4.0 will drive a major change in tomorrow’s workforce. It is mainly characterized by real-time connectivity, speed of implementation, culture change and skills adaptation.

CHAPTER 2

LITERATURE REVIEW: AUTOMATION OF FEA TOOL

2.1 Overview of gas turbine

Gas turbine is an internal combustion engine and one of the most versatile items of turbomachinery today. Gas turbines are widely used in power generation application with its range of output power from anywhere up to beyond 500MW. Designed for industrial power generation and mechanical drive applications, Siemens aeroderivative gas turbine is a proven benchmark for power output, fuel economy, and cost savings. Based on Rolls-Royce aero-engine technology, it also offers outstanding operating flexibility for a variety of demanding applications.

2.1.1 Concept

Gas turbine system follows Brayton cycle, in this thermodynamic cycle, the air is compressed, heated and expanded through what is called the expander by excess the power provided by the compressor to generate electricity. A gas turbine system is essentially composed of three main components, that is to say, compressor, combustor and turbine as shown in Figure 2.1.

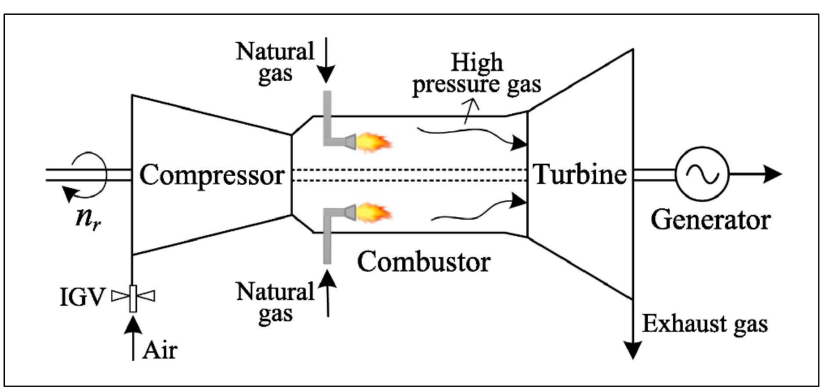

Figure 2.1 Gas turbine system diagram

In the power generation process, first, the compressor inhales and compresses air, so the pressure will increase. This high-pressure compressed air is provided to the combustor in order to ensure the combustion of natural gas injected. The mixture of natural gas and air is burned in the combustor. Then, the turbine rotates high-pressure and high temperature gas from the combustion of the mixture. Consequently, the internal energy of fuel is converted into mechanical energy to drive the generator to produce electricity (Hou et al., 2020).

2.1.2 Gas turbine model

A cross section of a gas turbine model is represented in Figure 2.2 below. The part reported in box is typically a 2D Whole Engine Thermal Model (WETM) used to run the analysis in SC03 numerical simulation software.

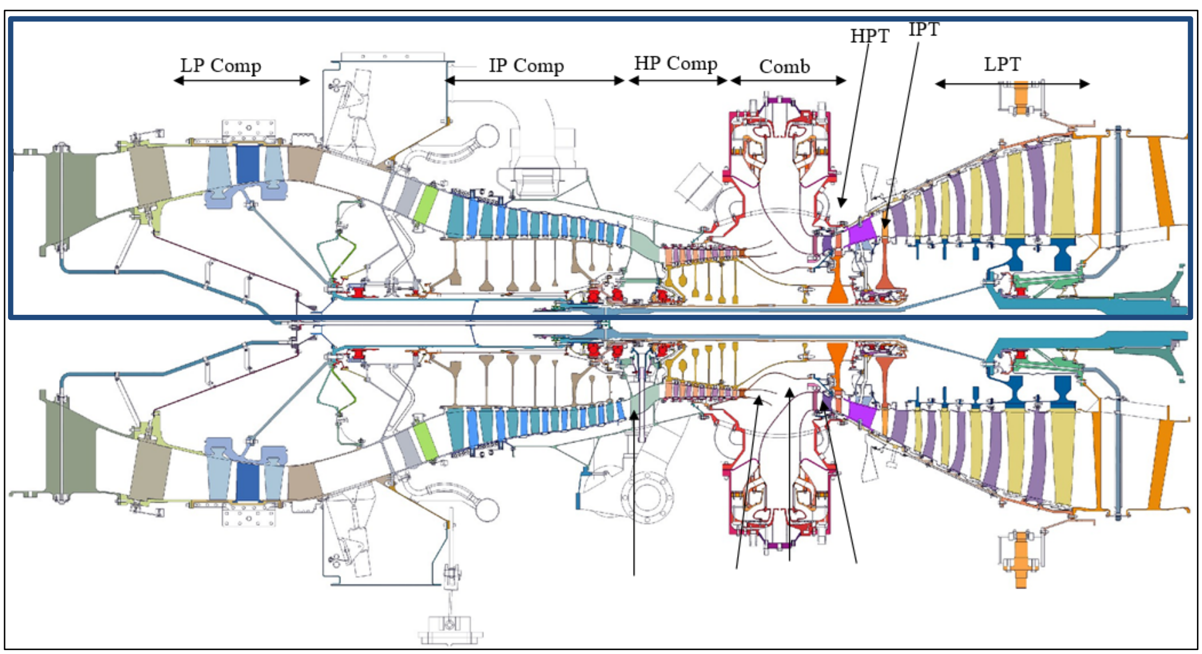

Figure 2.2 Cross section of a gas turbine

As shown in Figure 2.2, the whole engine is composed of some main components such as Low-Pressure Compressor, Intermediate Pressure Compressor, High-Pressure Compressor, Combustor, High-Pressure Turbine, Intermediate pressure Turbine and Low-Pressure Turbine.

The numerical simulations run for this study have been mainly done on the SGT-A65 2D model, formerly known as Industrial Trent. This highly flexible AGT benefits a high-power efficiency and is available with Wet Low Emission (WLE) and Dry Low Emission (DLE) combustion systems.

To create a WETM, it takes a significant amount of time and efforts due to the large number of boundary conditions. The WETM contains all the main components of the AGT. The geometry is prepared either by designer or thermal analyst, when it is ready, the meshing is made. Note that the WETM used for the automation tool is already meshed and ready to be imported in SC03.

2.1.3 Critical parts

Critical parts are the ones that deal with overheating, creep, corrosion, and fatigue failure during operation that can cause physical injury up to loss of life. These critical parts have a severe impact of failure and have consequences that can be a danger to humans. They are often over-designed to not fail and are changed during service maintenance even if they are in good condition. Thus, a lot of efforts are put on the analysis of their failure mechanisms. Discs are considered the most critical parts of the AGT, an example of a disc is represented in Figure 2.3 below where a propagation of crack is illustrated during engine operation. if a disc breaks in pieces, so much energy is released that the engine casing will not be able to support therefore all the material release and metal pieces will fly out which potentially hit anything or anybody.

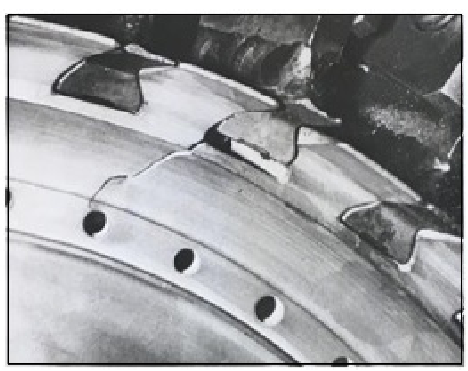

Figure 2.3 Example of a critical part – Disc

There are also components called “sensitive” parts which are most susceptible to failure that will render the engine inoperable such as blades. Their failure is shown by failure analysis to have hazardous effects and required special controls. In addition, the engine casing will be able to contain material release that implies no danger to human. The application of gas turbines in electricity generation shows that failure of these parts can cause great economic losses (Mirhosseini et al.). The failures of these components are mostly caused by fatigue, creep, hot corrosion and erosion. Particularly in gas turbine blades, the fatigue crack results from loads that vary during the startup and shutdown of the turbine and also vibrations.

In order to increase the reliability of AGT and prevent the damage on critical parts, assessments on the life of these components are made. For that, many analyses on the engine components are done. In that way, failure mode and mechanisms are inspected, and the origin of the cause can be identified. In addition, most of the time, ruptures are caused on the disc due to stress concentration in critical areas, therefore analyses are made to minimize the stress in locations affected by high stresses. Furthermore, the study of lifing on gas turbine is really important because critical and sensitive parts can cause accidents during operation hours and can represent a great economic loss. In order to have a reliable gas turbine, simulation should be done to test the model before operating on test bed. In that way, finite element analysis is done in a numerical simulation software to identify the areas causing problem and correct them thanks to the results collected during the analysis. FEA is mostly used to predict the distribution of stress and temperature on gas turbine components as it will operate during the service.

2.2 FEA simulation

2.2.1 Definition

The Finite Element Analysis or FEA is the simulation of any given physical phenomenon using a numerical mathematical technique called the finite element method. It is a computational method using partial differential equation to solve the model and calculates relevant quantities. It should be noted that FEA provides approximate solutions of the problem, the results will be predictions of the gas turbine behavior. FEA-based simulation has emerged as a powerful tool to analyze the mechanical and thermal behaviors of gas turbine during his operation. FEA can handle structural response, detect damage and mechanical failure due to thermal stress (Chakrabarty et al., 2016).

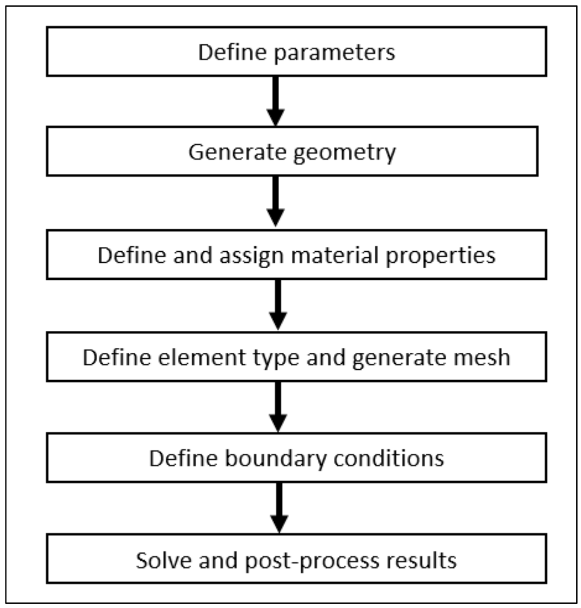

Figure 2.4 Flowchart of a FEA model

A general workflow of the FEA model creation has been shown through the flowchart in Figure 2.4. First, parameters are defined in the FEA model like geometry data, structure thickness, etc. Then, the geometry is generated by defining entities by lines and areas. In the next step, materials and its properties are assigned in different parts of the geometry. Then, the element type is defined, generally, a one-dimensional model is referred to beam element, the two-dimensional model to shell element and the three-dimensional model as solid element. Besides, elements connect nodes on the model, in our case, the 2D model is studied. After that, the mesh is generated to get high-quality elements. The next step, boundary conditions are applied on the 2D model of AGT. The type of boundary conditions depends on the type of analysis chosen. Finally, the model is solved using finite element method and the results are interpreted. Results of analysis such as stress, strain, temperature can be plotted and visualize using post-processing functions in the FEA software (Wang et al., 2016).

FEA parametric model is primarily used by engineers to reduce the number of physical prototypes and optimize the model during the design phase to have a better product. Furthermore, runs demand plenty of calculations, to have fast performances, analyses have been run in the local computer using six cores. To be even faster, analyses have been executed in remote desktop which is even more powerful and has more memory.

2.2.2 Finite element method code

The finite element method is used to perform engineering analysis with a computational software. In this study, SC03 is used to solve the engine model. This method is designed to solve fields problems. It consists to discretize the solution domain into many small size and interconnected elements which leads to solve each element and get approximate solution. The fact that the geometry of the field is known, it enables to have sufficient number of boundary conditions to solve the problem. The finite element method uses a series of simultaneous equations describing the behavior of fields. They are solved for the basic field variable such as temperature or displacement from which other derived quantities can be calculated such as heat flux, strain, stress. SC03 solves the differential form of Fourier's law of heat conduction given by the following equation.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Where x,y,z are the Cartesian coordinates, T represents the temperature, q is the internal heat source, k is the heat conductivity, t is the time and $\alpha = \frac{k}{\rho c_p}$ with ρ, the material density and c_p, the specific heat capacity.

2.2.3 Finite Element Model

The Finite Element Model (FEM) consists of results obtained when the WETM is solved in SC03. Gas turbine model is composed of two interrelated models. On the one hand, the thermal model calculates the temperature distribution of the WETM. On the other hand, the mechanical model also called the structural model computes the stresses and strains on the WETM or on a specific component of the engine. The stresses and strains are calculated considering the variation of the temperature distribution and the external load applied (Tinga et al., 2000). FEM is produced by SC03, the in-house software developed by Rolls-Royce. It contains various data and has a big size, when looking at storage, it is on gigabytes.

Results obtained for this analysis will be used to predict the life of gas turbine components. In this study, the numerical simulation is based on two-dimensional modeling of the gas turbine. As the number of developments of gas turbines has increased, FEA simulations are required. Thus, it is essential to automate tasks that request iterations, especially repetitive and tedious tasks in pre-processing (Sung, 2019). Therefore, an automated tool including interaction between different types of outputs of disciplines necessary to run the analysis is set up to accelerate the process and gain time. Consequently, this contributes to an important improvement in management tasks in the company and save time lost with exchanges of information. In fact, the D&A platform containing the automated tool enables more freedom for engineers because all the required tools to generate the FEA are present in the framework, which let them more independence.

2.2.4 Lifing

The FEM generated by SC03 will provide for mechanical integrity engineers, stresses and other data values depending of use case. They will assess components life with this data. Lifing study enables to predict life of components especially studies are done on critical parts. The department of lifing generally calculates total time to failure or number of cycles to failure for some components subjected to a specific load sequence. Many of life prediction models have been developed over the last twenty years, each model is appropriate for an application. (Tinga et al., 2000). Safety is the primary objective of processes involved in lifing of critical parts. This relies on procedures and technical methods which control: material characterization, design, manufacture, verification, validation and service life management. The reliability procedure to estimate life is fundamental and depends mainly on the definition of engine conditions during operation, the calculation methods for component's temperatures, stresses or strains and material data.

In addition, multiple mechanisms can cause the failure of a component such as crack growth, fatigue, creep or oxidation. Performance analyses for lifing use different quantities as stress, load, displacement, temperature provided by the FEM file to assess components. Thus, accuracy of method used in FEA permits to assess components of the gas turbine. In fact, it assures the safety of the components and save inspection costs at the same time by estimating and maximizing the life of them.

2.3 Need for automation

Automation is defined before as autonomation or "automation with a human touch" to characterize machine intelligence (Kagermann, et al., 2013). Today, it is part of Industry 4.0, the smart factory, with the autonomously interact with one another, with people, along the value of chain (Kagermann, et al., 2013). Today, companies are forced to produce small batch of data to test product by using complex organization which is not that efficient. Indeed, data represents a valuable business asset. The data flow can be addressed by integration of analysis in order to optimize the production processes. Nowadays, mass production with flexibility of custom production is a key factor in industry (Coito et al., 2019) and apply widely in gas turbine market.

As presented previously, FEA simulation is a task that takes a lot of time during the design process. And getting all the pre-processing data and post-possessing data are long in some point and also depend of interaction and collaboration of other departments. It is often necessary to perform a large number of similar simulations that differs only by boundary conditions or the model involved (Saratov et al., 2019). Automate FEA simulation methods enhance the product design approach and allow the reduction of design cycle time by minimizing errors and simplifying the workflow process in industry.

Deploying a FEA automated tool becomes mandatory because of the number of data and simulations required which represent a significant amount of data. Nevertheless, the aim is to improve productivity by automating tools in a framework to help the engineers and not replace them. Indeed, creativity and interpretation of engineers are primordial factors for the product development.

2.3.1 Integration requirements

Developing an automated tool by connecting with other tools in an engineering framework requires to overcome some challenges. First, the process integration, workflows and processes are usually designed for specific use cases and applications. The purpose is to automate workflows that are traceable, in consequence, that avoid duplications and go along the management in the product lifecycle. Secondly, the tool integration, as we have seen, different tools are used to generate different data. The data should be converted and exchanged in a way that can be reusable and traceable across the different activities in the D&A platform. Finally, the discipline integration, as different disciplines from different tools generate different artifacts, links between these disciplines and artifacts should be created to interact them by automation (Binder et al., 2019). In that way, through automation and integration methods, an automated feedback loop is established between engineering tools.

2.3.2 Approach of automation

To run a FEA on 2D model of gas turbine. First, we need to pre-process the model that is to say prepare the model to run the analysis. In that step, configuration of model is done, all the performance data and air and oil systems data are generated to solve the model. Then, the processing is done via finite element analysis in each node of the model structure. After that, the post-processing can be performed following the choice that the user does.

Pre-processing tools are already developed in the D&A platform by other developers in the company. One activity will run the performance model, the other one will generate air and oil systems data. After that, the FEA tool activity is launched so the processing, this task will be automated by collecting right data from the other tools. A post-processing user interface will also be able to run the analysis and extract some relevant values for engineers.

The framework will provide a single activity containing several tools integrated to run FEA and generate data. In that way, workflow automation contributes a better interaction between disciplines and a better technical support for engineers. This automated workflow will be fast than the regular workflow process using UNIX application. Besides, multiple iterations can be made in a limited time. Hence, so many non-value-added tasks are eliminated such as data collection, exchanging data from one department to another as well as the dependence with other disciplines. Thus, time is saved, and engineers can focus more in interpretation of results and in our case studying the results for lifing of AGT components. In fact, the approach of the Multidisciplinary Design Optimization (MDO) apply in this framework can handle this long run of analysis and complex iterative processes by providing adapted tools.

MDO applied to this platform leverages the automation of computations by reducing human intervention and design time. At the same time, it enables to run more than thousands of FEA and explore a huge amount of data results, in other words FEMs (Dupont et al., 2019). Gas turbine design cycle time is the key business driver. Customer wants new product in a shorter amount of time by spending less money with less labor hours, given thus less chance to change the requirements (Jenkins, 2005).

A multidisciplinary activity is developed to gather all the tools to run SC03 and solve the 2D model. But a multidisciplinary integration should be an interdisciplinary integration that is to say that each of the disciplines requires local integrations on an activity or sub-activity which will be linked to run the analysis (Ouellet et al., 2013). This activity must provide access to real-time information to all stakeholders and can connect with other disciplines. The FEA automated proposed is efficient for analysis of heavy simulation models and provides more feasible designs on a limited budget than the standard approach (Saratov, 2019).

The framework used in the company is composed of two parts, the front-end user interface and the workflow execution logic, both parts are connected.
The front-end component is assigned for definitions of workflows that is to say display of the UI which supports tasks execution. It will execute the different tasks that user asks via the UI. Execution of the workflow consists of accessing to the database namely the revisions where results are saved. Therefore, the workflow execution is permitted by the framework dashboard.

An overview of the AGT framework architecture is shown in Figure 2.5 below. It presents the main classes of the aeroderivative gas turbine framework. It is composed of the project class where engine workflows are defined which are related to components, in our study that will be the whole engine thermal model module not particularly specific to one component. As explained previously, a workflow is connected to a discipline where activity is created. An activity basically represents a workflow defined in the D&A platform and it is configured by definition files.

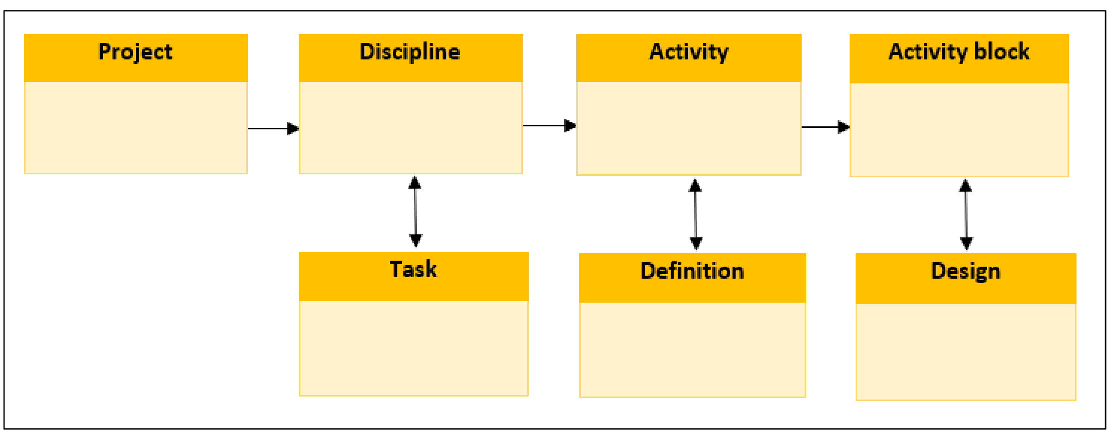

Figure 2.5 Simplified architecture of the AGT framework

2.3.3 FEA workflow

A finite element analysis approach is used to be able to run more than thousands of simulations with parametrically varying component geometry. This tool is developed to generate numerical simulation results of a 2D whole engine model of gas turbine. And it will contribute to a significant design improvement to enhance mechanism robustness and reduce manufacturing cost. The model used in the workflow is a steady state 2D Whole Engine Thermal Model (WETM).

The engine is simulated over a square cycle also called the "flight cycle" including conditions at idle described by an acceleration, a stabilization then another acceleration and a stabilization followed by a deceleration and rest. This cycle is used to assess component lifing and performance for typical operating conditions.

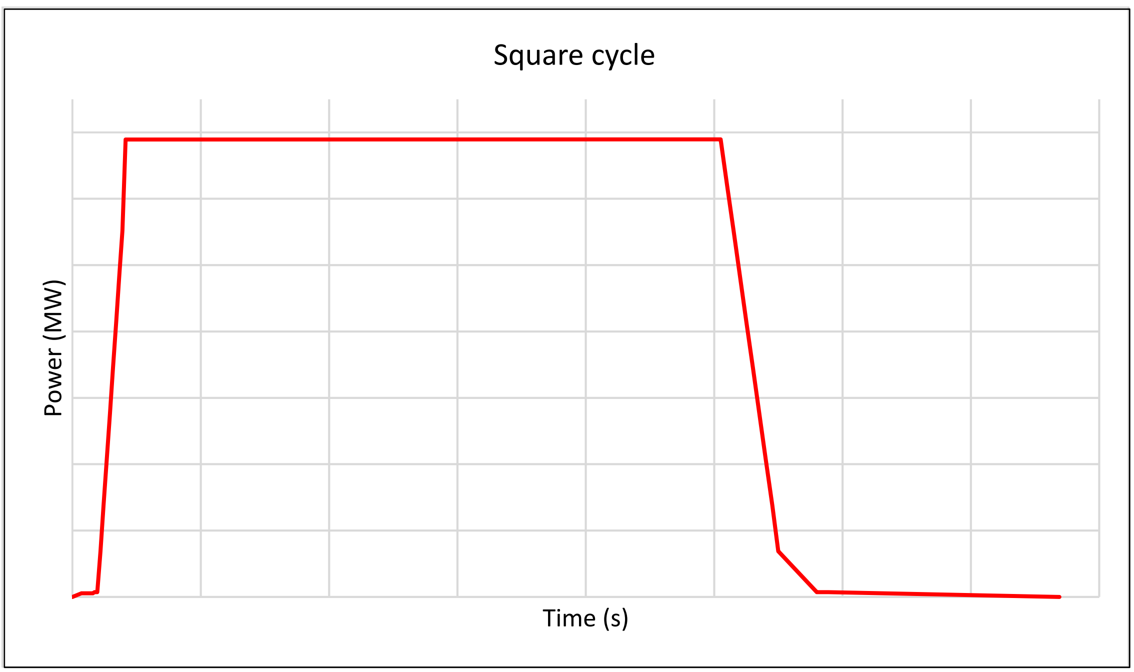

Figure 2.6 Square cycle

The cycle definition referred as ramp definition for square cycle is detailed in Table 2.1 below. The curve for the square cycle is shown in Figure 2.6 above. In Table 2.1 and Figure 2.6, numbers and time for acceleration or stabilization are not given due to confidentiality of the company but it gives an idea of how the cycle is defined. Besides it is the default square cycle, other cycles have been created to support the lifing. The ramp definition for square cycle is based on the starting, loading, unloading, and shutdown requirements of the engine.

Table 2.1 Cycle definition

Step	Action
1	Start up
2	Acceleration to sub-synchronous idle
3	Stabilization at sub- synchronous idle (dwell)
4	Acceleration rate of the shaft from sub-synchronous idle to synchronous idle
5	Acceleration ramp from synchronous idle to baseload
6	Duration of stabilization time at baseload
7	Deceleration ramp from baseload to synchronous idle
8	Stabilization at synchronous idle
9	Deceleration from synchronous idle to a complete engine shutdown

This tool will enable to run a FEA and generate FEM for different operating conditions and configurations of engines for more than one temperature ambient. In this sense, we can evaluate higher efficiencies for gas turbines operations.

The potential of the FEA tool developed here falls within the concept of Industry 4.0 that includes the digital twins for simulation models. Digital twin of an entity permits to provide business improvement (Lee et al., 2019). The analysis tool developed will permit to predict life of engine components with data produced but for many use cases not limited.

Help related to automation of the functional tools has been obtained by speaking to engineers at Siemens. Furthermore, past project script for automation of FEA tool existed to debut.

The integrated analysis tool presented is a sequence of software tools (Tinga et al., 2000). Engine performance is obtained by a tool developed by engineers where the user configures his model. This represents one of the most important steps in the workflow because the model should be set correctly in order to avoid the propagation of errors if the user chooses to run the model for a lot of ambient temperatures. This data generated will permit to process the engine so the FEA. The thermal FEM combines with heat transfer provides temperature distribution in engine components. And the structural FEA calculates the stress and displacement distributions of AGT components that will enable engineers to predict the life and determine the damage accumulation on the engine (Tinga et al., 2000).

First, engine performance tool calculates gas temperatures, pressures, shaft speeds and power outputs at each engine station from a database containing all the parameters values. The output file also includes the "flight cycle" conditions called the square cycle presented in Figure 2.6.

The purpose of this automated tool is to collect all the inputs data to produce the FEM file in order to do lifing and help mechanical integrity engineers to gain more time to analyze the results and assess the life of components by presenting a framework accessible by everyone. To get the FEM file, we need to create a Basic Design Data (BDD), this file is the input that will be imported into SC03 to run the FEA. The BDD defines the performance data and the engine cycle, a definition of a BDD is given with more details in the following chapter. SC03 automated workflow is described in Figure 2.7 for a WETM.

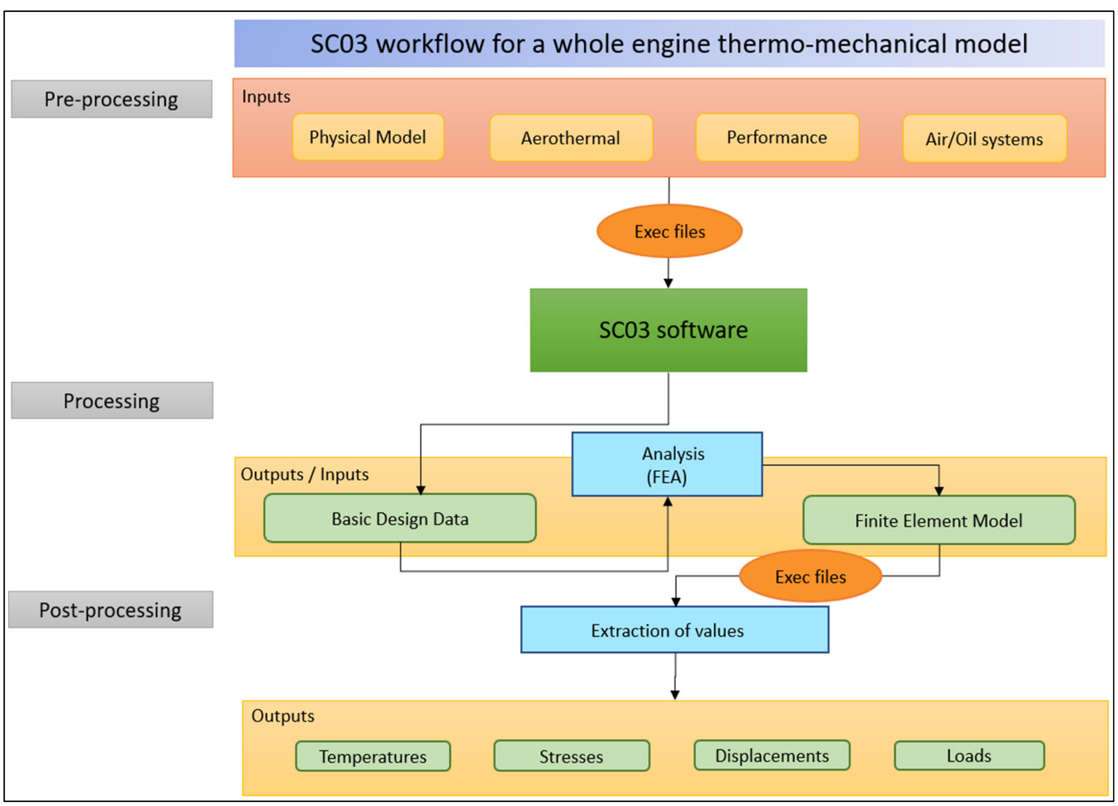

Figure 2.7 Workflow of SC03 for a WETM

- Aerothermal data are required for the air and oil model to achieve blade cooling. Incoming cooling air at a specific pressure and temperature are required. Aerothermal discipline predicts the cooling requirements for SAS based on pressures and temperatures predicted by the performance model. Also, it is used as boundary conditions for SAS as this latter draws the air from the gas path at specific locations and aerothermal predicts temperatures and pressures on those locations.
- Performance is responsible for the main gas path characteristics. Therefore, performance data is composed of pressures, temperatures, mass flows across the gas turbine stations and shaft speeds. This is where the execution of "flight cycle" is done which describes the steps from start to shut down of the engine. The user has the choice to use a default "flight cycle" or to edit it manually. The model can be run for a wide range of ambient temperatures.
- Air systems model is meant to deal with secondary flows (cooling flows, sealing flows, customer bleed, managing bearing loads). An air system flow network model is created which defines the internal flow paths within the engine. For example, air system provides the air at the right flow, pressure and temperature at the blade entry. A gas turbine engine experiences high pressures and high temperatures. Especially on the blades and vanes located directly following the combustion chamber, so cooling these blades is necessary. This is done by diverting a fraction of the main flow in compressor at low pressure and carrying it to the blades which need to be cooled. SAS provides boundary conditions for thermal analysis thanks to performance data produced.
- Oil systems model deals with lubrication and cooling of bearing. The outputs of oil systems model are similar of air systems model.

The combination of these data will create a BDD file that contains the performance model and the environmental parameters needed to solve the model. One BDD corresponds for one ambient temperature of an engine configuration. And this tool can provide the FEM files for more than one ambient temperature which was much slower to do before. Therefore, there is absolutely a need for automation because with an automated tool, we can execute a lot of FEA by using just one platform. The local history of every run can be tracked and accessible by everyone in real time.

A UI is presented to retrieve relevant quantities for the user, it can extract the temperatures, stresses, and displacements on the current framework. With the SC03 script executive file detailed in paragraph 3.1.3, the recovery of these values has been possible. This file contains command lines that SC03 executes and has permitted results extraction and model modifications. Indeed, a UI supports interaction between the user and the framework.

By programming in python, modularity has been a challenge when deploying the automated tool, but it is necessary in order to collaborate with other developers of tools. It is a delicate part because the main objective of the framework is to develop a generalizable workflow that can be usable for different use cases and engines.

2.4 Conclusion

This chapter has given an overview of the gas turbine presenting his concept. The gas turbine model used for this study is a 2D axisymmetric model. Numerical simulations are performed to test different operating conditions of engines and then to assess life of components using finite element analysis. The powerful computational finite element method is able to analyze the model by approximating solutions in order to minimize practical tests of the engine prototype. A workflow presentation, inputs and parameters necessary to run an analysis have been given. Indeed, Basic Design Data (BDD) is the major input to run a FEA in SC03 numerical simulation software. Therefore, most of the automated work will be around the generation of the BDD because its creation is mandatory to solve the WETM and to get the FEM results.

CHAPTER 3

AUTOMATION OF FEA TOOL: METHODOLOGY

3.1 Automation of FEA workflow

Automation can be used for repeatable process, as FEA workflow, in that way several benefits are presented. It would be the time saving of manual tasks used with the traditional method but also improvement of robust tasks that are performed. The ability to define a model, run and post-process the workflow in batch, in other words, using text file inputs is fundamental for automation. The process automation approach enables to deliver FEA workflow to a wider range of users.

3.1.1 FEA software

The FEA software used for this study is SC03, it is a tool originally from Rolls-Royce. The finite element analysis in design consists of an analysis on a Physical Model (PM) of the design. The PM is a numerical representation that would be solved during the analysis.
SC03 is a user-friendly software, its high capability interface includes a monitor or console window that helps experts of the application. Besides, SC03 is an automatic analysis system that allows fully integrated stress, displacement, thermal and vibration analysis in order to be extracted at any stage in the design cycle. Indeed, the FEA plays a major role in assessing the ability of the design to perform its duty.

The whole engine represents the physical model and can be solved with different types of analysis depending of the user need. Firstly, we have the thermal analysis, secondly, we have the structural analysis and finally the thermo-mechanical analysis. Furthermore, the thermal analysis enables to get the distribution of temperature in gas turbine model, in that way engineers get thermal predictions in order to assess components. The structural analysis calculates stress predictions on all components that will be used for lifing. The thermo-mechanical analysis is a combination of the thermal and mechanical analysis and the run-time of this one is long enough compared to the two others. The WETM used is a steady-state model that is to say a functional representation of the gas turbine engine. It can be used during all stages of the lifecycle management process. In addition, definition of model geometry and meshing are performed by design team before solving the model.

SC03 was originally created to meet aero-engine manufacturer need, but the success of the application in the market was widely appealed that Roll-Royce decided to offer the software to other users under a commercial license as Siemens.

SC03 have an interactive Graphical User Interface (GUI) that integrates multiple plugins, they are extensions of the functionality independently of the main SC03 software. It is a collection of subroutines that are loaded in SC03 and add some specific commands to SC03 menu. The one that we use for this study is the thermal systems utilities plugin.

3.1.2 Automation methods

During the process of automation, few steps enable to identify tasks that should be automated. First of all, automated the full workflow of SC03 is impossible. We are looking for tasks which can be automated to reduce the user work and give him more time on relevant tasks as analysis, interpretation and assessment. As an aeroderivative gas turbine is a complex structure containing numerous parameters, the aim is to develop an automated tool that is the most generalizable to be usable in many cases in an efficient way.

SC03 contains an automatic analysis finite element program. It means the automation of finite element analysis process is feasible as much as it is possible. The purpose of this automation is to remove all finite element details from the user and allow him to concentrate on the engineering aspects of the problem. In that case, user will be able to interact with the PM and not the FEM. All the input data detail is applied with expressions on the geometry of the AGT. Besides, even the meshing used is an automatic refinement, so the user does not have the need to involve in the finite element process.

3.1.2.1 Strategies: automatic analysis

Main strategies are to get a simple, robust and accurate finite element analysis. In addition, permit the user to not involve on the finite element calculations and present an easy process to use by intuitive interface. To do so, workflow should be easy to incorporate into the MDO automated process.

The idea with automatic analysis is to complete an inner loop. It enables to have a system that has inputs for the PM and produces the FEM. Except the mesh generation automation, tasks which need to be integrated are the physical model, the accuracy requirement and the refinement loop. First, automatic analysis requires to be usable for different types of engine models. This means that the problem must be defined independently for any model that is to say for any mesh of the PM. Note that the PM used in SC03 is associated with boundary which is described with solid model that comes directly from the design department. Besides, technical data with variation in time or space is found on the general expression definition. This varies because of the time points required by the selected discretization during the evaluation. Second, the accuracy requirement, indeed, it is defined by the user choice, namely, thermal analysis, structural analysis or thermo-mechanical analysis. Indeed, accuracy assessment is due to the association of mesh size and discretization. That permits to calculate a required element size with each element. Finally, these elements sizes are passed to the refinement loop which brings together the automatic analysis components.

The analysis in design can be summed up as an iterative loop as shown in Table 3.1. The tool developed will consist on the focus of step 4, that is to say, “Solve the numerical problem”.

Table 3.1 Automatic analysis loop

Step	Action
1	Prepare a candidate design
2	Prepare a physics model of the design and its duty
3	Prepare a numerical model of the physics model
4	Solve the numerical problem
5	Assess the suitability of the numerical model
6	Repeat if the numerical model is unsuitable
7	Assess the suitability of the physics model
8	Repeat if the physics model is unsuitable
9	Assess the suitability of the design
10	Repeat if the design is unsuitable

As we can see, to have a suitable physical model able to solve the numerical problem, some tasks need to be assessed in order to implement the automated tool in the framework. Many tests have been run to execute the analysis step and to solve it correctly without errors.

3.1.2.2 Identification of tasks to automate

The first step is to discover how SC03 works, so many tutorials, documentation and the help of engineers permitted the understanding of SC03 analysis. As this main task required the interaction of many disciplines to be executed. An analysis has been done to know which functionality can be automated and what inputs we need to run an analysis. The nature of tasks can be manual as choosing the physical model or computerized such as the calculation of performance data or solving the model. Then, understand the workflow to create the Basic Design Data (BDD), the input of the FEA. That enables to clarify which type of inputs are required and also which type of outputs are created with the different tools used. Last but not least, identify the connection between disciplines to place them on the automated workflow.

First, SC03 will be run in batch, in other words, without invoking the GUI, this is achieved by python script using SC03 .bat file in order to execute various actions. This batch is being used to control the execution order of different models and parse the inputs and outputs provided by them. The run of SC03 in batch is described in a simplified way in Figure 3.1. In the automated tool developed, SC03 is executed from a .BAT file and it is launched with appropriate command-line arguments. Then, the .EXEC file will be read, it contains all the instructions that SC03 will execute. The .EXEC file starts to read all the inputs files and rebuild the physical model in order to create the BDD and then prepare the PM to run the FEA. After the BDD created and loaded in the PM, it is ready to run the solver. The solver generates the FEA results, a diagnostic file is created at the same time containing the history of analysis.

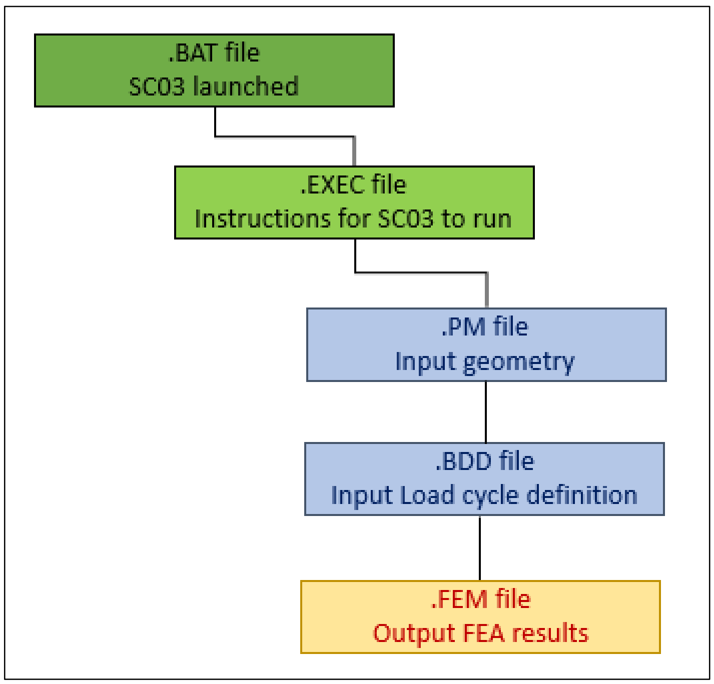

Figure 3.1 Running SC03 in batch mode

In the finite element analysis in design, a physical model is prepared and meshed. Note that material properties and meshing are already applied in the 2D model provided by the WETM department. The most important task to automate is the BDD creation in order to solve the model which is defined in paragraph 3.1.2.3.

An analysis has been done to know which quantities will be relevant to extract and study by engineers. Indeed, some meetings with the SAS and MI teams have enabled to brainstorm about the post-processing. The user need is an essential factor to automate the process because the main idea is to facilitate their work to be more effective on analysis and results interpretation in order to increase productivity and model robustness by reducing cycle time. The primary question is about tasks that can be automated and tasks that need human interaction. Then, the time cost using the traditional method and the automated method, say for the BDD creation for instance. Also, we need to pay attention if some differences appear and understand why. That would be the case for the BDD creation, engineers do not use the same plugin and same application to create the BDD. Some of the functionalities are present in UNIX and not in Windows and vice versa.

As presented on SC03 workflow in Figure 2.7, to create a BDD, three disciplines will interact in one frame in order to get the input of SC03 to solve the 2D AGT model. For that, the other tools should be integrated to communicate in a way that is consistent with their system roles. Besides, SC03 workflow including the performance tool and air and oil systems tool should perform the same function in different activities and for different use cases in order to run the analysis. One of the technical requirements applied is the interoperability which means the capability of the activity to use the same technologies, protocols and data representations (Barkmeyer et al., 2008). In several integration framework, resources are coded in a fixed way, the idea is to overcome this lack and create a more generalizable framework usable for many use cases for different types of engines. Thus, the python scripts are coded in a modular way to be usable by other developers and for other activities. Thanks to the object-oriented data-miming, in other words, the reusability of models (Ramamurthy et al., 2014), it is essential to access across different disciplines. Note that the different activities so the different workflows or sub-workflows of disciplines interact via metadata using JSON format. They seem to be very effective for automation and they participate in the elimination of non-value-added tasks and decrease the errors.

3.1.2.3 Basic Design Data

The Basic Design Data also called BDD is the file that defines the cycle definition of engine. It represents the key engine performance and air/oil systems data, in other words, pressures, temperatures, mass flows, power and shaft speeds. Moreover, the BDD describes how these parameters vary during a cycle at different operating conditions.

A BDD is composed of four sections. First, we have the secondary air system and oil system simulation setups, then a list of environmental parameters which is a combination of performance, air and oil systems parameters. It is followed by outputs of environmental parameters at every condition of the engine cycle, and finally the ramp details are mentioned. This BDD is the input of SC03, after its creation in the automation workflow, the next step will be the import of this file in SC03 in order to solve the model.

This BDD is created via a plugin called thermal analysis input processor by using UNIX application nowadays in the industry. The study of this project is to create a BDD via Windows through automation by interacting different disciplines to get the same FEM file that can be generated with SC03 UNIX tool with the traditional method. This method consists of generating all these inputs data mentioned previously manually, therefore producing a BDD takes much time. It takes 25 minutes to create one BDD manually. In addition, an important time is spent for exchanging software and doing each task manually. Note that BDDs are created in UNIX via a remote desktop accessible by one person at time which is delicate. Indeed, by automating the manual tasks in the framework deployed in Windows, a decrease of the amount of time is expected and also an application accessible across all the departments.

3.1.3 Executive script

The executive file is the intermediary between python environment and SC03 to run an analysis. The “exec” files are a sequencing script which is a list of sequential commands for SC03 that performs the same set of actions as the user in the GUI for setting up the model, running the analysis and post-processing the results. This file contains a set of SC03

commands, that will be the execution instructions. All the work completed so far in the D&A platform integrates the executive files in python script to communicate with SC03. It is the only way to get data from the FEA software. Engineers and documentation of SC03 helped to create these files to create the BDD(s), to run the FEA(s), but also to extract all the quantities needed for the user like temperatures, displacements, stresses, loads.
Thanks to these executive files, we can extract results from FEA, we can also do modifications of the model.

A user interface has been developed to permit the user to choose the type of analysis of the WETM and to be able to check boxes of quantities that he needs to extract after FEMs are generated. For that, another activity for post-processing has been created with a UI and has been implemented in the framework.

3.2 Development of the tool in D&A platform

3.2.1 Automation solutions

In the interest to balance conflicts between disciplines and design of an aeroderivative gas turbine engine with high comprehensive performance, we apply the MDO technology to the conceptual design of AGT. A total of three disciplines including aerothermal, performance, and air and oil systems are considered. The last two ones are integrated tools in the framework.

The concept is to implement a modular, customizable and adaptable activity in the D&A platform able to support powerful data and process to increase reusability of the workflow. Automation appears when repetitive tasks happened as for instance the generation of data for one model configuration. Using automation as solution enables to gain a huge amount of time by removing also non-value-added time. Blackbox helps to set up a solution just by including the inputs and the outputs. As the model must be performed for more than one temperature ambient, an automating loop is created to run multiple analyses on the 2D model in SC03 in one activity. That will be the case during the processing after having launched the SC03 batch file. During the processing, the run is already configured, SC03 is just executing instructions of executive files.

3.2.2 Inputs data

Pre-processing

In this first phase, the user configures his engine according to the use case. The user imports the PM file and the aerothermal data loaded in CSV files in order to get an accurate distribution of temperature and pressure in the SAS (boundary conditions). Then, the model is configured in the performance tool where user chooses at which ambient temperatures he wants to run the analysis, and can modify basic parameters such as acceleration rate, frequency and can choose the type of engine and his specification, WLE or DLE. A full range of ambient temperatures can be solved and incrementation can be specified, usually from -50C to +55C. In addition, the square cycle is created in that step and it will be a default one for the analyses done in this study in SC03. This step is fundamental to get the right model configuration and outputs. Here, we have a semi-automated tool that needs the user to fill the UI to execute the run. That is a time-consuming task because it needs the engineer's decision. It should be noted that with the concept of Industry 4.0, we are trying to reduce design cycle time but spend time on relevant tasks as this previously one.

Afterward, the user runs calculation of secondary air system and oil system tool in order to produce the boundary conditions of the gas path by computing pressures, temperatures and mass flows. To execute this tool, metadata has been used in order to interact with the performance tool and get his output files. The SAS and oil system tool read the metadata that it received as inputs and get the right configuration of the model. This data is retrieved via a JSON file.

We can see an example of a metadata structure here:

{Model: <string>,
 Engine Family: <string>,
 Engine Configuration: <object>,
 Ambient Temperature: <array>,
….}

In that way, the number of some non-value-added tasks is eliminated such as conversion of outputs data It also permits to get the different outputs of some disciplines in inputs for other disciplines.

2D analysis at static namely steady state and engine running conditions are performed with SC03 database file also called the physical model. For the current study, mainly thermal analysis has been run. The PM files containing the meshing is almost ready to run but before solving the model, the boundary conditions must be defined such as pressure, temperature, mass flow, shaft speed. These parameters will be applied on the environmental parameters, and expressions in SC03 used to run the simulation. All these parameters are summed up in the BDD file which is produced with outputs of different disciplines in the design phase.

3.2.3 Activity in framework

The activity in the D&A platform represents a predefined template that can execute a set of instructions in batch or interactive mode. In the framework, these activities and especially "activity blocks" can correspond to a software like NX, Ansys or a custom script as the python script that we use to integrate the tool in the framework.

The activity is composed of a set of inputs and outputs as it illustrates in Figure 1.3 in chapter 1. These inputs and outputs are called datasets. The activity block or "tool" block aims to take a set of inputs and perform one or numerous actions, to generate afterward a set of outputs.
In this study, the inputs will be the WETM, aerothermal data, the performance data and finally secondary air system and oil system data. And the outputs are the BDD(s) and the FEM(s) files as shown in Figure 3.2 below.

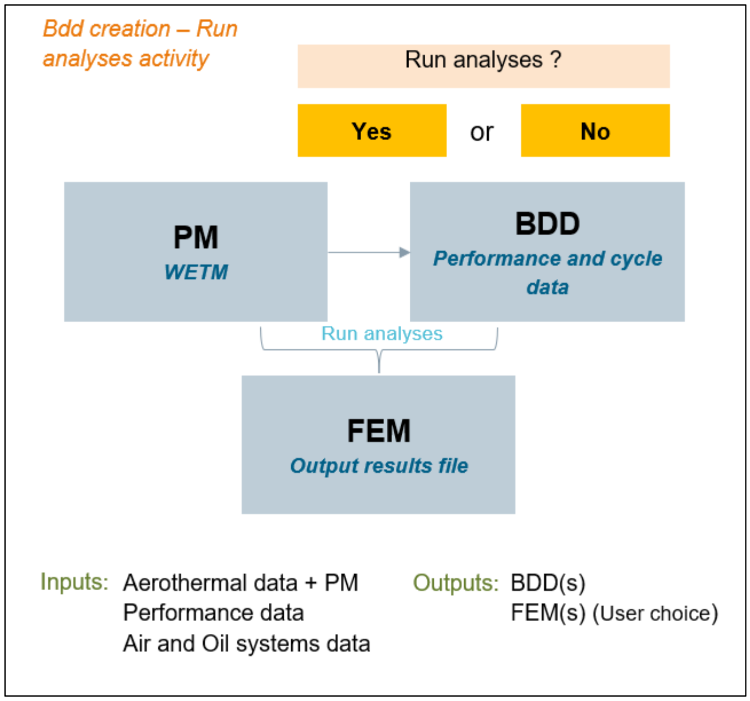

Figure 3.2 Outline of the activity developed

Processing

After the pre-processing, we have all the inputs necessary to create the BDD and run the analysis, one click on the rocket launcher of the activity starts the execution of batch file. During the workflow execution, SC03 monitor console opens and the processing is carried out through the "exec" files. So, after the batch session of SC03 starts, the "exec" file containing actions are performed, inputs are loaded and start to create the BDD, the FEA input. A nested loop structure is used to run through the data for each ambient temperature at static conditions. During the processing, we can see the errors due to geometry and missing parameters in the monitor, but it is also written in the diagnostic file. With this mean, debugging has been done in order to have in the end, an accurate and reliable finite element analysis.

For end use the predictive models are implemented with python, which allows to have applications in more versatile environments, such as cloud services. The model parameters are saved in configuration file. The python code reads the parameters from the configuration file and uses them to make predictions. Thus, the framework supports the integration of SC03 FEA workflow. Tasks that are repetitive and demanding multiple clicks are automated by using python script and executive files to facilitate engineer's works. In the current workflow, the user has to specify inputs and/or outputs required to run the FEA.

3.2.4 FEA results for lifing

Post-processing

After automating the processing step which includes the creation of BDD that represents the fundamental step to run a FEA to solve the model, as expected it is a tremendous time saver. So, after implementing this main task in the D&A platform, it has been interesting to carry out the post-processing of results after few meetings and request from engineers. Therefore, another activity has been created in order to extract results from the finite element model file that are relevant for engineers.

The idea of the activity is to include the step of FEA but add the extraction task of quantities such as displacements, temperatures, stresses in order to facilitate engineering tasks. Basically, post-processing tasks are done manually in the GUI of SC03 and can be long depending of the number of extractions to do. Eliminating these manual tasks by automating them can improve the efficiency of work and enable the user to focus more on analysis of results especially during the assessment part of engine components. Therefore, the workflow used run the model in batch by using automation scripts and read the results following the quantity chosen by the user. To facilitate the quantity selection, a UI has been set up, in that way, each quantity is linked to an executive file and will be launched and read after the analysis.

One of the objectives of the workflow is to quickly calculate the quantities for the user in order to assess critical parts life such as blades and discs. This workflow is used for robust design studies and can run more than thousands of models by few clicking in the framework activity. The post-processing requires manually many clicks in the GUI of SC03, in that case, automation is a solution that helps engineers to eliminate tasks and also reduce errors that can be made manually. In terms of time, a large scale of time is saved and can be spent for assessment of data extracted and improvement of the product efficiency in order to reduce inspection costs.

Thereby, SC03 post-processing facilities can be used with the results and both batch and interactive analyses create a FEM file in a binary sequential format containing all the information necessary for post-processing.

In this study, an outset of post-processing has been developed in a UI, that is to say, for now quantities like temperatures, stresses, displacements are implemented and can be used by engineers to assess the AGT model. But other quantities such as joint reactions, loads are implemented but not yet used for use cases. Furthermore, the large temperature gradients can have an adverse effect on component life. These temperature gradients should be considered when providing temperatures for stress or lifing analysis. One of the interesting facts about post-processing is the step of temperature interpolation that has been automated because this one required a lot of clicks. Engineers perform this step manually for each model run but SC03 offers a way to automate it and accelerate the process to get results to do lifing. This step consists of reading temperatures on a different mesh and interpolating onto current mesh. A case study has been done by including this interpolation step to run a lot of engine configurations for the High-Pressure Turbine disc to get the hoop stress.

3.3 Conclusion

This chapter has presented the workflow of FEA tool automation into the framework. It illustrates the tasks that are important to set up and automate in the D&A platform in order to run the finite element analysis. As we can see, multiple factors are targeted to provide a massive production of BDD and so FEM. Many tasks have been set up in the activity developed namely repeatability, elimination of errors, reduction of manipulation time of some long tasks for pre-processing and post-processing. Automation of SC03 AGT WETM by creating the BDDs using square cycle and related performance data outputs as well as air and oil systems outputs are fundamental to generate the FEM files. The main idea is to provide many BDDs and FEMs as possible to assess efficiently the engine components allowing to reduce failures of critical parts of engine and increase the performance and productivity of AGT. Integration of aerothermal, performance and air and oil systems models into a loop can be used to do dynamic lifing, indeed for now this tool is usable for static conditions, because both cases require repetitive model runs. The implementation of tasks and automation have been made possible mainly because of a user-friendly numerical simulation software and executives files that control the 2D model and help to automate the workflow of SC03 finite element analysis.

CHAPTER 4

IMPLEMENTATION IN D&A PLATFORM AND RESULTS

4.1 Whole engine model configuration

First of all, the user needs to know what type of analysis he should run because time is so valuable in the design phase, more time is saved better it is. The 2D whole engine model can be solved with different types of analysis as we mentioned previously. It depends of the user need. The thermal analysis calculates the temperature distribution in the gas turbine model. This analysis is used to get thermal predictions on all components. The structural analysis is used to have stress predictions on all components. Indeed, this data are important for lifing. Of course, other quantities like displacements, loads can be extracted. The thermo-mechanical analysis will be a combination of thermal and structural and solve the model containing thermal and structural boundary conditions. This analysis takes twice more times than the two other ones. So, it is important to choose the right type of analysis during the model configuration manually namely in the UI developed in the platform.

The usual way to run an analysis is to open SC03 software, GUI appears, user imports the PM then the BDD created before with UNIX SC03 tool and click on the "RUN" button. In that case checks are done then the analysis starts. The latter is performed under static conditions and can be run for these three different modes explained above.

During testing, when implementing the finite element analysis tool, debugging has been made many times, in consequence, many modifications have been done on the 2D WETM. It has mainly been some definitions of expressions on the boundary conditions. Some of the parameters have been added or removed in order to get right results during analysis. The purpose is to have a tool usable for all WETMs provided by the design team and to develop the most generalizable tool which is restrictive sometimes. Indeed, modifications on the WETM have been done after consideration with engineers and these changes have been reported to them to update the others 2D WETMs.

4.2 Execution of commands to SC03

The communication between SC03 and python environment is made via the executive files. As presented in Figure 4.1, scripts are read and executed thanks to the monitor that the user has access during the processing and even the post-processing steps. These executive files have been created and specific actions are assigned for each of the file. For instance, there will be a stress "exec" file, a displacement "exec" file and some of them are called or some commands lines are written directly on the python program like launch SC03, run the batch file and run the analysis.

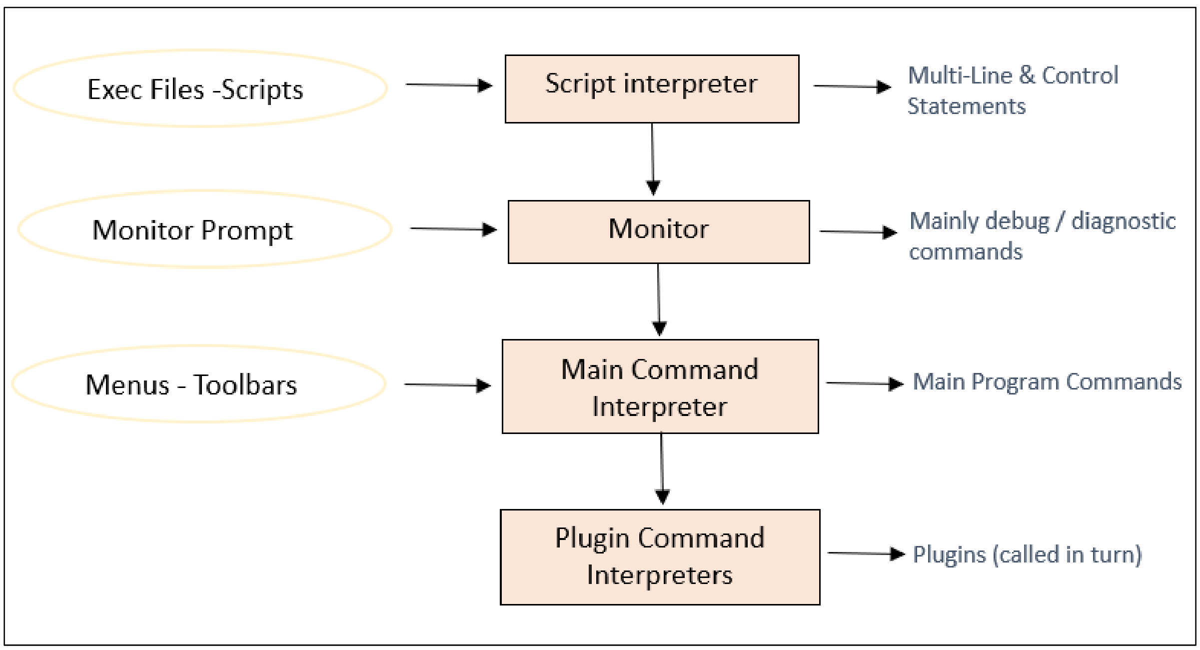

Figure 4.1 Control structure of SC03

As we can see in Figure 4.1 above, executive files are called, and the command lines are interpreted and can also call some plugins. In our case, thermal systems utilities plugin is called because it needs to read performances and air and oil systems outputs among other thermal functions.

Multiple activities have been developed representing different workflows by having in common the FEA solver. Modularity has been considered much sooner when being in the early stage of implementation of the tool through automation. In that way each workflow created can refer to the program coded as blackbox and can also be used by all the developers. As mentioned, many activities have been implemented namely create the BDD(s), read the BDD(s), create the FEM(s), extract quantities for post-processing.

A relevant time saver is the BDD creation. Indeed, this task demands a lot of time when engineers have to do it manually in UNIX version. The tool implemented in the platform can produce a massive quantity of BDDs and FEMs files. For that a multidisciplinary activity has been created to connect the different disciplines and generate the data needed. The next paragraph is focused on that activity, besides this latter has been performed by engineers in the company for real use cases.

4.3 Multidisciplinary activity

At the beginning when starting to integrate activity in the framework, each discipline was separated. So, to generate a BDD and run an analysis, we needed to go in each discipline, then import the inputs, run the activity and generate the data then create a revision to be stored in the platform. So, in our case, we need to go in at least three activities before launching the FEA activity. For at least 2 months, the generation of BDD(s) and FEM(s) have been done in that way.

After scripting in python, we have been able to connect each activity with the correct inputs and outputs and combine all the inputs in the same multidisciplinary activity. Now, we can create the BDD(s) and the FEM(s) in mass production by clicking on the rocket launcher on the right upper corner as we can see in Figure 4.2. Indeed, the display of the multidisciplinary activity in the framework is represented with the following form as in Figure 4.2 below.

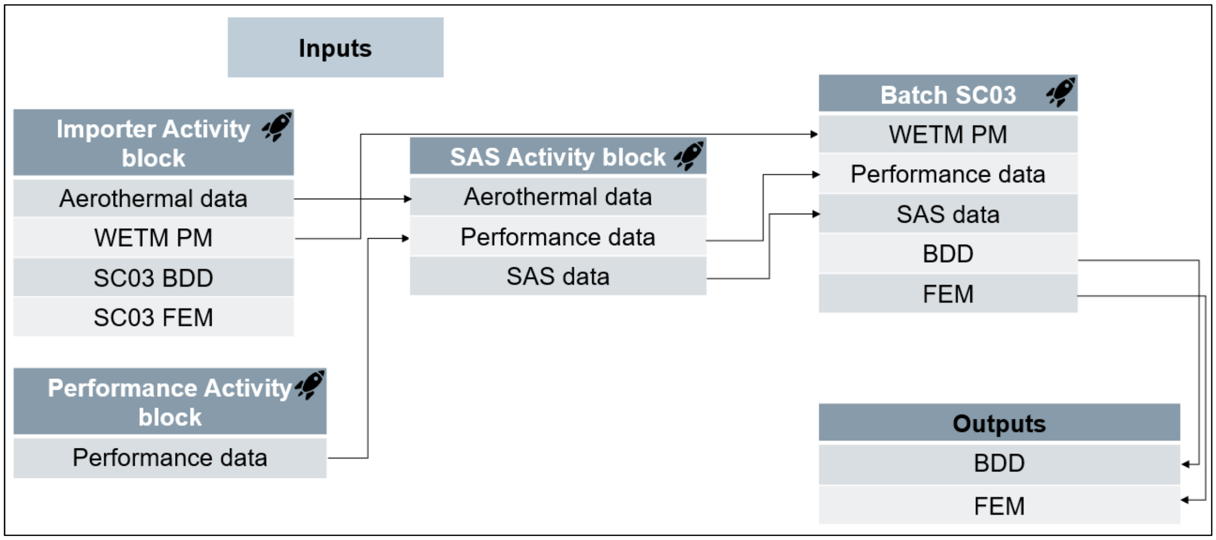

Figure 4.2 Multidisciplinary activity in the framework

First, this workflow-based tool integration in AGT framework provides engineers a rich environment to perform analyses. The workflow is facilitated by using activity blocks as mentioned in the chapter 1, especially if we refer to Figure 1.3. In fact, the blocks have been set up with definition files that enable to display the block as the developer wants who assigns the inputs and outputs needed to have a functional workflow. In addition, the activity block, in other words, the “tool” block contains configuration parameters to specify the FEA tool to be run and the mode of execution, in our case, a batch mode.

In separated activity, the user was obliged to create a revision to save his results and go back on the dashboard to choose the BDD and FEM creation activity and has to import the several inputs coming from the importer, the performance tool activity and the air and oil systems tool to run FEA in SC03. In that way, it requires the engineers to spend time in tasks such as saving, changing the activity, importation data which demands a lot of clicks. So, as a solution, we unite all sub-workflows in one activity containing the FEA main tool. Automate and integrate tools into a “multidisciplinary” activity permit to run FEA in only four clicks including three clicks for selecting the inputs data and another click to launch the tool. Thus, in few clicks engineers are able to generate a big quantity of results for different engine configurations and use cases by performing a full range of ambient temperatures.

Procedure:

1. Importer activity block is charged to import different types of file format as the PM files, the BDD files, the FEM files and the aerothermal CSV files. In the activity presented in Figure 4.2, the inputs from the importer are the WETM along with aerothermal data stored in CSV files, the latter are used to scale the boundary conditions for air system.
2. Performance activity is where the required engine performance conditions are identified such as ambient temperature, ambient pressure, etc. The extraction of data is done from a database containing all the performance data for each condition of the engine cycle.
3. Air and oil systems activity need the performance model and aerothermal data as inputs and produce files containing parameters across the air and oil systems such as mass flows, pressures, temperatures.
4. The user launches the "Batch SC03" to create the BDD and write the results of the numerical simulation in a FEM file. Then, a list of executive files is created via python script to get and read the inputs necessary to perform the WETM computation. A table of time against performance condition from the startup to shutdown of engine is created in local directory containing all the data with SC03 parameters values and units. The CSV table output file is used to create the BDD which is then loaded in the WETM imported to run the finite element analysis and generate finite element model through a series of commands from executive files.

Thus, this tool is successfully integrated in the platform and used by stakeholders to create the BDDs and the FEMs files for their case study at the ambient temperature and engine conditions desired. It is worth noting that the tool has been modified to be adaptable and solve three AGT engine models. Mostly tests have been made on the SGT-A65 gas turbine model. The integrated system through the workflow enables to do "unlimited" FEA and generates a large number of BDDs and FEMs for a full range of ambient temperatures from -50C to +55C. To save the data, user must create a revision to store the data generated in his workspace.

4.3.1 Creation of Basic Design Data

An SC03 Basic Design Data is composed of the “flight” cycle definition in which time and conditions of the engine appear as well as what is called environmental parameters. The latter are performance data along with air and oil systems data.

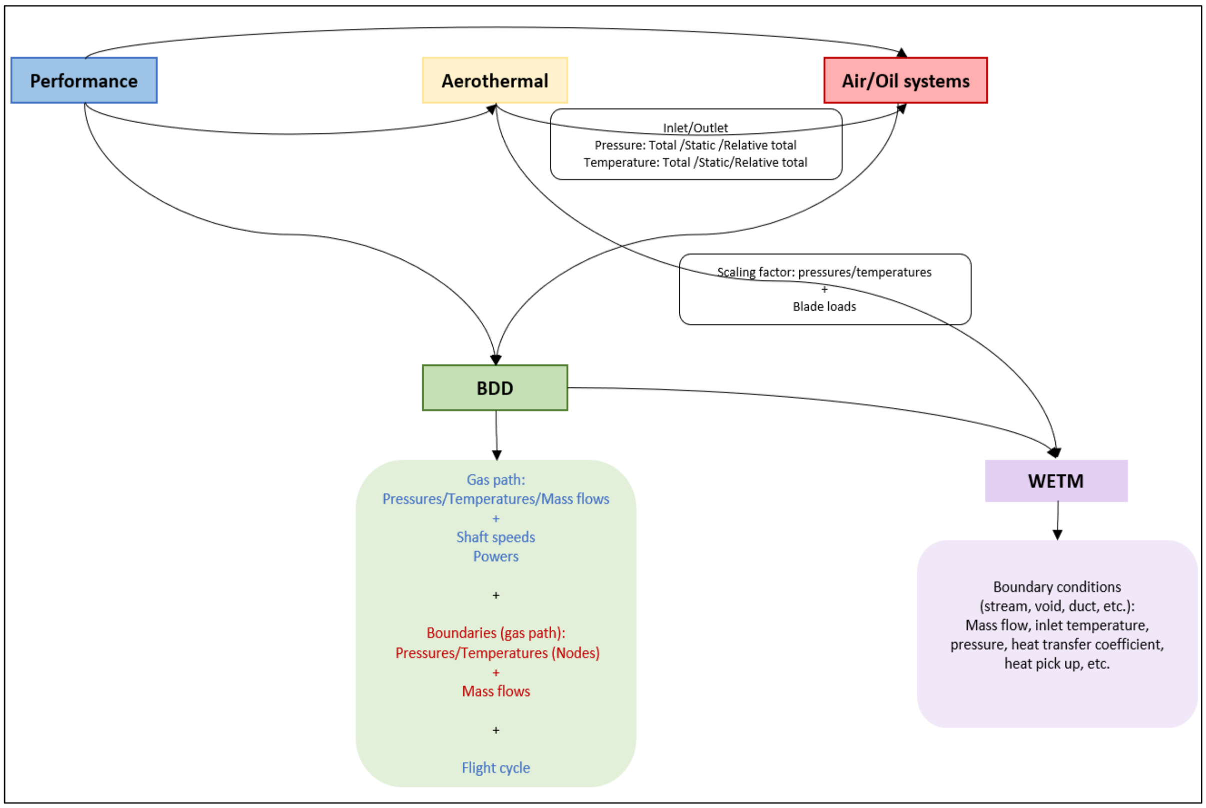

Figure 4.3 Creation of BDD

The content of the BDD is detailed in Figure 4.3 above. As we can see, the BDD will take all the parameters from the gas path such as pressures, temperatures and mass flows and the shaft speeds and power from performance outputs. Besides, BDD contains all the boundaries of the gas path, thus the pressures and temperatures are calculated from the secondary air system and oil system on the nodes, we also find the mass flows parameters. These parameters are defined as the “environmental parameters” in SC03. Then, we have the “flight cycle”, indeed the ramp is calculated to be exported on the WETM afterward. Finally, all this data list forms the Basic Design Data which is imported into the WETM in order to define all the boundary conditions of the WETM such as streams, voids, ducts, joints. In this way, the finite element analysis can be run to solve the model.

As mentioned previously BDDs are created with the thermal system utility plugin in SC03 software. During the implementation, some issues have encountered as parameters name or units between performance model and SC03 that are different. For instance, the speed is in rpm in the performance model but SC03 use rad/s or pressure is in psi from performance, but it was supposed to be in MPa for SC03. So, some conversions have been made with python script by multiplying them by the relevant factor to execute the workflow in order to get the right BDD and FEM. The Table 4.1 below shows the different units in which the parameters are in BDD so in SC03.

Table 4.1 Parameters units in performance model and SC03

Parameters	Units in performance model	Units in SC03
Pressure	psi	MPa
Mass Flow	lb/s	Mg/s
Temperature	K	K
Rotational Speed	rpm	rad/s
Time	s	s

4.3.2 Creation of finite element model

The activity gives the option to the user through a pop up to choose if he wants or not to generate the FEM files because it depends of the study case and team who is involved. In case that the user chooses to create the FEMs, when the BDD files are created, automatically python scripting adds command lines in the executive files to run the model. The BDD and FEM are created in a row for each ambient temperature. When creating a lot of BDD and FEM, it is preferable to use the remote desktops available, because it is safer by avoiding interruptions and it is more powerful in terms of CPU therefore faster than the user computer. The FEM file contains bulk results in binary format that are useful to visualize results like distribution of temperature, stress and so on, in SC03 thereby to do post-processing.

Furthermore, the FEM is also useful for interpolation when results need to be imported in another mesh such as critical parts like discs or blades. The FEM results are used to assess components life of the aeroderivative gas turbine.

4.4 Processing

The aim of this study is to automate the FEA run tool in order to gain time and improve productivity by automating tasks that require a lot of interactions between people and engineering tools. But also, in order to save cost and decrease the design cycle time of the product by permitting engineers to concentrate more on the assessment of components life. One of the main tasks is to create the BDD. In this section, a comparison is presented to explain the difference between the "old", traditional tool and the "new" automated tool developed in the D&A platform to create a BDD.

4.4.1 UNIX tool

The traditional way applied in the company to create a BDD is by using UNIX SC03 application. The user must create it manually by using thermal analysis input processor plugin accessible only in UNIX version. The main disadvantage is the use of the tool by one person at the time on a remote desktop. Furthermore, manual construction of the BDD is done by loading the performance data extracted from a database, by generating the air and oil systems outputs file. Then, the manual creation of the ramp occurs, in other words, the "flight cycle" which assigns the performance data in time during the cycle. So, creation of the time history and conditions, that is to say, the square cycle of the engine is manual. The extraction of performance data is done directly in the database. Besides, the extraction of all the nodes and bits containing temperatures, pressures have done by reading the air and oil systems outputs. After the user defines the ambient condition of the engine, the cycle is properly created with all the inputs extracted and the basic design data is saved in UNIX SC03. The creation of one BDD takes around 25 min to 30 min for an experienced user.

4.4.2 Comparison between UNIX and Windows versions

The tool is successfully integrated into the existing framework, and it is convenient for engineers at Siemens.

The traditional method to create manually a BDD by using SC03 UNIX one at a time by the engineers became delicate. One BDD takes 25 minutes to be created in UNIX. But now using the automated tool developed to generate the BDD, it takes only 4 minutes to create one BDD. For a case study, 100 BDDs have been generated in less than 7 hours whereas it took at least 41 hours to get these BDDs via UNIX tool. The workflow for the generation of BDD is at least 6 times faster than the traditional method as we can see on the chart presented in Figure 4.4. If we simulate for a creation of 1000 BDDs, if we need to run 1000 FEA cases for a study, the user can see a significant difference of time and the quality of data are accurate as the traditional method.

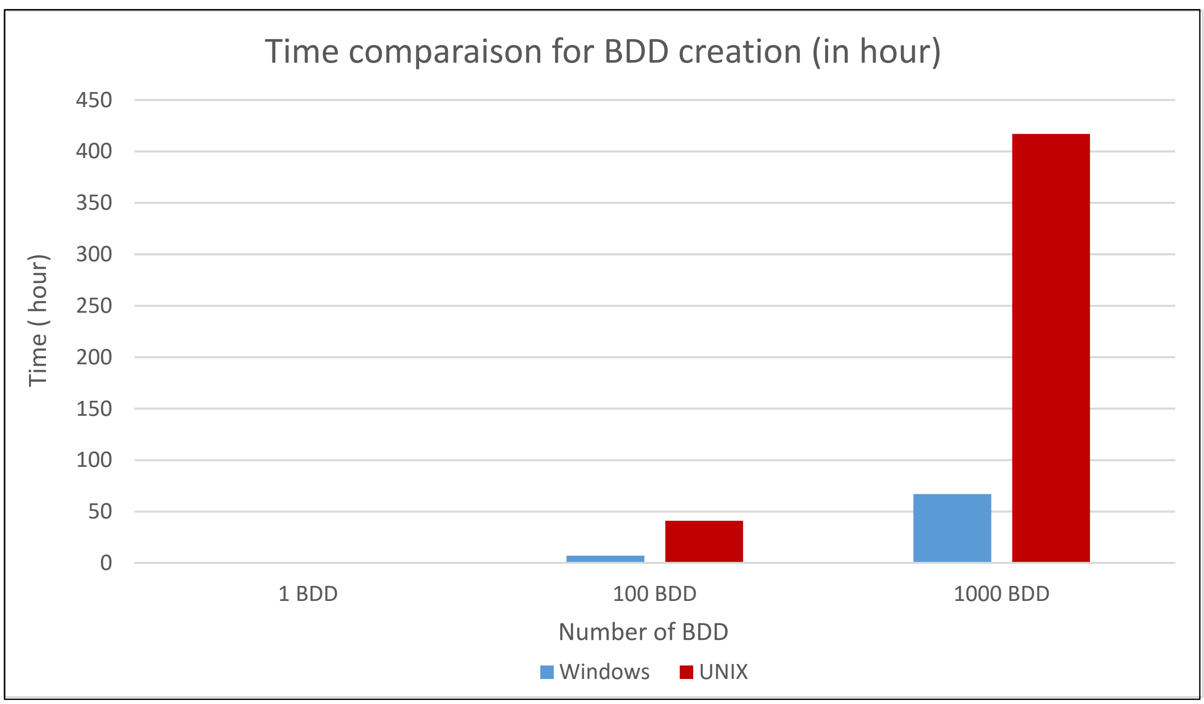

Figure 4.4 Time comparison for BDD between automated tool in Windows and traditional tool in UNIX

We can identify a huge amount of time is saved in this automated workflow. Concerning the case study above, about a week has been saved for the creation of 100 BDDs by counting 8 hours a workday. The FEMs are generated for this case by solving the model in thermo-mechanical mode, one FEA takes 1h30min. The generation of 100 FEMs takes at least 5 days if a remote desktop is used or few weeks in local computer. These analyses results presented have been run on a remote desktop because of the data amount generated. Not only we gain on time thanks to the BDD creation that has been totally automated but the fact that we can also choose the type of analysis of the model can reduce a lot of time on the FEA. Indeed, a structural or a thermal analysis takes only 25 minutes to solve the numerical model.

One of the main benefits of automated tools is the gain of time concerning the execution of work done in the background, that is to say, in that case user needs to configure his model and launch the analysis. He will not let the application opened in the foreground to see actively and wait until it is done especially for BDD creation. Because, engineers are usually actively on the GUI or software when using UNIX application for the workflow process of BDD creation for each ambient temperature. In the D&A platform, user will run his analyses on a remote desktop or on the local computer in the background. It allows users to complete other work tasks during the FEA workflow execution thanks to the batch mode.

Integrated this tool in the framework permits to engineers to run multiple analyses so more iterations are possible which was limited before. The benefit of such tool is the reduction of errors that can be made during manual construction. This tool can run more than thousands of analyses and generated BDDs and FEMs in mass quantities, that is what MI team works on nowadays. The tool deployed is faster but has also the potential to be more powerful. Besides, parallel computing is in development, a work is in progress to use SC03 as a service in docker containers which will enable to perform FEA workflow even faster.

4.4.3 Validation of results

Furthermore, studies have been done to compare the accuracy of the BDDs created in UNIX SC03 and the automated tool in Windows. A study has been done on more than 45 BDDs, with different engine configurations using three different types of engines. As mentioned previously, the automation script permits to use this activity for three engines types developed by Siemens Canada. The comparison of BDDs created by both applications, shows an error of at least 0.0001 on the parameters present in the BDD file. Engineers validate this range of error, which is a tiny difference of error due to rounding up of numbers. Otherwise, the BDDs are almost the same and the data are reliable and accurate so they can be used to create the FEM files.

In Figure 4.5, some parameters values have been chosen randomly because of the number of parameters presents in the BDD which exceed 1000. The values of temperatures, shaft speeds, pressures, mass flows and time history have been modified due to data confidentiality of the company. The idea is to show the comparison between UNIX tool and Windows tool namely the FEA tool implemented in the D&A platform. As we can see, for each plot, parameters values are superimposed on each other because the values are basically the same with a slightly difference. This difference is explained by the fact of the performance data extraction on the database which is not done with the same method in UNIX and Windows which do not generate the same number of digits after the decimal point.

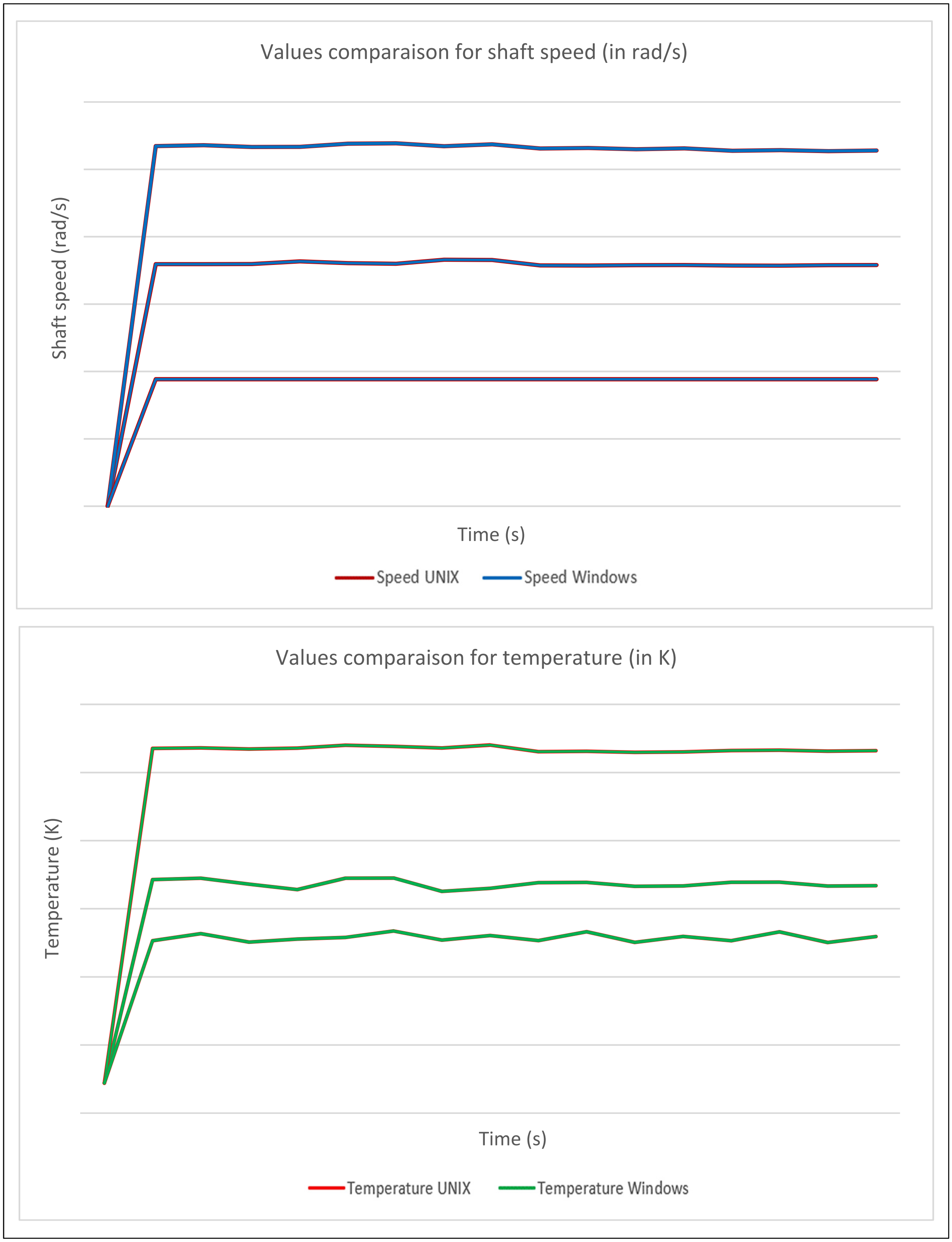

Figure 4.5 Comparisons of parameters values in the BDD

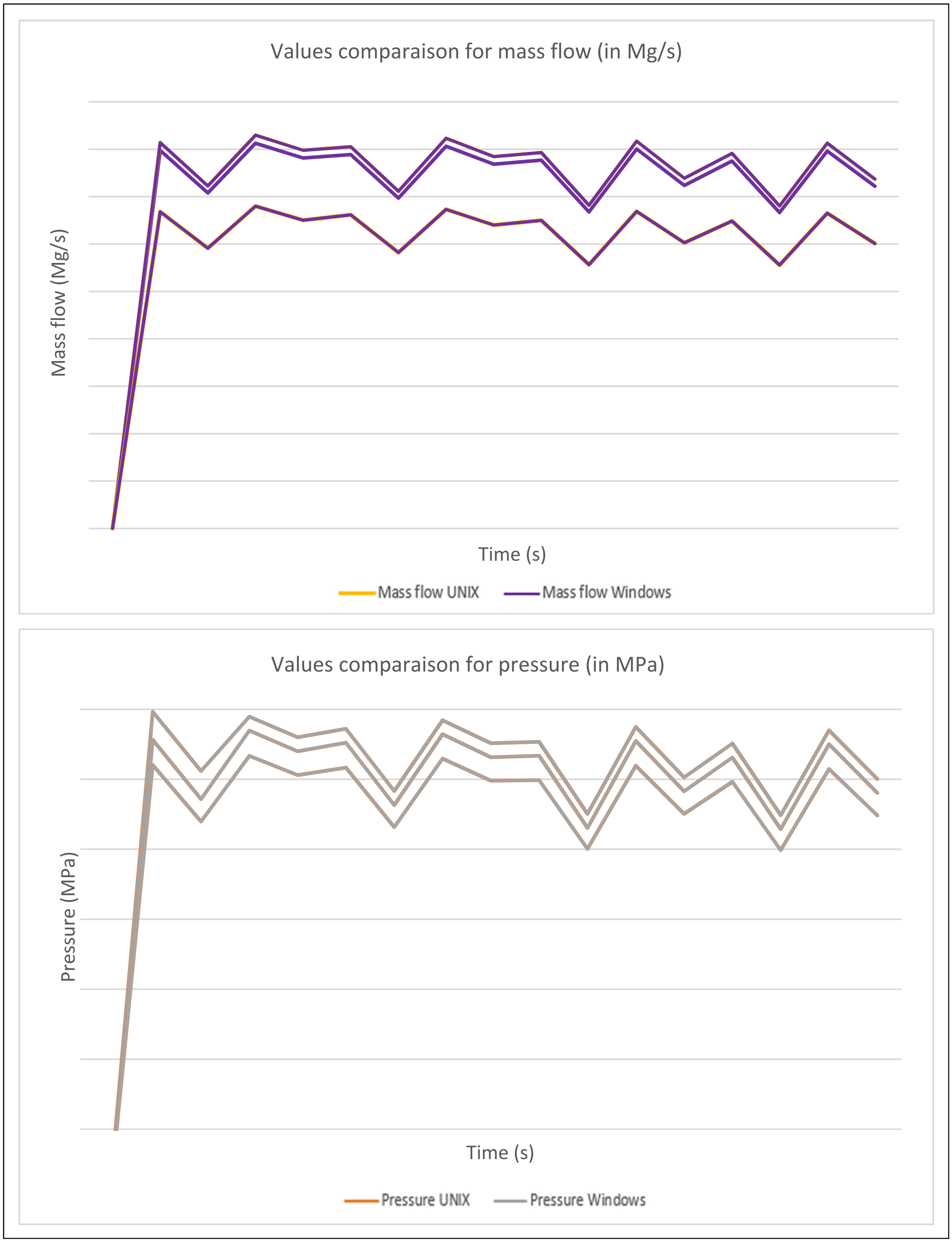

Figure 4.5 (continued)

The results of automated workflow in Windows have been successfully validated against the results obtained by performing manually the tasks in UNIX. Thus, this technical integration activity generates reliable data that can be used for engine components life assessment. It enables mass production of data which represents a real time saver that permits to enhance the efficiency and engineering productivity along the product cost reduction.

4.5 Post-processing

A post-processing UI has been deployed after the requirements of SAS and MI engineers, note that it is in early stage of development. It is a user-friendly UI which can be used by stakeholders of different disciplines.

It is possible in SC03 to automate the workflow to extract the maximum temperature or stress for instance from the 2D model at different ambient temperatures and different power outputs in order to assess a component. Like temperature distribution, 2D model stresses and displacements or any other SC03 outputs contained in the .fem file can be extracted. The list of relevant quantities has been shown in Figure 2.7 but given that the UI is at an early stage only temperatures, stresses, radial and axial displacements extraction have been implemented in the framework via automation scripts. The values are extracted in a CSV file as we can see in Figure 4.6 below.

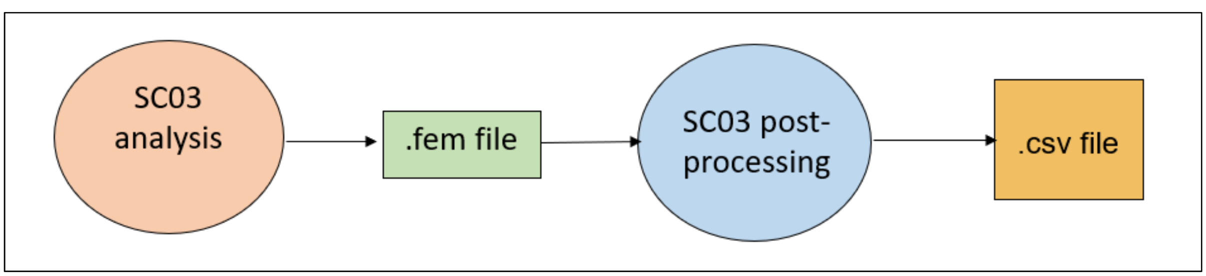

Figure 4.6 Workflow including post-processing

The workflow is the same as explained earlier but including the extraction of values with the FEM generated. For that, a new activity has been developed in the D&A platform which is described in Figure 4.7 below. The post-processor has been automated with SC03 scripts with executive files and can be used for any WETM. The automation of these scripts into the UI permits to extract several quantities and location of the maximum quantity is identified which is where engineers are most interested. They are identified thanks to references points assigned in the WETM.

There are two ways to get the values that user wants. The first option is to put a PM file, that is to say, the WETM file by adding BDDs already created. Then, directly the FEMs will be generated one by one and will extract data one by one on a CSV file for each BDD imported which is represented in Figure 4.7. Or, the second option is to put only the PM file and the aerothermal CSV files, then the BDD will be created and the FEM and so on, finally the extraction step will happen.

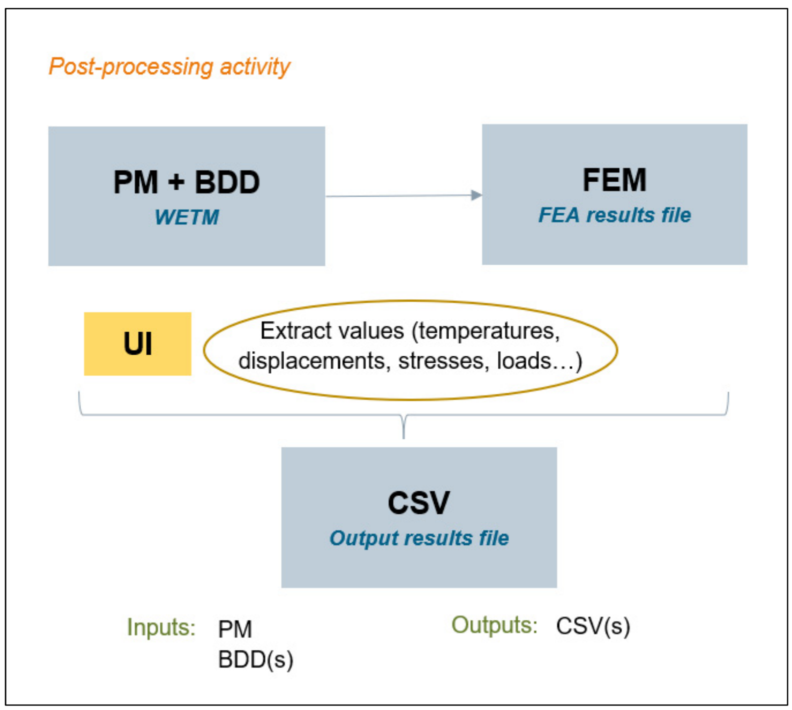

Figure 4.7 Post-processing activity

This step is essential because it saves so much time as post-process is literally a long process that demands a lot of "clicks" in SC03 GUI. Automating these tasks represents an important gain of time for engineers who used to do manual post-processing and the time saved can be spent on the analysis of extracted data.

Table 4.2 Example of table generated in a CSV file for temperatures values

Baseload temperature (K)	Maximum temperature (K)	Maximum temperature time (s)	Minimum temperature (K)	Minimum temperature time (s)
x	x	x	x	x
x	x	x	x	x
x	x	x	x	x
x	x	x	x	x

The data extracted is stored in a CSV file as illustrated in Table 4.2 above. It is an example for temperature values, the same format is applied for displacements and stresses. The table is longer, each line represents a specific reference point on the domain of the component for instance in a blade. These reference points are already created in the 2D WETM by designers in a precise position, usually in regions where there are high damages due to temperatures, fatigue, failure for example or the gap where displacements will be evaluated. In Table 4.2, values are not given due to industry data confidentiality and are represented by “x”.

Time is not the same for each extraction of quantity, it varies between 5 and 20 minutes in general for each run. It is definitely faster than the manual extraction in SC03 by the user because it implies to open SC03, loading the PM, BDD then the FEM and post-process for each FEM. Which constitutes a long process that usually narrows the user to produce a limited amount of FEM to study the problem.

4.5.1 Examples of study cases

Two examples among several study cases are presented using this tool implemented in the framework for industry purpose.

4.5.1.1 Safety issue

This study has been done by users by performing the multidisciplinary activity to compare the FEM results in SC03 GUI to identify the worst cases for creep and fatigue lives in the turbine. BDDs were generated at different ambient temperatures for WLE and DLE engines, so the SGT-A65 engine. The WETM analysis has been run in thermo-mechanical mode and data was post-processed to compare the temperatures between the baseline engine configuration and the over-fired engine by plotting temperature delta which is the difference of temperature between the two engine configurations. In addition, this study in SC03 has enabled to ensure that data presented in the BDD files are consistent.
This comparison has been possible with a standard feature set up in SC03 able to contour results by producing contour plots of differences between one model and another. The latter can have different meshes. The use cases are requested by mechanical integrity engineers in order to assess lifing of components after the results interpretation, especially focusing the study on the HPT disc. This study case has enabled to simulate the worst scenario and to improve the engine model to increase the life of critical parts.

Thus, this automated FEA tool on the D&A platform permits to users not only to push the limits to simulate different engine behaviors, it shows the efficiency of the model. It helps engineers to spend more time on results interpretation than the preparation of the model to run.

4.5.1.2 Hoop stress extraction

Study cases on the high-pressure turbine disc have been done where stresses have been extracted with the FEA automation tool developed in the framework. Multiple runs have been done on the engine at different ambient temperatures. The hoop stress is the mechanical stress which is defined for rotationally symmetric objects such as pipe or tubing (McKeen, 2016), in our case, the disc. Hoop stress is the result of forces acting circumferentially especially due to a pressure gradient. Engineers are most interested in the maximum hoop stress that always occurs at the inner radius or the outer radius depending on the direction of the pressure gradient. It can be analyzed at any investigation point within the disc wall which is done by creating a reference point in our study as shown in Figure 4.8 with the red point. Furthermore, reference point enables to identify the location in the component and is called in the automation script to calculate the stress at this specific point. So, the HPT disc 2D model will contain already this point before running the model.

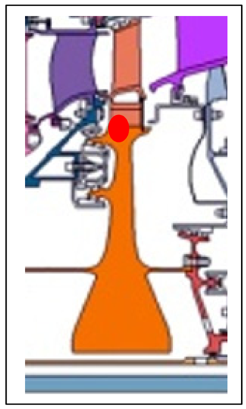

Figure 4.8 HPT disc

A study to get hoop stress on the HPT disc has been done for 10 ambient temperatures for one configuration of engine but with different engine cycles, that is to say, certain parameters vary like acceleration rate, deceleration rate for instance. For this case, 20 models have been solved with the FEA automated tool. First, 10 2D whole engine models have been solved in thermal mode. Then an automatic interpolation has been implemented to distribute the temperatures on the 2D HPT disc sub-model that is illustrated in Figure 4.8. It will be solved in structural mode to get the accurate stresses containing the right boundary conditions.

Note that interpolation step is a process regarded as time consuming, so we have chosen to automate this task to gain time during the analysis workflow. Indeed, this task requires to go in the sub-model, the HPT disc, and import the FEM file generated for the 2D WETM in SC03 to read temperatures from this model with a different mesh and interpolate onto the current mesh. In that way, results for hoop stress during structural analysis will be more accurate because it contains all the thermal boundary conditions. Manually this task demands a lot of “clicks” by defining the mapping from coordinates and selecting the option “stress all-time points” to ensure the interpolation of all-time points analyses and finishing by compressing the data and importing the FEM. Then, applying the interpolation settings to all domains and finally run the FEA in HPT disc model in structural.

Table 4.3 Time spent for manual and automated temperatures interpolations

Interpolation \ Time (min)	Manual	Automated
1	6	3
10	60	30

After implementing the automation script for interpolation in the framework, we can see as mentioned in Table 4.3 above that we gain twice the time as long compared to the manual interpolation. Indeed, 6 min is the average time to interpolate the distribution of temperature manually by an experienced user but doing this task for more than one FEM can quickly be fastidious. So, it represents an important time saver for engineers by automating it and enable them to focus more on the life assessment of the engine. This automation permits to do more iterations and affects the workflow performance significantly.

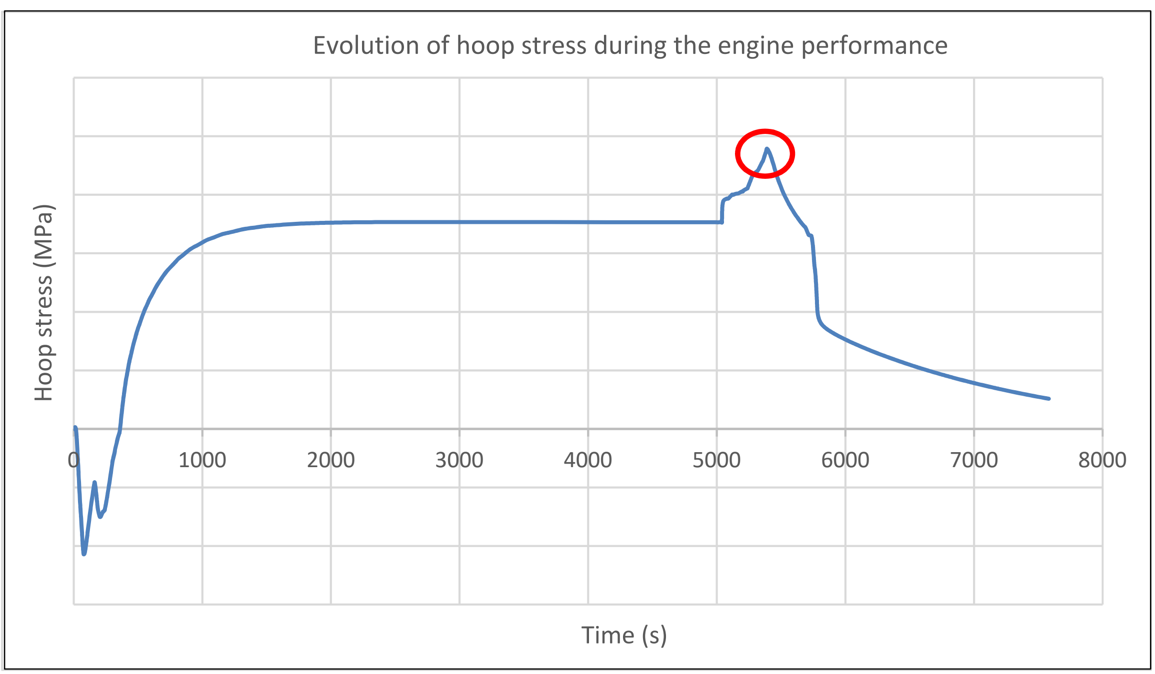

Figure 4.9 Hoop stress plot

Engineers are interested on the maximum value of hoop stress for that in the post-processing activity when running the FEA, the values of maximum and minimum stresses and their respective times are extracted in a CSV file. The plot of hoop stress against time is represented in Figure 4.9 above as in SC03, engineers need the maximum value, encircled in red. Values have been changed due to data confidentiality.

After that, engineers will analyze the results and will correct the design in order to increase the components life. Concerning the data extracted, they have been validated by MI engineers in the company and a manual checking has been done for these 20 FEA runs to see if we get the same results.

4.5.2 Post-processing results

Post-processing plays a vital role for lifing, what is presented previously is just a beginning of what can be extracted to study the life of components. So many other quantities such as tip closures, heat rejections, blades and vanes loads can be extracted. The automated post-processing tool presented is in development but can extract some quantities like stress, temperature and displacement which is useful for some case studies as seen previously. Indeed, the determination of the maximum and minimum values for each quantity are required. Which is done by doing a sweep on the values from the peak starting time to the peak end time. Output results values are accurate and confirm the reliability of the automated tool generating BDDs and FEMs. Results will allow the life prediction of the aeroderivative gas turbine and increase the engine efficiency and productivity by reducing cycle time. Thus, post-processing which is manual and long can be automated through SC03 scripts with executive files. A huge amount of time is spared for engineers in that way, without counting the model run-time.

4.6 Conclusion

This chapter describes the implementation of FEA automated tool in the D&A platform. The workflow implementation using tools from different disciplines namely performance, air and oil systems is presented, in order to create BDD. The latter is the fundamental file being the input to run finite element analysis containing all the boundary conditions that permit to get finite element model, results of FEA. These results help to find errors and failures of components, at the same time enable to predict components life. More iterations are possible which permit to try and simulate several use cases in less time and more efficiently. The automated workflow main benefit is the gain of time.

The key aspects of SC03 solver including pre-processing tools, batch execution of SC03 numerical simulations and the interface have been presented. Analysis setup is a fundamental step, and user must be careful during engine configuration. This framework is a digital platform that unites tools, algorithms, analyses, and coordination between disciplines and users. Engineers therefore have at their disposal this design and analysis platform with several capabilities including pre-processing, processing and post-processing which represents a huge time saver that increase the productivity of their work as well as the AGT.

CHAPTER 5

BENEFITS AND DRAWBACKS OF FEA AUTOMATED TOOL

5.1 Benefits

5.1.1 Gain of time and mass production

Using this tool is very helpful for the whole engine team who is charged to create BDDs for mechanical integrity team. And of course, the FEA tool automated in the D&A platform is beneficial for both teams.

Engineers spend a considerable amount of their time on non-value-added tasks like exchanging data, converting output data and this tool eliminates a lot of these tasks thanks to digitalization and automation methods. The idea in the future is to store the data in Teamcenter, Siemens Product Lifecycle Management (PLM) software that will allow anyone to get access to a specific activity done by someone else, this latter will be labeled to trace the information. The traceability is a key point that should be noted here. The fact that user wants to run many simulations points out the factor of repeatability, which is a great advantage for engineers when it is automated. In fact, automating repetitive tasks permit less human error.

In addition of the process time reduction, integrating multiple disciplines into one module consists of a huge gain of time for users because all the information is now accessible in one framework. The automation of tools becomes mandatory to perform more models in a limited amount of time, in this way we optimize the productivity in engineering. With this user-friendly automation tool, engineers can run more than thousands of simulations. Contrary to before, when they have to spend most of their time on executing the models manually. Now, this automated tool enables engineers to spend more time on the analyses of data and improve the quality and the robustness of their designs.

5.1.2 Project management triangle

This project is part of what is called "project management triangle" or "iron triangle" which is a model that is wisely used to measure the success of a project thanks to time (schedule), scope, cost and quality criteria (Jha et al., 2007) as defined in Figure 5.1. Indeed, this automated FEA tool got multiple assets in the scale of industry. The automation enables to practice more iterations so more simulations which increase the quality of decision. Consequently, it decreases the cost of manufacturing and reduces considerably inspection cost for critical parts. Besides, time is relatively reduced by replacing manual tasks such as repetitive or non-value-added tasks by automated tasks. One of the main points from users of this tool is the ability to push the limits by simulating different engine behaviors in an "unlimited" way and ensure to have coherent data that increase the quality of work and product.

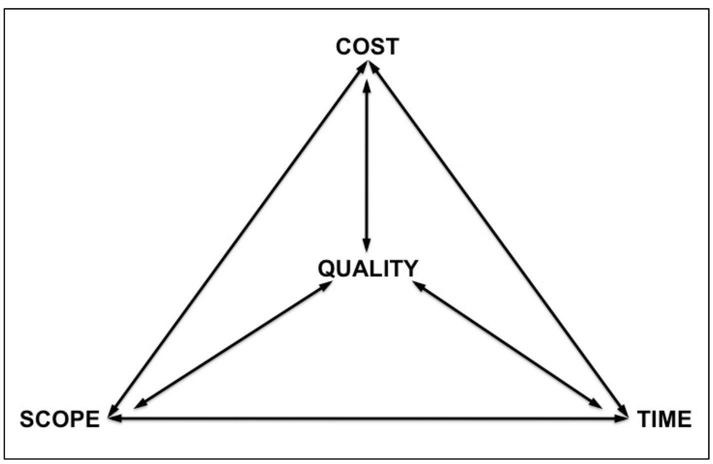

Figure 5.1 Project management triangle

It should be noted that the old and traditional way using UNIX application will not disappear. It will be important to double-check time to time with the manual way to validate results. Furthermore, one point that has been mentioned previously is that automated tools enable engineers to work in parallel on other tasks than FEA processing. Especially for BDD creation, where they need to focus actively and continuously on software when creating each BDD manually. Time is spared once again and used for other work tasks in parallel.

5.2 Drawbacks

We can notice few drawbacks by using this tool. First as a user, if there is any issue with the tool, user will not be able to know where the problem comes from because of the workflow script coded as blackbox. Secondly, the fact that we can generate a huge amount of data should not permit the user to "overanalyze" a model or a component. In that case, running thousand analyses will be a wrong decision therefore a preliminary study must be done before running analyses. Also, the user should be careful when configuring his model, in other words, he should put the right inputs data to get the right outputs files. Indeed, one little mistake made in pre-processing step can spread errors for all the runs in the process. Furthermore, if we see the iron triangle in Figure 5.1 presented above, concerning the scope it might be difficult to automate in a generalizable way, even though it works for different types of engines thanks to modularity in automation methods. At some point, scope of automation may be restrictive for developers.

Another point is, if the base model, so the WETM, aerothermal data and/or SAS model are wrong, in that type of framework, that will spread false information rapidly even if the user does not notice. The user must not be overconfident and must pay attention on his results.

5.3 Conclusion

This chapter deals mostly with the feedback from users explaining the benefits and drawbacks of the computational tool deployed in the digital platform. Appropriate training is required for users, considering that they are not necessarily expert on all disciplines. For that, recorded videos and documentation including user guide are provided to users not only for the FEA automated tool also for the framework. Thus, we should consider that this improved tool, and methods used to create it, represent a great value to engineers at Siemens Canada. Furthermore, other developers will also integrate their workflows for other disciplines to improve the framework so that it is usable by most engineers of the industry.

CONCLUSION

To conclude, this thesis presents the integration and implementation of a finite element analysis tool in a design and analysis platform through automation. The main purpose has been to reduce the time that engineers use to execute their models manually, therefore eliminate tedious tasks. As well, non-value-added tasks are removed such as data transmission, data collection for instance. Consequently, it enables engineers to spend more time to improve the efficiency, quality, productivity and robustness of gas turbines.

This FEA automated tool has been deployed by working with other teams in order to test, correct and have feedback to enhance the tool in the framework and put the engineering work to another level. The FEA automated tool deployment enables now a very large number of whole engine thermo-mechanical predictions of life. The latter is a task that would have taken weeks to perform but now it has been reduced on few days. This long process requires models from different disciplines especially performance, aerothermal, secondary air systems and whole engine thermal model. And it is run sequentially by different people and requires exchanges from one department to another which has created a certain dependence and sometime waiting time to get output data. Today, the whole workflow is done entirely by a few clicks of a button on one framework thanks to activities and is accessible to everyone at any time. In that way, engineers save time and can invest more on the analysis and interpretation of results to assess the components life of aeroderivative gas turbines particularly the critical parts.

Thus, the execution of a whole engine thermal model analysis in the in-house finite element analysis software, SC03, is possible by selecting few input files and launching the tool. This user-friendly FEA automation tool is useful in the company daily work and is available via the D&A platform where integration of engineering tools and workflows have been possible by means of python scripts. This digitalized engineering environment permits to increase design robustness, tackle complex design easily and at the same time increasing the engineering productivity of the company.

Automation in the multidisciplinary platform of aeroderivative gas turbines represents an innovation that improves significantly the process workflow in the industry. Valuable time is gained by tool integration using parametric design. Automated tools implemented in the framework aim to enhance the day-to-day engineering design process work. Furthermore, this project includes many aspects of Industry 4.0 concept particularly factors such as simulation, system integration and big data are integrated in order to deploy the FEA automated tool. Indeed, it reduces considerably the time currently spent by engineers on non-value added and manual tasks, which fits in the context of Industry 4.0. Thus, this will lead to significant performance improvements on gas turbines processes.

RECOMMENDATIONS

As mentioned during this thesis, emphasis has been made in the FEA tool integration which is successfully implemented in the digital platform which is usable for several types of engines. It is capable to run a huge amount of FEA and generate a lot of FEM in remote desktop or even on the engineer's powerful computer.

But nowadays, it is possible to run these analyses in parallel, indeed running SC03 in batch enables parallel processing capability. Docker containers are used to run SC03 as service, it is like a computer system but in virtual. In that way, it will be connected to the framework and will be able to run many analyses in parallel using the multidisciplinary activity. Calculations will be even faster. Parallelization and use cases tests are in progress in the company for instance to get turbine disc stresses for different engines configurations. After that, the idea is to use this data and try optimization via machine learning. In addition to containers, cloud computing service such as Amazon Web Services platform is an option to run analyses and generate data that are heavy. Works to host the engine execution by cloud computing has started which represents an excellent environment to produce this type of data.

Furthermore, other works can be implemented in the D&A platform to improve even more the tools, options such as comparisons of WETM FEMs can be automated and can help post-processing. Besides, the post-processing tool can be developed in order to contain as much as possible all the quantities necessary to predictions of life. This can then be extended by implementing lifing tools with SC03 specific plugins to assess for instance fatigue and creep in aeroderivative gas turbines.

BIBLIOGRAPHY

Barkmeyer, E. J., Feeney A. B., Denno P., & Flater D. W., Libes, D. E., Steves, M. P., & Evan W. K. (2008). Concepts for Automating Systems Integration. NIST Interagency/Internal Report (NISTIR) 6928. Retrieved from: https://www.researchgate.net/publication/242281654_Concepts_for_Automating_Systems_Integration

Binder B., Gottschall M., Blochwittz T, & Kirsch L. (2019). PLM- and Microservice-based Integration Approach of MBSE and System Simulation for Federated Continuous Engineering Platforms. NAFEMS. Retrieved from : https://www.nafems.org/downloads/dropbox/watermarked/resource_center/conference/nwc19/nwc19-349.pdf

Chakrabarty A., Mannan S. & Cagin T. (2016). Chapter 5 - Finite Element Analysis in Process Safety Applications. Multiscale Modeling for Process Safety Applications (pp. 275-288). Retrieved from : https://doi.org/10.1016/B978-0-12-396975-0.00005-X

Chernukhin O., Thunes J., Reuss S., & Wolfe C. (2019). A Coupling Solver Architecture for Multiphysics Simulations. NAFEMS. Retrieved from : https://www.nafems.org/downloads/dropbox/watermarked/resource_center/conference/nwc19/nwc19-349.pdf

Coito T., Viegas J.L., Martins M. S. E., Cunha M. M., Figueiredo J., Vieira S. M., & Sousa J. M. C. (2019). A Novel Framework for Intelligent Automation. IFAC. Retrieved from: https://doi.org/10.1016/j.ifacol.2019.11.501

Dupont C., Tromba A. & Missonnier S. (2019). New strategy to preliminary design space launch vehicle based on a dedicated MDO platform. Retrieved from : https://doi.org/10.1016/j.actaastro.2018.04.013

Hou G., Gong L., Yang Z. & Zhang J. (2020). Multi-objective economic model predictive control for gas turbine system based on quantum simultaneous whale optimization algorithm. Retrieved from : https://doi.org/10.1016/j.enconman.2020.112498

Jha K.N. & Iyer K.C. (2007). Commitment, coordination, competence and the iron triangle. Retrieved from : https://doi.org/10.1016/j.ijproman.2006.11.009

Kagermann H., Wolfgang W., and Johannes H. (2013). Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group, no. April: 1–84.

Lee J., Cameron I. & Hassall M. (2019). Improving process safety: What roles for Digitalization and Industry4.0? Retrieved from: https://doi.org/10.1016/j.psep.2019.10.021

McKeen L.W. (2016). Fatigue and Tribological Properties of Plastics and Elastomers (Third Edition)

Mirhosseini A. M., Nazari S. A., Pour A. M., Haghighi S. E. & Zareh., M. (2019). Failure analysis of first stage nozzle in a heavy-duty gas turbine. Retrieved from: https://doi.org/10.1016/j.engfailanal.2019.104303

Ohno, T. (1988). Toyota Production System: Beyond Large-Scale Production. Taylor & Francis

Ouellet, Y., Garnier, F., Roy, F., & Moustapha, H. (2014). A Preliminary Design System for Turbine Discs. Retrieved from: http://dx.doi.org/10.1115/GT2014-26167

Oesterreich T.D. & Teuteberg F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Retrieved from: https://doi.org/10.1016/j.compind.2016.09.006

Peoc'h T. (2019). Automation & Integration of secondary air system workflow for multidisciplinary design optimization of gas turbines. Retrieved from : http://espace.etsmtl.ca/2373/1/PEOC%27H_Timoth%C3%A9-corr.pdf

Ramamurthy, A., Valenzuela-del-Rio, J., Villeneuve, F., & Veer, J. (2014). DEVELOPMENT OF A SysML FRAMEWORK FOR GAS TURBINE DESIGN UNDER UNCERTAINTY. In Global Power and Propulsion Forum (Vol. 1). Retrieved from https://www.gpps.global/documents/events/zurich17/papers/general/GPPF_2017_paper_159.pdf

Rolls-Royce. (1986). The jet Engine 5th Edition. Dans (pp. 80-93).

Saratov A., Stepanov M. & Kshesinskii D. (2019). Automatic Detuning of Steam Turbine Rotor Blades' Eigen frequencies Away from Critical Areas. Retrieved from : https://www.nafems.org/downloads/dropbox/watermarked/resource_center/conference/nwc19/nwc19-349.pdf

Sung S. (2019). Development of Pre-processing Automation Tools for a Seat FE Analysis. NAFEMS. Retrieved from: https://www.nafems.org/downloads/dropbox/watermarked/resource_center/conference/nwc19/nwc19-349.pdf

Tinga T., Visser W.P.J., & De Wolf W.B. (2000). Integrated lifing analysis for gas turbine components. Retrieved from: https://doi.org/10.1115/2000-GT-0646

Walsh, P. P. & Fletcher P. (2004). Gas Turbine Performance. Second Edition. Blackwell

Wang L., Kolios A., Nishino T., Delafin P. & Bird T. (2016). Structural optimisation of vertical-axis wind turbine composite blades based on finite element analysis and genetic algorithm.Retrieved from : https://doi.org/10.1016/j.compstruct.2016.06.003

Warde S., Goddin, J., & Naker, S. (2019). Materials and Simulation: From CAE to ICME A 2040 Vision. NAFEMS. Retrieved from : https://www.nafems.org/downloads/dropbox/watermarked/resource_center/conference/nwc19/nwc19-349.pdf