Modularity Integration in the Gas Turbine Sector for Performance and Cost Optimization

by

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Intégration de la modularité dans le secteur des turbines à gaz pour l'optimisation des performances et des coûts

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RESUMÉ

Les changements de production induits par l'industrie 4.0 (I4.0) permettent aux industries de répondre aux besoins des clients de manière beaucoup plus précise. Cela permet également aux entreprises de se concentrer sur le développement de solutions durables et plus efficaces. Le secteur de l'énergie a besoin d'évoluer et la mise en œuvre de l'I4.0, et plus précisément de la modularité, pourrait contribuer à résoudre de nombreux problèmes. Cette recherche vise à combler les lacunes de la recherche sur la mise en œuvre de l'I4.0 dans le secteur des turbines à gaz (GT). Une application de conception modulaire pour les turbines à gaz a été développée. Son principal objectif est de faciliter la relation entre le client et l'ingénieur, en fournissant une application de conception rapide et accessible, mais aussi des cycles préconçus, qui proposent des solutions simulées et optimisées en fonction des exigences du client. Cette recherche présentera le fonctionnement de cette application, les différentes variables utilisées et la variable de décision, à savoir le coût de l'énergie. La simulation et la comparaison avec les cycles GT de la littérature ont été effectuées pour prouver la précision du processus de simulation. Enfin, un cas d'étude est présenté, plaçant l'application dans un contexte hypothétique pour illustrer ses avantages et les solutions qu'elle offre. L'application s'est révélée capable de simuler correctement les cycles GT et son utilisation correspond aux objectifs fixés. Cependant, elle peut être améliorée de nombreuses façons, avec l'ajout de composants, de cycles thermiques, l'optimisation du code ou l'intégration de variables d'entrée multiples.

Mots clés : Industrie 4.0, Modularité, Turbines à gas, Optimisation, Simulation

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ABSTRACT

Production changes brought about by Industry 4.0 (I4.0) enable industries to respond to customer needs in a much more precise way. It also allows companies to focus on the development of sustainable and more efficient solutions. The energy sector needs evolution and the implementation of I4.0 and more precisely modularity could help solve many problems. This research focus on filling the research gap on I4.0 implementation in the Gas Turbine (GT) sector. A modular design application for GT has been developed. Its main objective is to ease the relationship between customer and engineer, by providing a quick and accessible design application but also pre-designed cycles, that propose solutions simulated and optimized with the customer requirements. This research will present the functioning of this application, the different variables used and the decision variable i.e., cost of energy. Simulation and comparison with literature GT cycles has been made to prove the accuracy of the simulation process. Finally, a study case is presented, placing the application in a hypothetical context to illustrate its benefits and the solutions it offers. The application has been found to correctly simulate GT cycles and its use corresponds to the stated objectives, however, it can be upgraded in many ways, with the addition of components, heat cycles, the optimization of the code or the integration of multiple entry variables.

Key words: Industry 4.0, Modularity, Gas Turbines, Optimization, Simulation

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LIST OF ABREVIATIONS

I4.0	Industry 4.0
CP	Craft Production
MP	Mass Production
MCP	Mass Customization Production
MPP	Mass Personnalisation Production
CPS	Cyber-Physics System
IoS	Internet of Service
GT	Gas Turbine
PR	Pressure Ratio
FT	Flaming Temperature
TE	Thermal Efficiency
MDA	Modular Design Application
OH	Operating Hour
PEC	Purchased Equipment Cost
CRF	Capital Recovery Factor
sLCOE	Simple-Level Cost of Energy
RNG	Renewable Natural Gas

LIST OF SYMBOLS

$	2023 US Dollar
kW	Kilowatt
K	Kelvin degree
kPa	Kilopascal
kWh	Kilowatthour
MMBTU	One million British Thermal Units
kg	Kilogram
s	Second
h	Hour
N	Newton
m	Minute
ft	Feet

INTRODUCTION

In an era of rapid technological advancement and evolving energy demands, the gas turbine industry stands at a key point in its history. Within the actual context of ecological crisis, societies need to transition towards cleaner and more efficient energy solutions. Gas turbines continue to play a pivotal role in power generation, aviation, and various industrial applications and are therefore a technology rooted in these profound changes. The aim for improved performance, enhanced efficiency, and cost competitiveness requires innovative approaches to gas turbine cycle design and optimization. This thesis has for objective to open the landscape of gas turbine engineering toward these changes by introducing a novel application that employs modularity to design, simulate, and optimize gas turbine cycles, ultimately leading to enhanced efficiency and cost analysis.

The concept of modularity has emerged as the future of modern engineering, enabling the creation of flexible and adaptable systems from interconnected components. The global industrial landscape evolves towards Industry 4.0 (I4.0), characterized by data-driven decision-making, automation, and interconnectedness. Modularity, as a fundamental principle of I4.0, is among the solutions that fits best with this evolution. It allows more flexible, agile, and more efficient solutions, with a high degree of customer involvement. Indeed, products are individualized as the client can choose the major design of most of the products. The concept of modularity involves breaking down complex systems into modular components that can be easily interchanged, upgraded, and reconfigured. This modular approach enables businesses to respond quickly and effectively to changing customer demands, market trends, and technological advancements.

Siemens Energy (SE), as a major player in the sector of energy production, wants to position itself as a precursor in the industry changes. SE acknowledged this paradigm change and customer requirement evolution and want to keep up with it. Therefore, SE need tools to implement I4.0, including modularity, in their production system.

The present study aims to advance the incorporation of modularity in industrial applications. The methodology employed in this research has been specifically applied to heat engines, with a focus on the gas turbine application within this category. Importantly, the method's generic approach renders it adaptable to diverse systems, extending beyond heat engines to encompass applications in areas such as automotive, aeronautics, and various other domains.

Therefore, this thesis has for objective to address the multiple challenges of heat engine cycle design and optimization through an application that includes the concept of modularity in multiple ways. The primary objective is to create a design application, capable of designing any type of heat cycle, optimizing it, and approximating main cost values. Secondly, this application should be able to compare different cycles from a database for global parameters (power, ambient conditions, cost limits, etc…) to determine the best cycle for a given scenario. This application will then have two levels of modularity, with the design of multiple cycles, and the easy comparison of solutions to fit best the customer will.

This master thesis, after a literature review on modularity, its concept and application and also gas turbines, how they work and how to optimize them will extend more on the main objectives of the project. It will explain how the modularity is incorporated on a Gas Turbine Design System. A peer-reviewed research article has been written for this project. It presents the methodology of the application, the main validation results, and a study case to give an overlook of the power of the application. In another chapter, some optimization programs are detailed, and more focus is put on components configuration. Finally, a discussion on the application upgrades and the ways to improve the modularity of the system have been added in the final chapter.

CHAPTER 1

LITERATURE REVIEW

This literature review summarizes existing knowledge on Industry 4.0, modularity, and especially how it can improve performances of a solution and ease the relation with customer. In the specific context of gas turbines, research focuses on design and optimization, yet a conspicuous research gap exists, notably in the comprehensive application of modularity within the gas turbine sector. While modularity studies have flourished in the automotive sector among others, there is still few documentations on the gas turbine sector. This research seeks to fill this void, by connecting modularity literature, gas turbine studies, and Industry 4.0 principles, to contribute to existing knowledge and address the identified research gap.

1.1 Industry 4.0 and the need for modularity

This part of the review will focus on the market evolution from mass production to personalized production. The upcoming of I4.0 is altering the relationship between companies and customers. These differences must be analysed and the different tools at stake identified in order to ease the transition to new production paradigm. After an analysis of the 4 major industrial revolution, the review will focus on I4.0 and on the concept of modularity, that Siemens wants to implement into the GT sector.

1.1.1 The 4 Revolution and the Industry 4.0

Industrial period has been market by 4 major revolutions, (Pereira et Romero, 2017). Each revolution brought a major change in paradigm production.

Figure 1.1 synthetize the chronology of these revolution. It insists on the different paradigm of production. From this figure, multiple phases can be identified. The Mass Production (MP) revolution transformed the products from small batches with high variety to large batches with few varieties. The revolutions that follow have since tried to bring back variety in our product design while keeping a high productivity. I4.0 can then be characterized by a mix of different types of production.

The first introduced revolution is the Craft Production (CP). At that time, every product was donebased on the client'srequirement (Wang *et al.*, 2017). There was a large panel of the product, but each productwas very expensive. It can be associated with the first steam engine (Pereira & Romero, 2017). Therefore, the second Revolution came with Mass Production (MP), which means the same product produces in huge amount. As a result, the price dropped as the variety of the production. The most famous example is the Ford automobile Industry (Wang et al., 2017). Chemical and electrical energy was introduced at that time (Pereira & Romero, 2017).

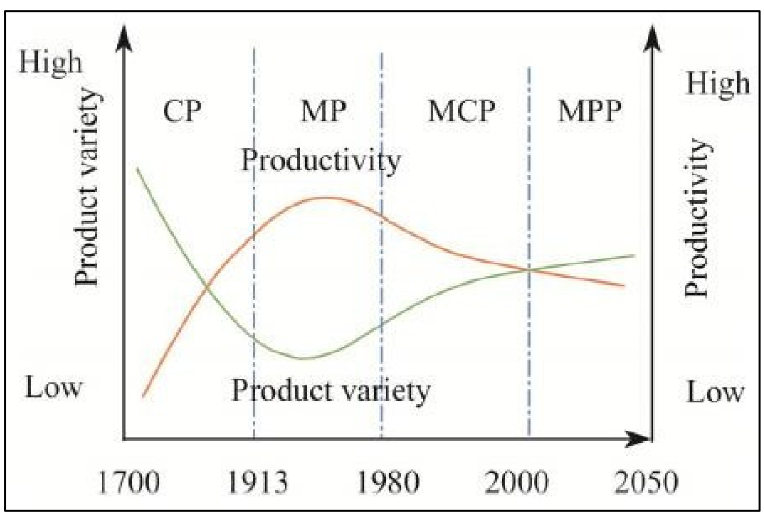

Figure 1.1 : Evolution of production paradigm
From Wang et al. (2017, p312)

With advances in technologies, production lines became more modular, autonomous. It brought the Mass Customization Production (MCP), resulting in the third revolution. Then, companies were able to add options to their product, e.g., sunroofs, heated seats, sports models for the automotive industry. Subsequently, arriving to the current era of I4.0. This era is connected to Mass Personalization Production (MPP). MPP is described more in detail in the next section.

I4.0 is the main driver to enable this MPP revolution. The first appearance of this I4.0 term can be found in an article published in 2011 by the German government (Zhou et Le Cardinal, 2019). I4.0 is characterized by a blurring of the boundaries between the physical and the digital (Wang et al., 2017). The idea is to bring them together and to develop a lot of new technologies like Cyber-Physical-System (CPS), Internet Of Services (IoS) or Smart Factories. These technologies have opened a lot of gates (Simon *et al.*, 2018 ; Weyer *et al.*, 2015). I4.0 comes to disrupt all the industry design. It changes everything, including interactors, methods, or standards (Simon et al., 2018). I4.0 is anchored in a changing need from the customers (Fathi et Ghobakhloo, 2020). Due to environmental concerns, economic pressure, and constant competition, the market needs innovative solutions. Manufacturing has changed and industries cannot only rely on "globalized and decentralized manufacturing" (Mourtzis et Doukas, 2014). The solution to answer these concerns is mainly modularity (Gupta, 2019). The market is evolving towards a paradigm more flexible, quicker, and more efficient, where the customer is involved. Products are individualized as the client can choose the major design of most of the products.

Small batches of personalized parts, where the geometry changes per part, must be produced in an economically viable manner (Hof,2018.)

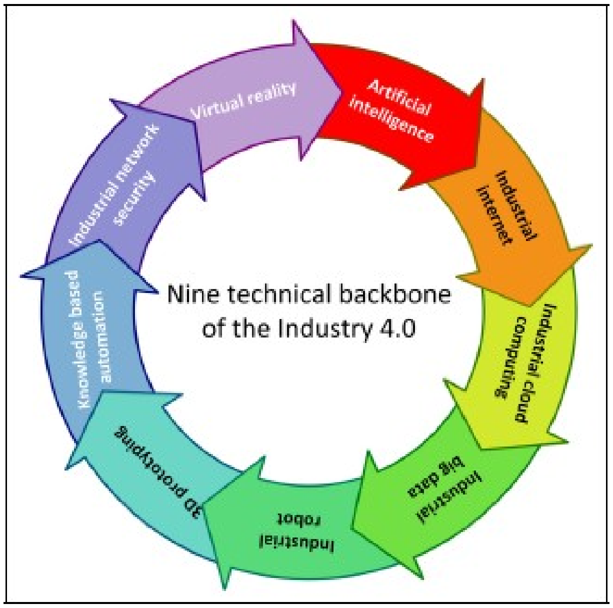

Figure 1.2 : Basic elements of the Industry 4.0 standard
From Simon et al (2018, p2)

Moreover, Figure 1.2, (Simon et al., 2018) describes the 9 main elements of Industry 4.0. These processes are more and more connected, e.g., products, elements, or humans. Hardware and software are now tight together and are interconnected in a circle. Every technical backbone has an impact on the other and is used to improve and optimize the behavior of each other backbone.

1.1.2 Mass personalization production

As discussed in Chapter 1.1, MPP is the step of production that I4.0 is bringing and that is starting to be incorporated into the market. As described in (Hof, 2018.; Mourtzis & Doukas, 2014; Pereira & Romero, 2017; Wang et al., 2017), each revolution brought a new production paradigm that has each its advantages and disadvantages.

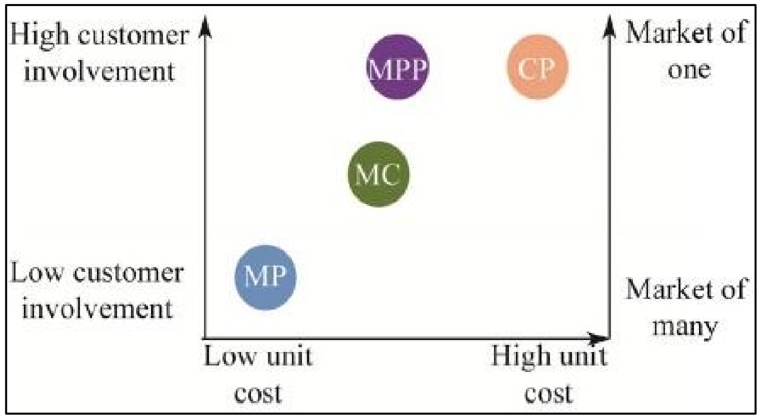

Figure 1.3 : Taxonomy of paradigm of production
From Wang et al (2017, p313)

These advantages and disadvantages are summarized In Figure 1.3 (Wang et al., 2017) and Figure 1.4 (Mourtzis & Doukas, 2014). As illustrated in those two graphs, the different types of products do not fill the same purpose. Some will be inexpensive, not very flexible, and will not require any investment from the customer, while others will be very customizable, very expensive but will mostly involve the customer.

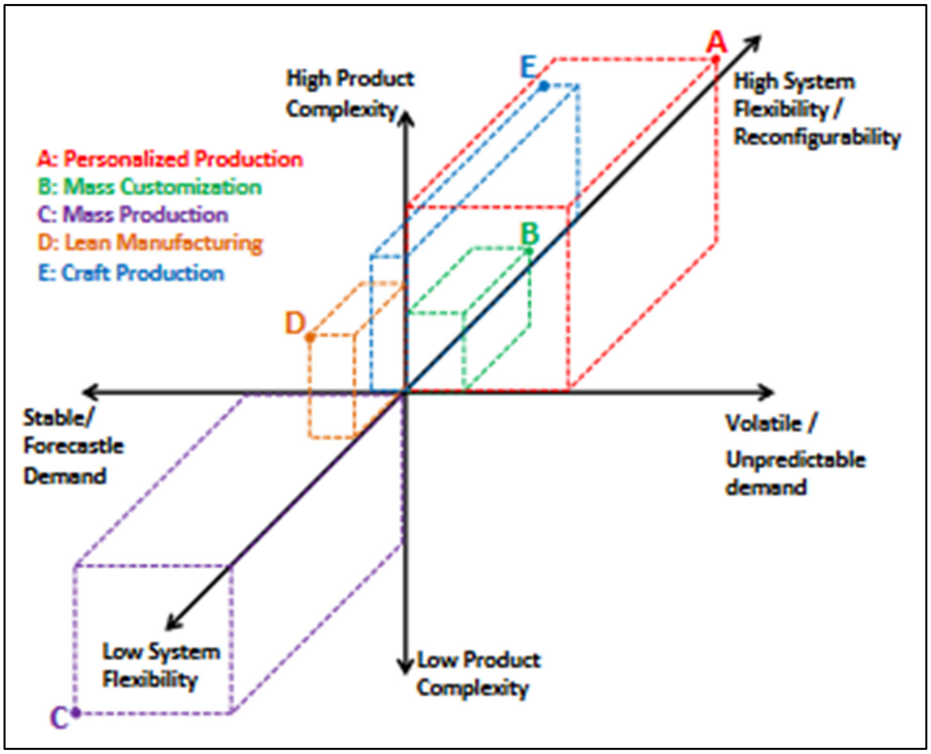

Figure 1.4 : Characterization of production paradigm
From Mourtzis & Doukas (2014, p4)

How does MPP fit into all these production paradigms? As Hu explains in his article in 2013: “The personalization of production is adapted to the individual customer’s requirements and needs” (Hu, 2013). It brings more value to the product as customers and producers are working together, producing customized products of high quality with less lead time (Wang et al., 2017). The customer feels involved and can obtain what he exactly needs for a not-so- high price.

Figure 1.3 (Wang et al., 2017) and Figure 1.4 (Mourtzis & Doukas, 2014) illustrates the characteristics of the MPP, e.g.; unpredictable demand, high system flexibility, high product complexity, medium unit cost, high customer involvement. MPP is a part of the “Market of one” (Wang et al., 2017).

Figure 1.5 (Mourtzis & Doukas, 2014) summarizes the differences between the 3 axes of production discussed, i.e., MP, MCP and MPP. The added value of Personalization compared to Customization is clearly illustrated, where personalized part takes a major place in the part repartition. Especially when talking of big and complex machinery as GT, not all the parts can be personalized, and a proper common basis is needed.

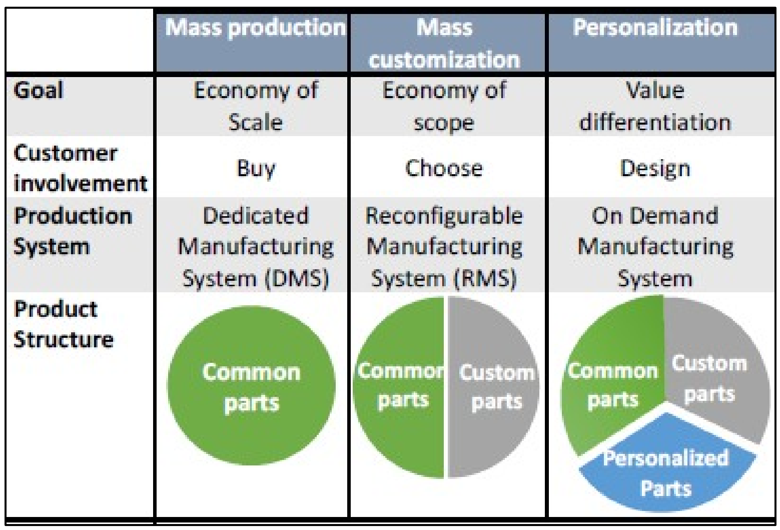

Figure 1.5 : Difference between production paradigms
From Mourtzis & Doukas (2014, p4)

In which paradigm does this research most effectively align? The goal of Siemens is to offer modular solutions that would fit innovative solutions such as external solar heated cycles, or combined Brayton/Rankine cycles. Therefore, this project is not about the customer designing exactly the turbine that he wants but Siemens designing and offering modular solutions that would fit some constraints. As a result, it is not possible to affirm this project enters MPP. However, It's neither MCP because the objective is to provide true modularity in the turbines, not just some options for the customer to choose from. The essence of the project is then a transition from MCP to MPP. Siemens is evolving towards I4.0, starting to adopt new standards and technologies. Indeed, this is only the first step in a long process of production change, therefore it's normal that the project is not 100% MPP-anchored. Nevertheless, Siemens has a long-term vision, and this project is just a gateway to the real implementation of I4.0 and MPP.

Understanding the technologies that drive Industry 4.0 is essential. Knowing their features and functionalities is crucial for their effective implementation in the design of modular GT.

1.1.3 Technologies behind Industry 4.0

Industry 4.0 and MPP couldn't be achieved without a revolution in the technology used. This revolution concerns computer science and information technology development (Pereira & Romero, 2017). As said in Chapter 1.1, innovations mostly concern CPS, IoT, and IoS. But what are they exactly?

Cyber-Physical systems are "bridges" (Wang et al., 2017) for the cyber world. They allow information, communication, and intelligence to interact with the physical world, due to sensors. (Wang et al., 2017) CPS can be defined as innovative technologies that enable the management of interconnected systems through the integration of their physical and computational environments (Pereira & Romero, 2017, p6) from (Lee, Bagheri et Kao, 2015) The main objective of CPS is to allow Smart Production (Pereira & Romero, 2017) Integration of this technology in factories allow the interconnectivity between all the supply chain and the integration of IT systems (Lee et al., 2015) By deploying RFID technology to various manufacturing objects, the real-time data of manufacturing production processes can be sensed and captured. In doing this, manufacturing data such as material consumptions, workforce situations, machine statuses, and order progress are collected and managed at a level that is accurate, complete, and real-time (Zhong *et al.*, 2013).

The Internet of Things is a CPS connected to the Internet. (Jazdi, 2014) The interconnectivity between computers has allowed the creation of smart objects and smart factories. Objects and computers can interact with their environment, collect data, and exchange data with other objects. (Borgia, 2014) They can gather and analyze production data, from instant production or the previous production. The system can then learn and anticipate manufacturing issues or changes of the production stand. Indeed, in a modular production paradigm, it is important to anticipate when it is needed to produce different pieces than the actual. Anticipating the change of tools or modules will allow gaining time of assembly.

Figure 1.5 (Wang et al., 2017) presents a Framework of an MPP system. It shows how CPS interact with each other's, and what are all the resources used in a smart Factory to make everything work.

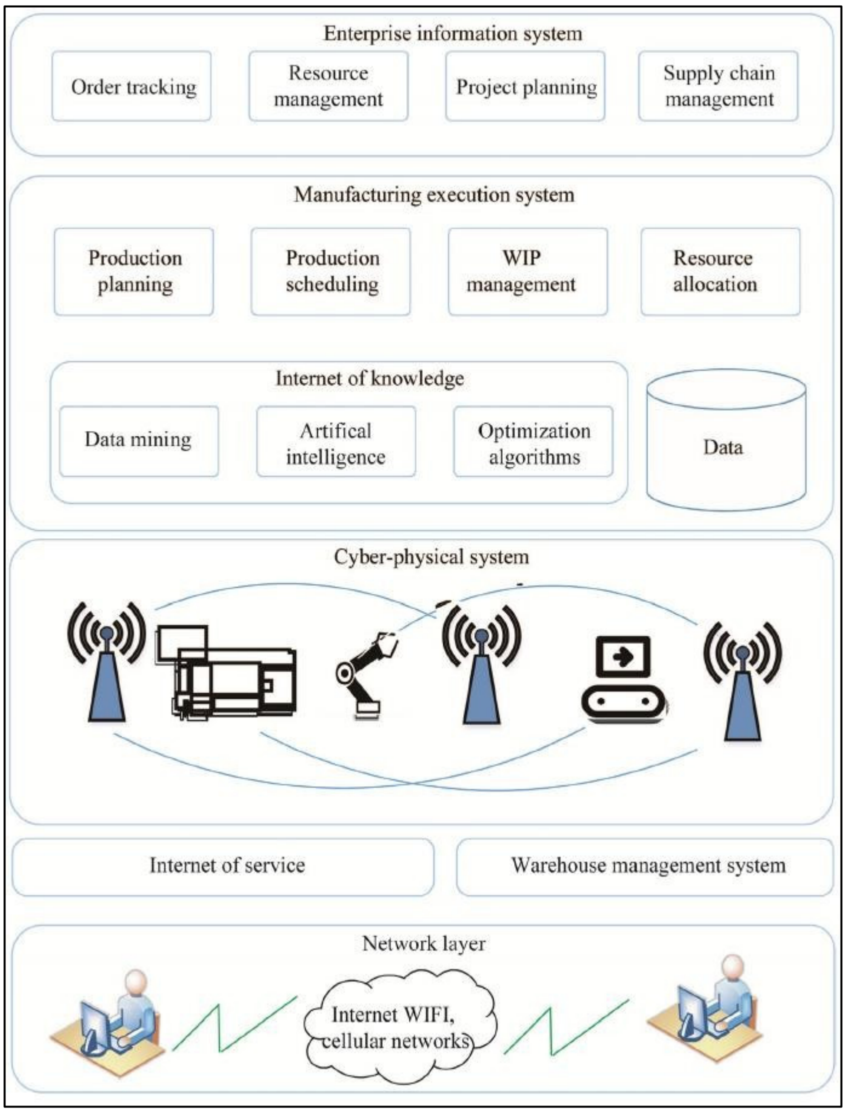

Figure 1.6 : Framework of an example MPP system
From Wang et al., (2017, p315)

Industry 4.0 has its roots in the continuity of the industry's evolution. Different needs of customers are made possible due to the emergence of new technologies. In the case of I4.0, it is the integration of IT science, the evolution of the Internet, CPS, and smart products that made this advancement possible. Different needs from customers imply a change in the production paradigm with a emphasis on MPP. It means more involvement of the customer in the design part, more flexible products.

The integration of Industry 4.0 and modularity in the industrial sector could be really pertinent for the improvement of solutions in terms of performance, cost, and ecology, or for the relation with customers. Modularity could be implemented in many sectors. This research has decided to focus on the heat engine sector for the implementation of its modular design method. Therefore, the following section will address this topic.

1.2 Heat engines generalities

Companies like Siemens need to invest in these new technologies to stay competitive, attract customers, and develop their market. This research is a part of the great transition started by Siemens with for objective Mass Personalization Production. Gas Turbine (GT) solutions have been designed and optimized for multiple decades. with its proven solutions and stability. Therefore, they seem to be an ideal candidate for the implementation of modular solutions. And more, the heat cycle structure is ideal for modularity, as components can be decompartmentalized according to their function in the process. The framework of this study will then be heat engines and gas turbines, even if the solutions proposed in this research could easily be declined to other solutions.

As discussed in the introduction, the methodology employed in this study is specifically applied to the sector of heat engines, with a particular emphasis on the concept of gas turbines. Consequently, the literature review will concentrate on pertinent studies within this domain. It is important to note, however, that given the adaptable nature of the modular concept presented, this literature review could be extended into other diverse areas of application.

This section will focus on the major heat cycles used in the heat engine sector. Mainly the Brayton cycle, as the most commonly used cycle, will be studied in depth. The chapter will also address two other traditional heat cycles, the Rankine cycle, and the combined cycle.

1.2.1 Classical gas turbine using Brayton cycle

GTs have a wide array of applications. It spans from jet engines, generators for remote areas, to the nautical industry (Sheikhbahaei, Vossughi et Alasty, 2019). Turbines are praised for their high-power unit, their adaptability to variable uses, and a long time of use without repair. (Bouam et Aissani, 2008) Moreover, they are known for their “reliability, high availability, flexibility, and their relatively lower GHG emissions” (Hachem et al., 2022, p1).
They are mostly used in a difficult environment as petroleum platforms, remotes areas where the supply of electricity is complicated, and an independent producer is appreciated (Bouam & Aissani, 2008.).

Classical GT have been studied for centuries. The first works have been dated around 1791 (Meyer, 1939), (Islas, 1998) but the theorization of the Brayton cycle happened in 1872 (Peoc’H, 2019). The first true Gas Turbine have been experimented within 1900 (Meyer, 1939). The first idea behind a GT was to replace the steam engine because is the solution was considered to be simpler and allowing the creation of a rotational movement only by injecting air in a turbine. (Meyer, 1939). Technology has evolved a lot since the 19th century, but the principle has stayed the same.

Most GTs are using a well-known thermodynamical cycle, the Brayton cycle, whose temperature-entropie (T-s) diagram is represented in figure 1.6 (Bouam & Aissani, 2008.).

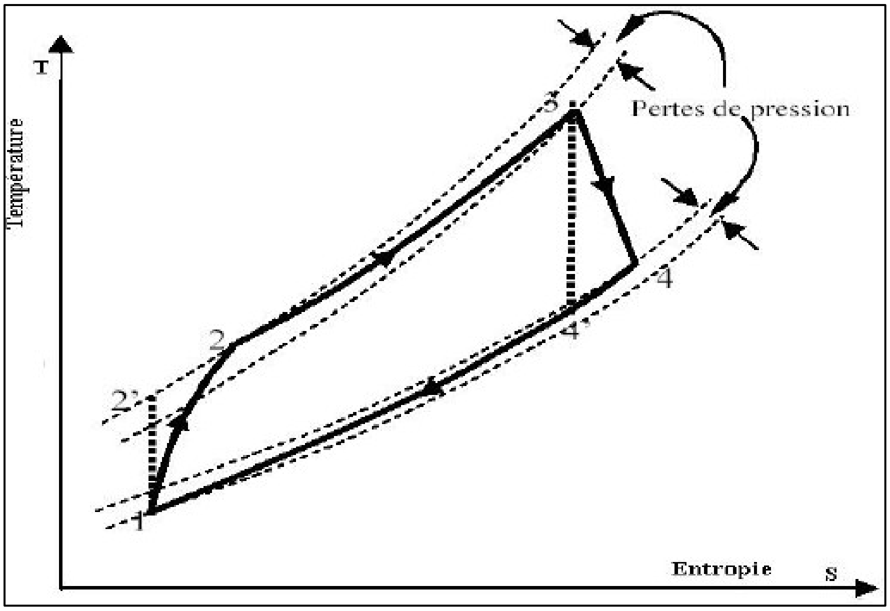

Figure 1.7 : T-s thermodynamical cycle of a simple Gas Turbine
From Bouam & Aissani (2008, p293)

The principle of the GT is pretty simple. There are three main components. A multi-Stage compressor, a multi-stage turbine, and a combustor (Islas, 1998), (Cohen & all, 1996). Air is vacuumed into the compressor that will increase the pressure of the air. Then it comes through a combustor where the air is mixed with hydrogen (in the more current use) or natural gas (as methane) and is blown up. This mixture, high-pressurized and at a high temperature, go through the turbine, creating a rotational movement that drives an axis connected to both the compressor and an alternator. This principle is summarized in figure 1.7 (Islas, 1998).

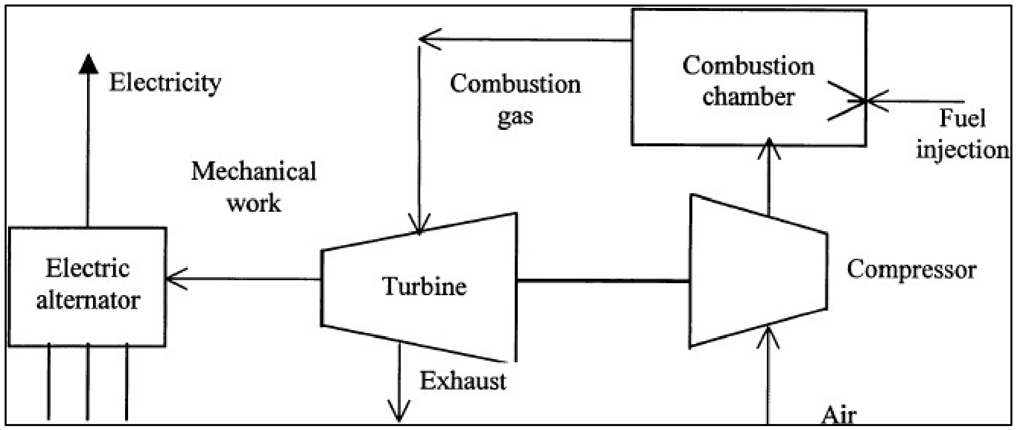

Figure 1.8 : A simple Gas Turbine
From Islas (1998, p132)

A. Bouam & al. (2008) presents equations to characterize the operation of these three parts. Most relevant for us will be the specific work of the compressor ($Wcomp$) denoted in Eq. (1.1); and of the turbine ($WTurb$) as provided by Eq. (1.2)

$$Wcomp = Cpa,2\,(T,p) \times T2 - Cpa,1\,(T,p) \times T1 \tag{1.1}$$

$$WTurb = Cpg,3\,(T,p) \times T3 - Cpg,4\,(T,p) \times T4 \tag{1.2}$$

Classical GTs can be divided into two types, with single or twin-shafts (Cohen & al, 1996). Figure 1.9 (Sheikhbahaei et al., 2019, p3) illustrates the difference between both types. Indeed, contrarily to the single-shaft gas turbines, the twin shaft possesses two turbines that aren’t connected to the same shaft. The first turbine is used to power the compressor and the second one is connected to the alternator and is then used to generate electricity (Hannett, Jee et Fardanesh, 1995).

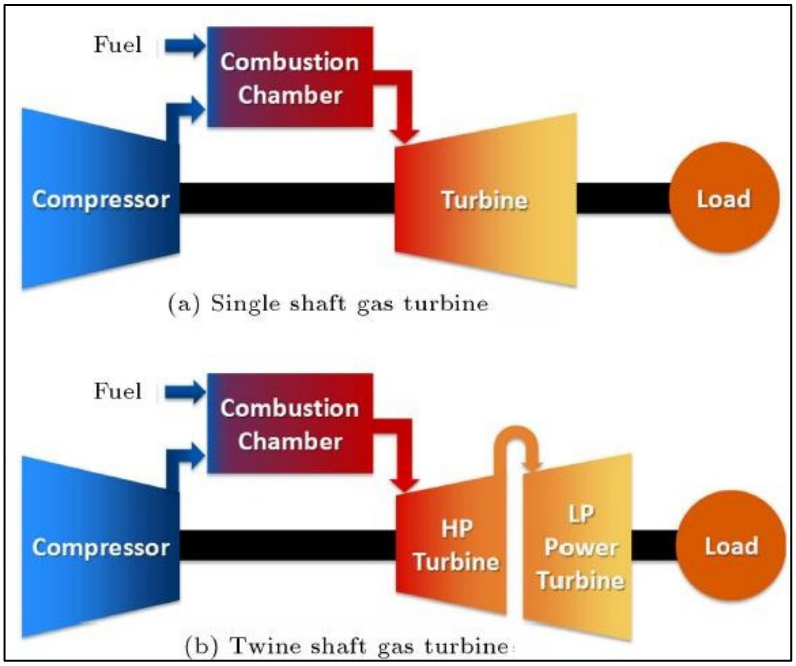

Figure 1.9 : Single-shaft and twin-shaft gas turbines
From Sheikhbahaei et al (2019, p807)

Having two shafts separated allows a desynchronization of the rotational speed of the compressor and the turbine, allowing the LP turbine to rotate at her synchronous speed and the compressor to rotate by variations in fuel input (Hannett et al., 1995). It is then very interesting for our modularity issues.

This is the functioning of a classical gas turbine. It is very important to comprehend how it works to be able to modularize it without a loss in performance. The different influencing factors need to be understood to improve the performance of the GT.

1.2.2 Influencing factors and loss reduction

To characterize modular turbines, it’s important to determine the factors that have a major impact on their performance. It would allow the anticipation and counterbalance of these factors to produce more efficient turbines.

These factors can be divided into two categories, inherent to turbines and associated with the external environment.

Three main variables govern the functioning of the gas turbine. The main variable that will consider is synthesized in table 1.1 (Siemens, 2005).

Table 1.1 : Nominal Design point specification for SGT-600
Adapted from Siemens (2005, p2)

Parameters	**Value**
Output Power (MW)	24.77
Thermal Efficiency (%)	34.2
Compressor pressure ratio	14
Exhaust gas temperature (K)	816
Exhaust mass flow rate (kg/s)	80.4
Gas generator rotational speed (rpm)	9705
Power turbine rotational speed (rpm)	7700

The three main variables that affect our system are the pressure of the air/gas, its temperature, and its volumetric flow. Fuel consumption can also be considered as a critical variable.
Figures 1.10 a) and 1.10 b) (Meyer, 1939) show a correlation between temperature, pressure, and fuel consumption. Fuel consumption decreases when higher temperature is reached, whereas it increases with the increase of pressure ratio.

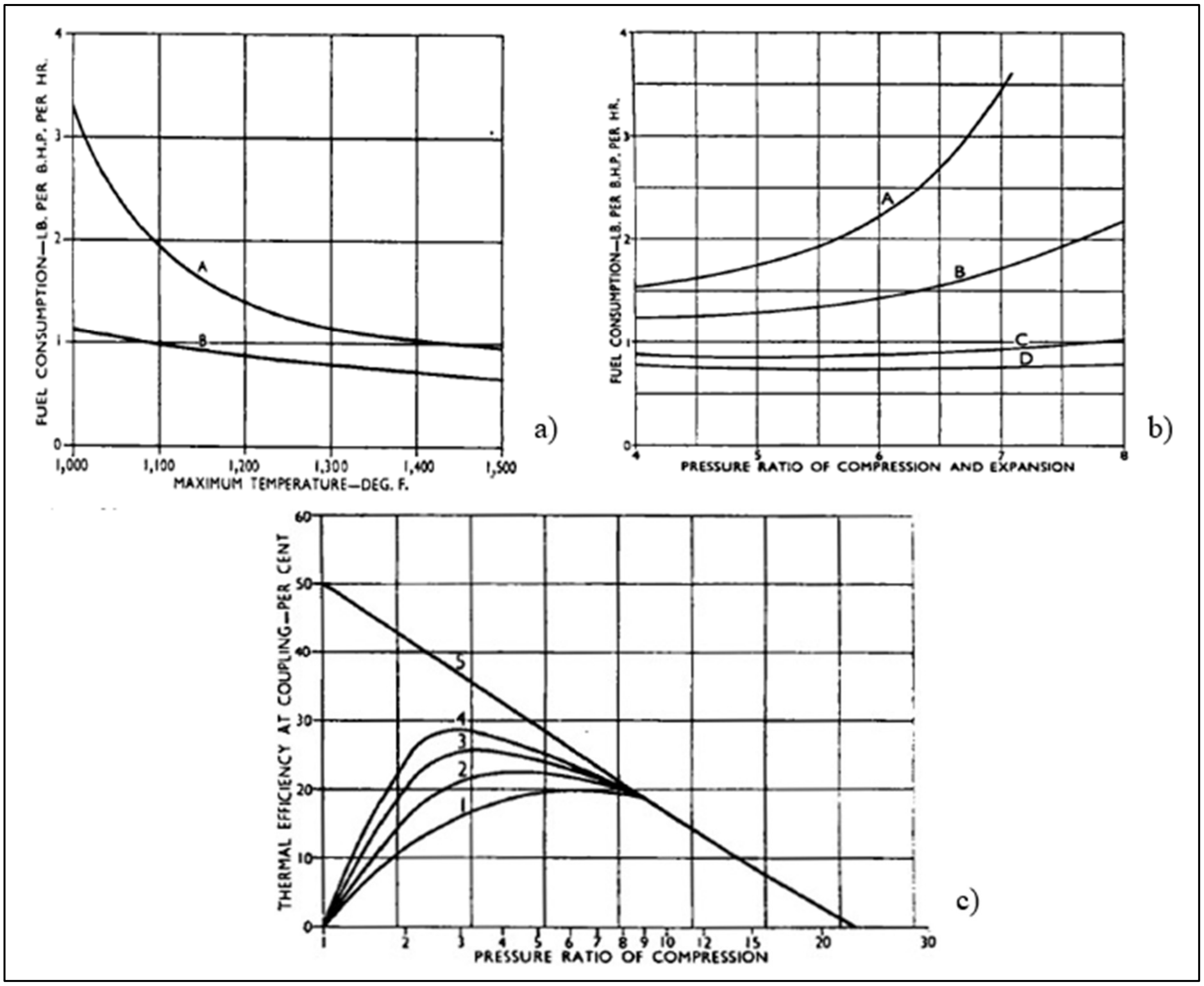

Figure 1.10 : a) Effect of maximum temperature on fuel consumption b) Variation of fuel consumption with pressure ratio c) Effect of pressure ratio on thermal efficiency
From Meyer (1939, p215-216)

Figure 1.10 c) also shows that the pressure ratio has a direct impact on thermal efficiency. It illustrates that it is possible to find an optimum thermal efficiency by using the right pressure ratio on the proper setup.

It can be easily understood that it is very important to find the optimum set of variables to have a more efficient turbine. Horlock describes this point as "the optimum pressure ratio for a CCGT plant falls between the pressure ratio for maximum (gas turbine) efficiency and that for maximum (gas turbine) specific work" (Horlock, 1995, p6). This optimum point differs for each turbine and will be needed to develop the best turbine possible. As modular turbines lose efficiency due to unregular components, finding the optimal functioning will be primordial to stay competitive.

One other main aspect to consider when discussing modular gas turbines is the gas will input. Indeed, even if Hydrogen is the favorite gas used for gas turbines, some customers components have another gas at their disposal and would like to use it. Using a different gas will inevitably impact the character of the turbine. First, the fuel/air ratio will be a lot different. The chemical reaction will not be the same either, which means that the gas coming out of the combustion chamber will not be at the same temperature or pressure. This will impact the turbine behavior, the pressure ratio, and the power output (Dicampli, 2013). Siemens Energy commonly uses gas as Ethane, Methane, Propane, Butanes, Nitrogen, or H2S in their GT (Siemens, 2021).

One major external factor is the temperature of the ambient air. Indeed, the ambient air is a requirement for a turbine to work (Bouam & Aissani, 2008). As seen in Chapter 2.1, turbines are mainly used in remote locations, where the climate can be rude. The temperature of the ambient air can go from extremely cold temperatures to very hot ones. These variations lead to very different behaviors that need to be analyzed and solved.
This question is partially answered in Bouam & Aissani's article (2008). They researched to demonstrate this influence and proposed a solution to counterbalance losses in performances. The focus can be made on Figures 1.11 to 1.13 (Bouam & Aissani, 2008) to understand how the temperature of ambient air impacts performances.
First, Figure 1.11 shows that « for the two extreme temperature values, compressor power input and turbine power output increase with rising ambient temperature, and vice versa for power output. » (Bouam & Aissani, 2008).

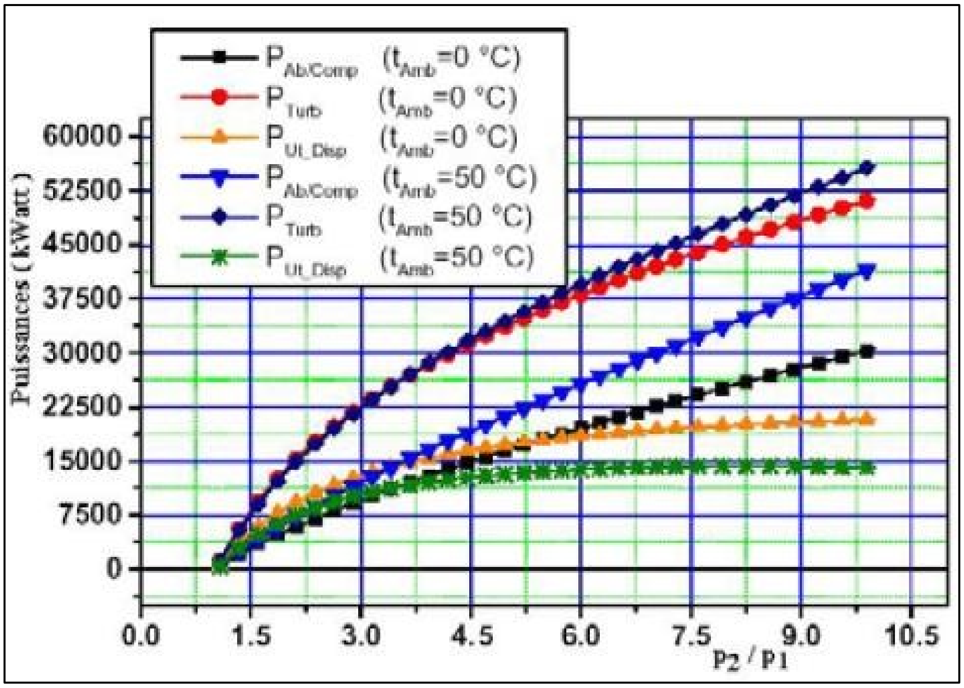

Figure 1.1 : Different power
From Bouam & Aissani (2008, p 298)

Next, we can interpret from Figure 1.12 a variation of the fuel/air ratio in function of air temperature. Indeed, the hotter the air, the more it is dilated, then the more the ratio is diminished.

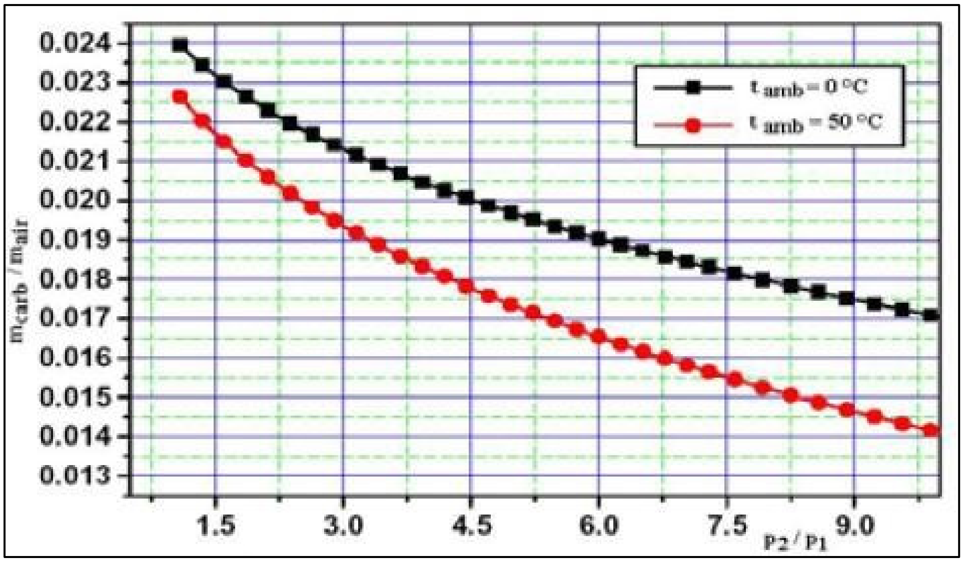

Figure 1.2 : fuel/air ratio
From Bouam & Aissani (2008, p297)

Finally, Figure 1.13 presents us with the global thermal efficiency of a turbine, and we can see that turbine are way more efficient at low temperatures. These data's needs to be considered when we'll design modular solutions to provide better turbines

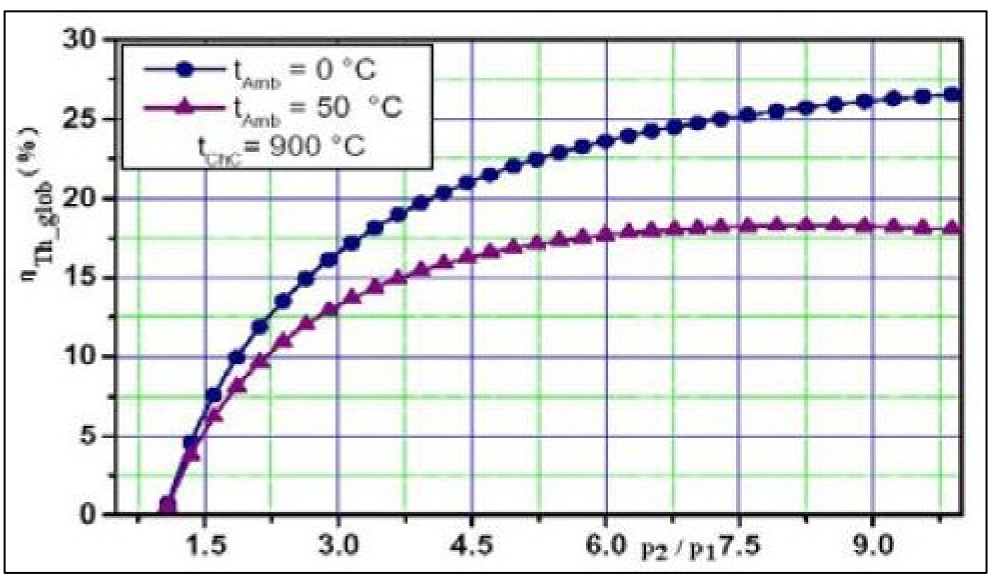

Figure 1.3 : overall thermal efficiency
From Bouam & Aissani (2008, p299)

In Annex 1, an excel sheet summarizing the variations of different variables at each step of a GT Brayton cycle can be found. This data is used in the cycle decomposition Chapter 2.4.1.

1.2.3 Other cycles: Rankine and combined cycle

When considering GT modularity, the study cannot be locked only in the classical Brayton heat cycle. Another cycle, mainly used in steam turbines, the Rankine cycle can be added to the cycles in many cases.

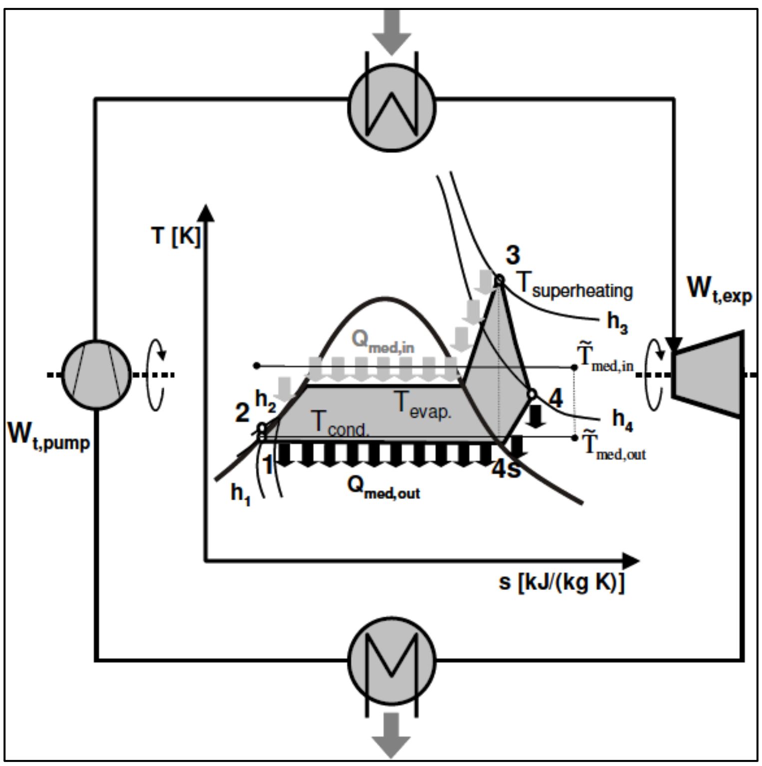

Figure 1.4 : Fundamentals of the Rankine cycle
From Ringler et al (2009, p68)

Figure 1.14 (Ringler et al., 2009) presents the T-s thermodynamical diagram of a Rankine cycle and the components of a steam turbine. The liquid (water or organic fluid) passes through a pump, that will apply an isentropic compression. Then the compressed water will go through an evaporator that will heat the water and transform it into superheated steam. This steam will drive the turbine in rotation, allowing the user to use this energy to produce electricity or to use it as pure mechanical energy. As for a GT, the turbine shaft will drive the pump. The steam will then pass through a condenser and be turned back into the water. Then the cycle starts again by passing through the pump (Ringler et al., 2009).

The main interest of Rankine cycle in the GT domain is for the use of combined cycle. Combined cycles are a mix between Brayton cycle and Rankine cycle. To reduce the thermal loose from the exhaust of the Brayton turbine, it is possible to connect this exhaust to the heater of the Rankine cycle. Therefore, the energy is transferred to the other cycle. Figure 1.15, (Ibrahim, Rahman et Abdalla, 2011) presents the schematic of a combined cycle. The composition is evidently depicted as a combination of a Brayton cycle and a Rankine cycle, interconnected through a heat exchanger.

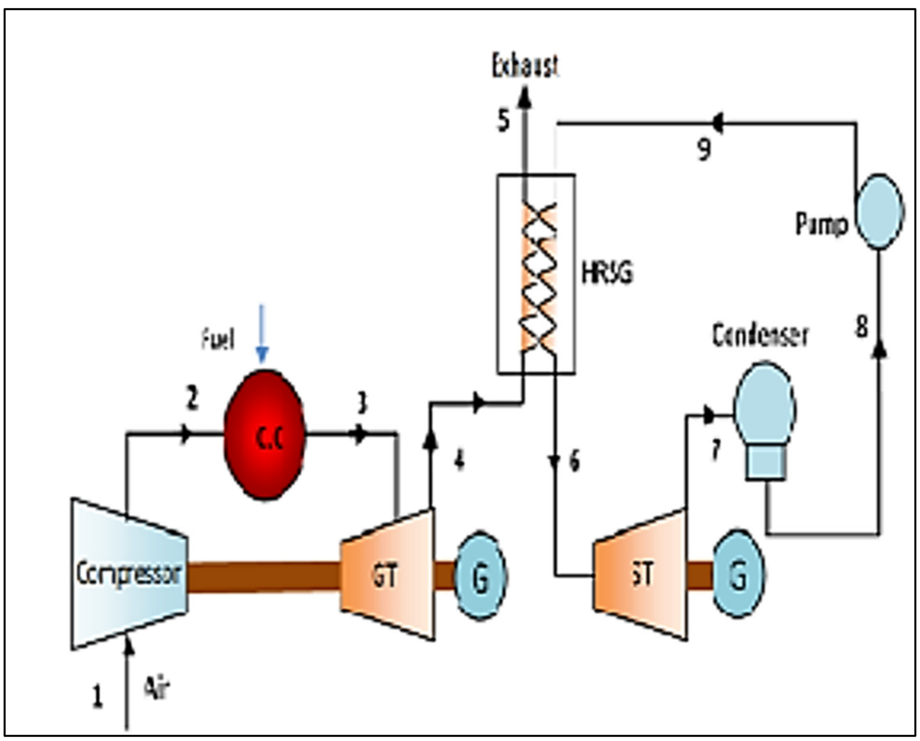

Figure 1.5 : Combined cycle schematic
From Ibrahim et al (2011, p4218)

Combined cycles are really interesting to as they reduces the cost of energy and reduces energy waste inside the Brayton cycle (Najjar et Akyurt, 1994).

1.3 The research gap

As seen in 1.1, modularity is a concept well described in the literature. Its ins and outs have been identified, so as the ways to implement it in industrial sectors. Sectors such as the automotive one has already taken a bigger step in the implementation of modularity from every perspective. Modularity in this field extend to integration of external sources (Cabigiosu, Zirpoli et Camuffo, 2013), structural optimization of the design (Liu *et al.*, 2018), and the concept of mass customization (Alford, Sackett et Nelder, 2000). Therefore, it is demonstrated that modularity has been a major interest of the automotive sector for the past decades. But what about the GT sector?

Some work has already been done on the integration of modularity into the gas turbine sector, but clearly not as much as others. It is possible to find some articles explaining a part of this implementation, but there is not yet a global perspective on what are all the possibilities available. In particular, some articles try to implement external components as by adding external components as a solar heater (Poživil *et al.*, 2015) original fluid medium as Helium (Liu et He, 2020) or by adding solid fuel cells and oxidizer (Mueller *et al.*, 2010). Others have tried to implement tools to simplify the design (Cao *et al.*, 2005) or the optimization (Camporeale, Fortunato et Mastrovito, 2006).

However, even if research begins to be interested in modularity in the gas turbine sector, there is still few articles, and they are in globality more recent than for the automotive sector. No article tends to a full modularity implementation, incorporating multiple external components, complete modular design, simulation and optimization tools, and customer involvement. One article tries to answer these questions, by researching a modular design and optimization for a gas turbine. They used a helium reactor to make the gas turbine uncommon. However, they only focus on one type of gas turbine, and do not expand to the integration of their system on any kind of cycle.

Therefore, a gap in this research field is clearly identified. This work will then try to fill this gap by creating a modular design system, which will englobe all the major points of I4.0 and modularity discussed previously.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

This chapter will describe the objectives of the project, and how these objectives led to the solution designed in this research.

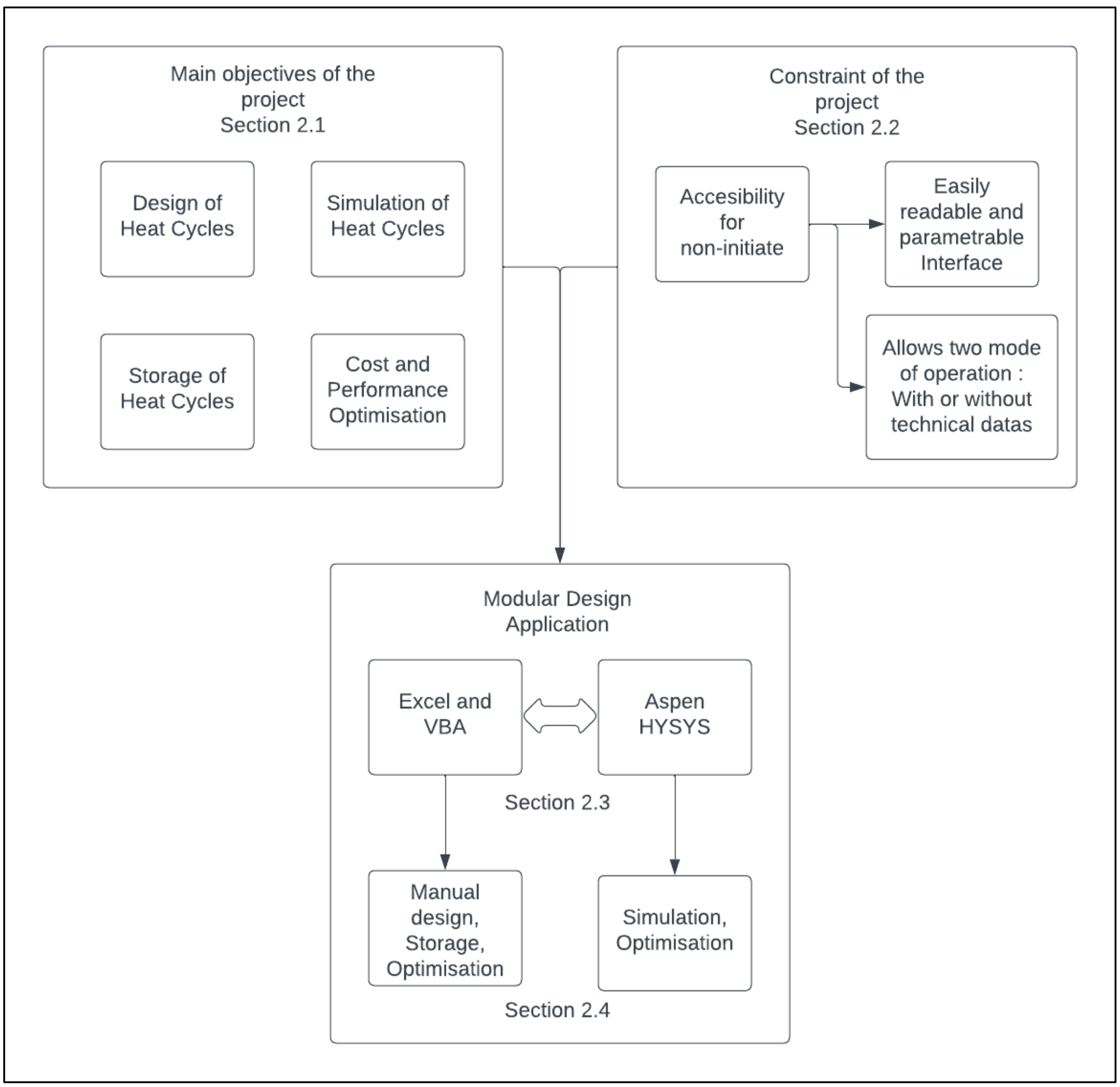

Figure 2.1 : Decomposition of the methodology described in Chapter 2

Figure 2.1 presents the content of each section of this chapter. Three (3) main topics will be addressed in this chapter. Section 2.1 discuss the main objectives of this research, and what must be done to bring modularity to heat engines design. Section 2.2 addresses some limitations that the aimed modular design application (MDA) must respect to be more accessible and supports the I4.0 paradigm. From these objectives and constraint, section 2.3 explains what software have been choose for the creation of the MDA and what are their main advantages. Finally, section 2.4 presents how the different software have been used to respect the objectives and constraint.

2.1 Main objectives

The primary objective of this research englobes the design, simulation, and optimization of gas turbine cycles, concurrently assessing their efficiency and cost implications. The goal is to furnish GT engineers and designers with a user-friendly and robust modular design application (MDA). This tool is intended to facilitate the exploration of an extensive array of cycle configurations, enabling a comprehensive analysis of their performance characteristics and the identification of economically viable solutions. In order to fulfill these objectives, the application must address several key objectives:

- Designing Gas Turbine Cycles: The MDA must enable users to create custom gas turbine cycles by selecting various components and setting different inlet temperatures. It offers a comprehensive library of components, including compressors, combustion chambers, turbines, and heat exchangers, allowing engineers to assemble unique cycle configurations that align with specific project requirements. By providing a versatile and modular approach to cycle design, the MDA empowers users to tailor gas turbine systems for optimal performance and efficiency.

- Simulating Cycle Efficiency: The MDA incorporates advanced simulation algorithms to predict the thermodynamic behavior of gas turbine cycles under various operating conditions. It calculates key performance indicators, such as cycle efficiency, power output, and specific fuel consumption, providing valuable insights into the cycle's behavior. Users can analyze the effects of different component choices, inlet temperatures, and other parameters on the overall performance, aiding in the iterative refinement of gas turbine designs.

- Optimizing for Efficiency and Cost: Leveraging optimization techniques, the application aims to find the most efficient and cost-effective gas turbine cycles. By considering a multitude of design variables and constraints, it searches for the optimal combination of components and operating conditions that maximize cycle efficiency while minimizing operational costs. This optimization process ensures that gas turbine designs not only meet performance targets but also achieve cost competitiveness in real-world applications.

- Building a Database of Cycles: The MDA also facilitates the creation of a comprehensive database of pre-designed gas turbine cycles. This database acts as a repository of well-characterized cycle configurations, enabling users to quickly compare different cycles and select the most suitable solution for specific customer requirements. The database's modular structure ensures easy updates and additions, making it a valuable resource for both designers and customers seeking reliable and readily available gas turbine cycle options.

By accomplishing these objectives, the MDA seeks to revolutionize the gas turbine design and optimization process, providing engineers with a powerful tool to create cutting-edge and cost-efficient gas turbine cycles that align with the demands of the modern energy industry. Through its modular approach and data-driven optimization, the application aims to support the gas turbine sector in achieving sustainable and competitive solutions for power generation and industrial applications.

2.2 Constraints of the MDA

Objectives have been defined in the last section. What the MDA is supposed to do is now clear. However, in order to respect the main principles of I4.0, e.g., the ease of customer-engineer relationship or the accesibility of solutions to gain the more time possible in the process, it is vital to set up some limitations and constraint.

First, as the MDA aims to ease the interaction between customer and engineer, it is needed to define what part of the application will be used by which type of user.

Therefore, in its globality, the MDA must be accessible, in terms of parameter used and knowledge, by non-initiates. Which means, it needs an interface where non-technical and important data are printed. In the context of Cost Optimized Gas Turbine, the major data's will be cost of the turbine, the type of turbine (that will define Size and Components) and the fuel used. Information like Ratio of Compression (PR), Flaming Temperature (FT) or Efficiency are not relevant for the customer or the commercial.

The objective is also to build a heat-cycle designer in the MDA, that will increment a database. Then, the MDA needs to push deeper for engineer that will need to design these cycles. Therefore, at another level than previously, the MDA must be axed on more technical terms, with a precision on parameters, calculation methods and possibilities, to allow an engineer to design at best.

Another constraint will be the accesibility of the interface. Interface must be simple and clearly identify the different options available. Whether it's for Customer interaction of Engineer's, key parameters must be well identified. Userforms must be incorporated to fix the design process line and ease the comprehension of the application. Results must be displayed in its own sheet, with well identified key parameters.

2.3 Software choice

Considering all objectives and constraint, multiple software are needed. Mainly, a heat cycle simulation software is required, which can be connected to another software, managing GT design, results extraction, and cycle storage.

The first software considered was Excel. Excel is a very performant and stable software, available on most computers. It's configuration in sheets is well-adapted for the separation between design and results. It is also very practical to create a template used for each heat cycle. Therefore, it becomes very easy to create heat cycles and understand them. Most of all, with the help of Visual Basics for Application (VBA), the automation of the process can be done, with the use of userforms to guide the user. Heat cycles can also be stored in hidden sheets. Finally, VBA is perfect for the interconnection with simulation softwares. Excel seems to be the perfect software for the application aimed in this project. Therefore, the best simulation software must be found. A comparison between some software have been made to find the most fitted one.

Table 2.1 : Comparison of different simulation software

Software	Cost	Performance	Connection to Other Software	Documentation
Aspen Hysys	2000$/year	+++	++	+++
EMSO	Free	+	-	- -
GasTurb	200£/year	++	+	+

The software choose for the simulation is Aspen Hysys, even if it's price if higher than other solutions, its accessibility, documentation, and interconnection make it the best software for this research. The connection with Excel is detailed and can even be parameterized inside of the software. (Not used for this research). A lot of documentation is available, and many forums talks about issues they had. Contrarily to EMSO, it is not open source, and has a real customer service. Therefore, the service is more trustable from an industrial perspective. Aspen HYSYS also includes a component creation module. Therefore, this opens many doors for the creation of multiple original heat cycles. GasTurb provides some similar characteristics as HYSYS, with predefine Cycles or implemented design, but seems to be less connectable to other software.

2.4 Basics of the application

In this section the basic interface and globality of the modular GT design application will be presented. An overview of the different interfaces accessible to the user and how the results are printed will be presented.

2.4.1 Input and display of parameter

As presented in the objectives, the MDA needs to do 2 distinct actions. First, it needs to help the user to design various heat cycles with multiple components. The creation must be done in an Excel sheet, to ease the comprehension of cycles, the storage and accesibility of said cycle. To achieve this objective, the easiest solution in Excel is to use Userforms. Userforms are interactive windows where the user is guided through a process. This way, with proper VBA security, the user can’t do any mistakes and the cycle will be created properly. Figure 2.2 presents the userform used for the choice of components used in the cycle. It is composed of multiple cases that appear and disappear in function of the component chose. The user has to parameter each component, its name, the cycle where it is involved, its connected input, output, and energy streams. The userform is parametrized as presented in Chapter 4 and Annex III.

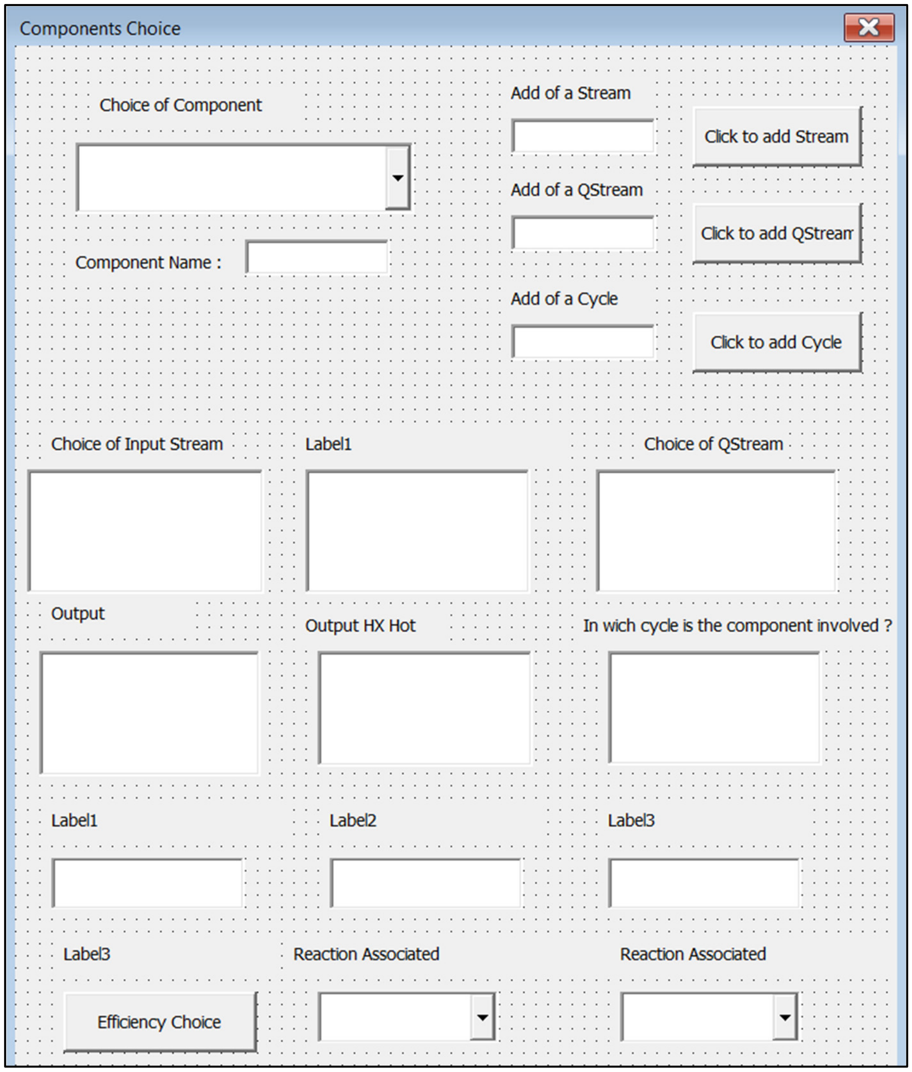

Figure 2.2 : Userform for Component Choice

Once the cycle has been parametrized with userforms, data is formatted in an Excel sheet using a specific template. This template, represented with the Brayton Cycle in Figure 2.2, synthesize all the data required for simulation, from the cycle itself to the gases involved in the process and the various customer variables such as power requirements, ambient conditions, and maximum cost, among other. Data is separated in different tables to facilitate readability.

Brayton Cycle

Bouton 1

Components and cycle definition

Table				
	TypeComp	Compressor	Combustion Chamber	Gas Turbine
	NomComp	Comp	CC	Turb
	Feed	Feed	Comp	CC
	Feed2	0	Methane	0
	Product1	Comp	CC	Turb
	Product2	0	0	0
	EnergyStream	QComp	0	QTurb
	Reaction	0	Reaction 1	0
	PR	10,27	0	0,112
	DP1 (%) / Split 1 (%)	0	4	0
	DP2 (%) / Split 2 (%)	0	0	0
	DT (K)	0	0	0
	T out (K)	0	1300	0
	Isentropic Efficiency (%)	85	0	88
	Rotating Speed (RPM)	15749	0	6000
	Cycle involved	Brayton1	Brayton1	Brayton1

Gas Turbine Parameters

Succesive Run	
Power of the Gas Turbine (kW)	25000
Maximum Temp of the GT (K)	1400
Ambient Temperature (K)	280
Ambient Pressure (kPa)	101
Type Of GT	Brayton
Mode Of resolution	Design One Cycle

Fixed Feed
Fixed Power

Parameter Fixed	Fixed Power	**Interest Rate (%)**	15
Cost of Electricity ($/kW)	0,067	**Number Of Annuities**	10
Maximum Budget ($)	2500000	**Maintenance Factor**	1,1
Operating Hours Per Year	8000	**Years to Rentabilise**	10

a)

Cycles Involved

Cycles Involved	Type Of Cycle	Pilot Stream
Brayton1	Brayton	Feed

Major Components of Cycles

Wich Cycle	Name of Comp	Type of Comp
Brayton1	Comp	Compressor
Brayton1	Turb	Gas Turbine
Brayton1	CC	Combustion Chamber

b)

Figure 2.3 : a) and b) Excel Heat Cycle Template for GT design

For each cycle created in the application, an Excel sheet is created. These sheets can be accessed by the user, or they can be hidden once validation has been completed. in this way, they join the other cycles, and can be used for the second use of the software.

The second objective of the application is, for given conditions (customer requirements), to simulate chosen cycles, optimize them and to find the cost associated to each cycle. Therefore, it is possible to find the best cycle for the customer need.

For this objective, userforms are also used to parametrize the global parameter like the power wanted, Ambient conditions, financial parameters, the gas used for combustion, the chemical reaction associated and the different cycles to run and compare. Figure 2.3 is the excel sheet where this data is printed. From there, the application is ready to run. It will run each cycle selected and print the results.

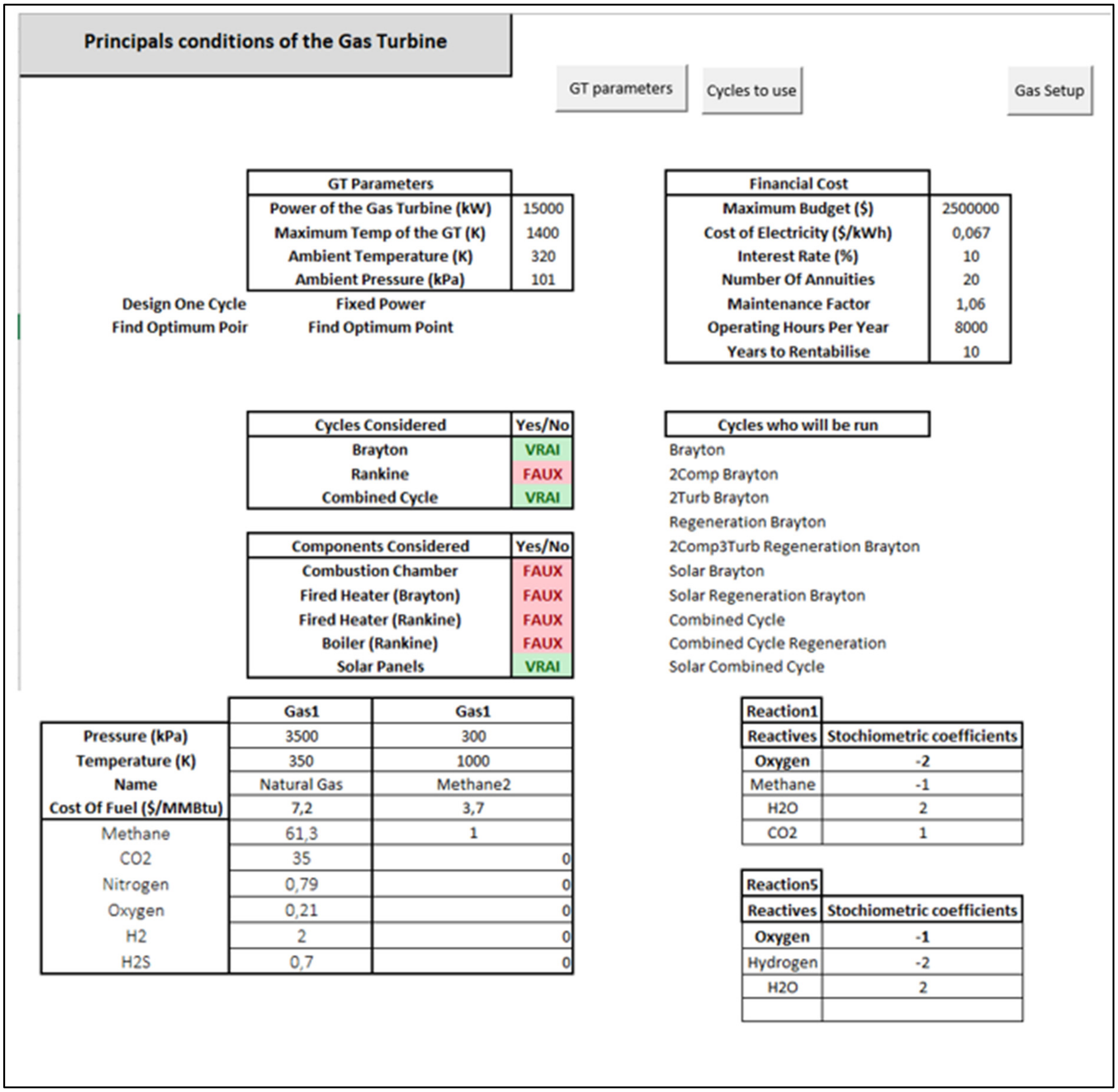

Figure 2.4 : Interface of the Gas Turbine Global Parameter

2.4.2 Simulation and display of results

The MDA has two modes of simulation for a given cycle. It can either simulate the cycle for one pressure ratio, giving the results for one cycle, or for a range of pressure ratio, which will give the optimum point of functioning.

The results for one pressure ratio, Figure 2.5, allows to the major parameters for each component at stake. Therefore, the user can make sure each component works properly and does not have a weird behavior.

N° Results	Name of the cycle	Type of cycle	Name of the component	Type of Component	Power (kW)	Isentropic Efficiency
Results18	Brayton1	Brayton	Comp	Compressor	-7665,746742	85
Results18	Brayton1	Brayton	CC	Combustion Chamber	0	0
Results18	Brayton1	Brayton	Turb	Gas Turbine	13665,73161	88
					5999,984865	
Name of cycle	**Type of Cycle**	**Power Produced by Cycle (kW)**	**Efficiency of the cycle**	**Pressure Ratio**	**Piloting Feed Name**	**Feed Mass Flow (kg/s)**
Brayton1	Brayton	5999,984865	0,268348023	10,27	Feed	23,05779864

Pressure Ratio	Flaming Temperature (K)	Fuel Mass Flow (kg/s)	Number of Stages	Tip Speed (m/s)	Rotating Speed (RPM)	Mean Diameter (m)	Cost ($)
10,27	0	0	5	898,5128001	15749	0,331848978	9218176,27
0	1106,938938	3,178183206	0	0	0	0	357335,741
0,112	0	0	5	326,0385791	6000	0,039540684	4110251,07
							13685763,1
Fuel Mass Flow (kg/s)	**Cost ($)**						
3,178183206	13685763,09						

Figure 2.5: Results obtained for one pressure ratio

The results obtained for a multiple PR run is summarized in Figure 2.6. In this mode, only the results for the globality of the cycle is displayed. The most important variables are printed, as Power generated, pressure ratio, flaming temperature, fuel cost, equipment cost. From the results from each cycle, Excel will find the optimum point of functioning of the cycle in these conditions.

Pressure Ratio	Efficiency	Power (kW)	Fuel Cost ($/kWh)	PEC+OM Cost ($/year)	PEC+OM Cost ($/kWh)	Total Cost ($/kWh)
3	0,344304845	197580,0138	0,094314599	818672,0564	0,000517937	0,094832536
10	0,434877762	207714,0896	0,049800949	1500620,998	0,000903057	0,050704006
17	0,450232817	205020,6259	0,046111382	2238177,793	0,001364605	0,047475987
24	0,447922501	201123,7496	0,046631179	3030504,025	0,001883482	0,048514661
31	0,436030302	196949,5294	0,049503639	3866579,725	0,002454042	0,051957681

MaxPR	MaxEFF	CostOpti
16	0,449927432	0,044347934

Figure 2.6 : Results obtained for multiple pressure ratio

For the first part of the application, “design one cycle”, both simulation mode are available. Therefore, the user can validate the functioning of its cycle and that everything has been parameterized properly.

For the second part, "Find the optimum cycle", only the second mode is used. Indeed, cycles in the storage are considered valid and does not need to be checked again. The user needs the optimum cycle with the optimum pressure ratio. Finding this point ensures that the cycle is the cheapest possible for the amount of power generated. Once the best cycle has been selected, the user can rerun this one cycle for the same conditions with the optimum pressure ratio using the first resolution mode. Therefore, it will be able to access each component parameters.

For the first mode of the MDA, "Design One Cycle" (1), the runtime of the simulation is relatively fast. This runtime can take from 10s to 20s in function of the size of the cycle.
The second mode of the MDA, "Find Optimum Point" (2) takes more time, as there are more cycles and more points to calculate. A calculation of 5 pressure ratio (PR) points for one cycle can take from 50 seconds to 1 minute and 40 seconds. Therefore, a calculation for 19 cycles can take more than 15 minutes.

The basis of the MDA has been presented. The algorithm behind the simulation and calculation will be described more deeply in Chapter 2.

The next chapter will present the article submitted to the *Journal of Engineering for Gas Turbine and power*. It includes a small literature review, a more precise presentation of the functioning of the application. A validation of the results with comparison to literature results, and finally a study case, that presents the utility of the application in a concrete case.

CHAPTER 3

A MODULAR DESIGN APPLICATION FOR THE IMPLEMENTATION OF MODULARITY IN THE GAS TURBINE SECTOR

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3.1 Abstract

Production changes enabled by Industry 4.0 (I4.0) allows industries to respond to customer needs in a much more precise and agile manner. It also permits companies to focus on the development of sustainable and more efficient solutions. In this context, the energy sector needs evolution and the implementation of I4.0 and modularity could help solve such issues. This research study contributes to address the research gap on I4.0 implementation in the Gas Turbine (GT) sector by developing a design application for modular GT configuration. The main objective of the developed modular design application (MDA) is to facilitate the relationship between customer and engineer, by providing an accessible application (program), including pre-designed heat cycles, that proposes optimized modular GT solutions, according to customer requirements, using simulation. Indeed, this study presents the functioning of the novel application, the different deployed variables, and the decision variable, e.g., the costs of generated energy. Simulations and comparisons using reported GT cycles in literature have been performed to validate the accuracy of the simulation processes. Finally, a study case is presented, placing the MDA in an industrial context to illustrate its benefits, and offered solutions for GT modularity. It was concluded that the developed MDA correctly simulates GT cycles and enables a first step towards modular GT design and its architecture allows for continuous improvement and expansion of, e.g., the addition of GT related components, heat cycles, or the integration of different entry variables.

Key words

Modularity; Gas Turbines; Optimization; Simulation; Industry 4.0; Heat cycles

3.2 Introduction

In today's rapidly evolving industrial landscape, driven by the advent of Industry 4.0 (I4.0), companies face the challenge of meeting increasingly personalized customer requirements while remaining competitive and considering new challenges such as global warming and ethical production (Lei *et al.*, 2023 ; Khan *et al.*, 2021). I4.0 is characterized by a blurring of the boundaries between physical products and/or systems and their digital representations and environment (Wang et al., 2017). It represents the convergence of digital technologies, automation, and data-driven decision-making. I4.0 emphasizes the integration of cyber-physical systems, the Internet of Things (IoT), big data analytics, and artificial intelligence to enable smarter and more efficient industrial processes (Simon *et al.*, 2018 ; Weyer *et al.*, 2015), and driving novel approaches for intelligent sustainable manufacturing methods (Delpla, Kenné et Hof, 2022).

Product modularity, existing before the introduction of I4.0, is among the fundamental principles of I4.0 manufacturing systems as I4.0 technologies allow for an effective adoption of modular product manufacturing (Gupta, 2019). Modularity allows more flexible, quicker, and more efficient solutions, where the customer is involved in product design. Here, products are more individualized as the client can choose the major design of most of the product components. The concept of modularity involves breaking down complex systems into modular components that can be easily interchanged, upgraded, and reconfigured. This modular approach enables businesses to respond quickly and effectively to changing customer demands, market trends, and technological advancements (Hof, 2018) and is promising to achieve more sustainable manufacturing (Sonego, Echeveste et Galvan Debarba, 2018 ; Ghimouz, Kenné et Hof, 2023).

In extreme cases, by pushing modularity to its limits, Mass Personalization Production (MPP) can be achieved (Mourtzis et Doukas, 2014). Such a MPP paradigm implies a high customer involvement, medium unit costs and aims at a market of one (i.e. unique client) (Wang et al., 2017). PP addresses best most of the customer's requirements (Hu, 2013), while avoiding wasted parts or over-specified products.

Implementing I4.0 and its related technologies is starting in some industries, such as the automotive industry (Liu *et al.*, 2018 ; Cabigiosu, Zirpoli et Camuffo, 2013). Indeed, the automotive industry finds itself withing the mass production paradigm, including many parts that can be modified without altering the integrity or performance of the product. However, in most industries, in particular small and medium-sized enterprises (Mohamed, 2018) such I4.0 implementation is more challenging (Nimawat et Das Gidwani, 2022). In some industrial sectors, e.g., energy production, there are few margins for product modifications. Here, components are purely functional, and not concerned with aesthetics, i.e., their design is optimized for optimal operation only. Combined with low production volumes and demanding customers, I4.0 implementation is a significant challenge for the energy supply equipment sector (Schröder, 2016). Therefore, research on novel approaches is needed to address this challenge. Moreover, it is vital to contribute to change key sectors such as energy production. In the current situation of global climate change, the energy sector is among the most crucial industrial sectors for accelerating change (Bhagwan et Evans, 2023).

In fact, climate change is undeniable the biggest challenge the world is currently facing, affecting human sustainability on earth (Intergovernmental Panel On Climate Change (Ipcc), 2023 ; International Atomic Energy Agency, 2019). Global net anthropogenic (GHG) emissions, including a 75% share from CO2 (Intergovernmental Panel On Climate Change (Ipcc), 2023), are its main driver (Intergovernmental Panel On Climate Change, 2023). Together with an ever-increasing demand for energy (International Atomic Energy Agency, 2019 ; Anon, 2021) and knowing that the energy sector represents 73.2% of the total global

GHG emissions (Climate Watch, the World resources Institute, 2020) , action and innovation on sustainability and reducing its carbon footprint are needed in this sector.

In addition, pollution of affiliate sectors needs to be addressed as soon as possible. These include coal-, gas- and oil-fired power plants. The integration of I4.0 could lead to a significant reduction in carbon emissions, by improving the performance of these power plants (Javaid et al., 2022). To begin with this implementation, smaller sub-sectors could be considered, sectors with on-site production. A well-suited sector for a preliminary modular implementation case study in the field of energy production could be the Gas Turbine (GT) sector. Undeniably, GTs must respond to the new customized manufacturing paradigm challenges, as customers want GTs more optimized to their business' individual requirements, adapted to their needs, and responding to climate changes and decarbonization measures. Moreover, the reuse of old components in a new GT system could be of interest to improve the life cycle of components.

GTs are constituted of many complex components (Wood, 1982) but their functioning principle is well-known and can be adapted for a wide range of applications and needs. Indeed, two main heat cycle types are commonly used; (1) the Brayton cycle, which is composed of four operations (Islas, 1998), and (2) the Rankine cycle (Yamamoto et al., 2001).

For the Brayton cycle (1), in a first step, the working fluid, a single phase-gas, is compressed at a certain Pressure Ratio (PR). This medium is then heated to a Flaming Temperature (FT) in a second step, where the. FT is defined by the maximum temperature reached inside the GT. The heating process can be realized in multiple ways, e.g., by combustion with a fuel like methane or hydrogen, or by heat exchange utilizing solar heated water or an external burner. Then, in a third step, the fluid medium is expanded in a turbine, which will produce electricity and subsequently power the compressor. Finally, as most of Brayton cycles are open process cycles, the air is released in the nature (Wood, 1982). Typically, Brayton cycle-based processes are flexible, and their modeling can be done in different ways, such as addition of many compressors or turbines, and heat exchangers to reduce the fuel consumption or via the addition of external components, e.g., solar panels, external heaters, oxidizers. The output fluid can be reinjected into a heat exchanger located just before the thermal addition to reduce the heat loss, hence increasing the cycle thermal efficiency (TE), resulting in regenerative cycles.

The Rankine cycle (2) is based on a phase change, from liquid to steam. The working fluid, e.g., water or organic fluid, is compressed with a pump, then externally heated to change its phase, followed by reaching a maximum temperature. In a next step, it enters a turbine to produces energy. Contrary to the Brayton cycle, the Rankine cycle is commonly a closed process cycle. Therefore, the working fluid must pass through a condenser to return to the liquid phase and to its initial temperature and pressure (Park et al., 2018).

Combined cycles constituted by the combination of Brayton and Rankine cycles are also commonly used cycles(Ibrahim, Rahman et Abdalla, 2011). Here, the exhaust excess heat from the Brayton cycle is reinjected into the Rankine heater, allowing a reduction of energy waste. However, these cycles have the disadvantage of having a rather large footprint, hence requiring more space at a given location.

GTs, and more generally heat cycles, are by their nature solutions where modularity has a promising potential as components are independent and performance can be optimal for multiple configurations. However, the GT sector is not in need of mass production since its customers are limited to a small range of customers, each having specific requirements that impacts the functioning of the product. Hence, implementing modularity without drastically increasing the cost of functioning is a significant challenge and needs to be further investigated by academic and industrial research. Therefore, when adding modularity to GT design, the cost optimization is among the most important parameters to consider (Aji et al., 2018).

Indeed, GT Customers can be located at many different places, where the ambient situations, environments, can greatly affect its performances (Bouam et Aissani, 2008). The available space, technologies, and resources, and the required power are just a few of the many variables that makes a GT client's request unique. Thus, integrating modularity into the GT design process has strong potential to meet a customer's requirement and so reduces the cost for each unique solution (Guo et Gershenson, 2007). Nevertheless, including modularity into GT design introduces some issues on the GT performances. Indeed, as these specifically designed GT solutions have been matured over many years, decomposing an optimized system into modularizable components will inevitably result in GT performance losses. As such, a novel modular design system will be needed to optimize the components' assembly to compensate for these losses.

Modularity, as a concept, has been developed in some specific industrial sectors , e.g., automotive (Bouam et Aissani, 2008 ; Guo et Gershenson, 2007), and academic literature. However, its general application in the manufacturing and energy industry is rather recent. The industrial GT sector is starting attempts to implement modularity in their GT developments. Some enterprises have sought to modify the GT cycles by adding external components, such as a solar heater (Poživil et al., 2015), a novel fluid medium, e.g., Helium (Liu et He, 2020), or by adding solid fuel cells and oxidizers (Mueller et al., 2010). Others have striven to implement tools to simplify the design (Cao et al., 2005), or the performance optimization (Camporeale, Fortunato et Mastrovito, 2006). However, current GT industries do not have integrated solutions to allow full-scale modularity, neither including a focus on the classical GT hardware components, as on designing peculiar cycles. So far, in-depth studies on full-scale modularity developments are mostly present in the automotive sector (Liu *et al.*, 2018 ; Cabigiosu, Zirpoli et Camuffo, 2013).

As illustrated in Table 1, existing research articles address topics that are connected to the main subject of this research study. Literature reports discussion on various topics, such as modularity design and optimization, however global solutions suitable for GT design in the paradigm of I4.0 and modular design are not yet proposed. Even, as scientific, and industrial research work exists for the automotive sector, a clear research gap on the comprehensive implementation of modularity in the GT sector can be identified. Therefore, the objective of this research study is to contribute to addressing this gap.

Only few research work, such as the studies by Liu and He (Liu et He, 2020) and Mueller (Mueller et al., 2010), is reported on GT modular design studies. Here, the authors discussed a modular GT design and its optimization, but only performed on one single GT type. Liu and He (Liu et He, 2020) used a non-standard type of GT including a helium reactor and Mueller (Mueller et al., 2010) deployed an atypical oxidizer cell controller, hence reducing the relevance for industrial adoption of modular GT approaches. Other research work (Cao et al., 2005), focus on creating a component database for GTs. This is certainly a first step towards accessible information for GT modularity; however, it does not propose to use this database on a larger scale for GT modular design. Camporeale et al. (Camporeale, Fortunato et Mastrovito, 2006), on the other hand, presents an interesting simulation and optimization code relevant to any kind of GT powered plant. Its global approach is pertinent to modularity integration, but it lacks strategies to design efficient heat cycles. The work by Liu et al. (Liu *et al.*, 2018) aims to develop such strategies by creating an optimization method for industrial component design. However, this study is limited to the automotive sector, and more precisely to only one automobile model., hence lacking pluri-system design. Similar studies in the automotive sector are proposed by Cabigiosu et al.(Cabigiosu, Zirpoli et Camuffo, 2013), presenting the integration of external components in modular design approaches. In summary, research is ongoing and emerging in the field of modularity for industrial manufacturing and GT design, e.g., by adding external components, creating global optimization programs, or building databases. However, none of the reported studies in literature are proposing comprehensive and integrative solutions needed to introduce modular design in the GT industry.

Table 3.1 : Comparison of modular design and/or GT elements addressed in literature compared to the present research study. Elements addressed in each study are marked with a green check mark

Article	One Component/Cycle Modularity	Global Modularity	Design	Optimization	Use of external components	Gas Turbine
(Lommers, 1995)	✓	✗	✗	✓	✗	✓
(Alford, Sackett et Nelder, 2000)	✗	✓	✗	✗	✗	✗
(Cao *et al.*, 2005)	✓	✓	✗	✗	✗	✓
(Camporeale, Fortunato et Mastrovito, 2006)	✓	✗	✗	✓	✗	✓
(Cabigiosu, Zirpoli et Camuffo, 2013)	✓	✓	✓	✗	✓	✗
(Poživil *et al.*, 2015)	✓	✗	✗	✓	✓	✓
(Martinez et Xue, 2016)	✓	✗	✓	✓	✗	✗
(Liu *et al.*, 2018)	✗	✓	✓	✓	✗	✗
(Liu et He, 2020)	✓	✗	✓	✓	✓	✓
(Rastegarzadeh, Mahzoon et Mohammadi, 2020)	✓	✗	✓	✓	✓	✓
This research (2023)	✓	✓	✓	✓	✓	✓

Hence, the present research study is a pioneering work integrating modularity in the full design space of typical GTs as used in industry, hence contributing to the adoption of modular design in GT development.

This research study proposes a novel Modular Design Application (i.e., program), which aims to support the relation between customer and GT design engineer. Then, using only general parameters, such as maximum costs, required power, desired energy source, geographical localization, number of operating hours, and external components to be used, based on the customer's specific requirements, the engineer would be able to quickly find an adapted GT configuration or design a new one and optimize it.

This research presents the implementation of modularity in the GT sector by the creation of a Modular Design Application (MDA) composed of an accessible GT design tool, where most common heat cycles, including all needed components, can be created, optimized, and stored in a database. Hence, an intuitive comparison of multiple cycles, using different parameters, which quickly provides the best cycle adapted to the customer requirements, can be realized.

In this study, the functioning of the developed application (program), and its principal design and decision parameters will be presented and discussed. Preliminary test runs, based on GT data from literature (Bouam et Aissani, 2008 ; Gorji-Bandpy, Goodarzian et Biglari, 2010 ; Rahman, Ibrahim et Abdalla, 2011 ; Ibrahim, Rahman et Abdalla, 2011 ; Maier, 2023), have been deployed to validate the developed application. Finally, a case study was conducted, to illustrate the functioning and practical use of the application and to reveal its added value for GT design.

3.3 Methodology

In order to achieve the research study's objective to develop the Modular Design Application (MDA) for specific GT design, the developed methodology is described in this section 2.
In the framework of this study, based on typical industrial usage (Razak, 2007), the MDA needs to comply to several requirements, e.g., it needs to be able to:

- handle the design of different GT types (heat cycles), such as Brayton, Rankine, combined cycle, solar heating, and others;
- include a wide variation of input parameters, such as fuel type, ambient temperatures, temperature limits among others;
- optimize multiple GT parameters, such as Fixed Power (FP), varying PR, and optimum efficiency;
- compare different GT configurations and extract the best cycle for a given set of input parameters;
- display an easy access to cycles in order to facility their modifications.

The selected software for simulation of the heat cycles was Aspen HYSYS, a process simulation software developed by AspenTech (AspenTech, 2023), which selection was based on several advantageous attributes. These include its accessibility, well-documented nature, and its capacity for seamless integration with other software applications. The intended MDA demands the incorporation of an additional software solution, proficient in interfacing with Aspen HYSYS, providing a user-friendly visual interface, and facilitating the storage of cycles and associated results. Within this context, MS Excel has emerged as the preferred software (Kongkiatpaiboon, 2019). Its merits for this purpose are notable, as it exhibits seamless connectivity with Aspen HYSYS, offers a spreadsheet-based interface that enhances the visualization of cycles and associated parameters, and streamlines the storage of data in distinct and easily reconfigurable sheets, hence facilitating accessibility and data modification as required.

The MDA is modeled under the commonly adopted assumptions for GT design (Razak, 2007):

- the system is at steady state;
- pressure and temperature losses in pipelines are ignored;
- gas is considered non-ideal;
- the Peng-Robinson model (Trawiński, 2019) is used for calculations.

As proposed by the work of Trawinski (Trawiński, 2019), the Peng-Robinson model is appropriate for the simulation of combustion and heat cycles and ideally suited for GT simulations. Indeed, the Peng-Robinson equation (Trawiński, 2019) (Eq 1) necessitates specific fluid characteristics to accurately compute thermodynamic data. Such information is predetermined in Aspen HYSYS. Steady state is the most common mode for GT calculations (Davison, 2012), and it also is the primary solving mode of Aspen HYSYS. The Peng-Robinson equation (Eq 3.1) can be formulated as follows:

$$\left(p + \frac{\alpha a}{{V_m}^2 + 2bV_m - b^2}\right)(V_m - b) = BT \tag{3.1}$$

Where p represents the pressure, T is the temperature of the medium, Vm is the molar volume of the medium, B is the universal molar gas constant (8.314 J·K−1·mol−1), a denotes the correction constant for molecular interactions (cohesive pressure), b presents the correction constant for volume of molecules (co-volume), and α is the correction coefficient for the acentric factor of molecules.

In the actual state of the MDA development, for the sake of simplification and generalization of the design-tool, piping design simulations have not been implemented and are beyond the scope of this study. Consequently, the minor pressure and temperature drops typically encountered in real-world scenarios are not yet factored into the calculations.

3.3.1 Application principle

GT systems can be sub-divided into components that each has a specific task to achieve in the energy creation process. Compressors compress the air to a certain PR, heat exchangers capture the waste energy from the turbine output to reintegrate it into the system (i.e., combustion chamber) by the mixture and combustion of air and a fuel, rising the temperature to the FT, and finally turbines allowing for expansion of the created gas, generating a rotational motion that allows a generator to produce electricity. Therefore, as illustrated in Figure 3.1, the heat cycles can be divided into individual components, or modules, where each module has one or multiple input and output, e.g., as for some components as the heat exchanger. Each connecting stream, represented by arrows in Figure 3.1, will be defined by its pressure, temperature, mass flow and composition.

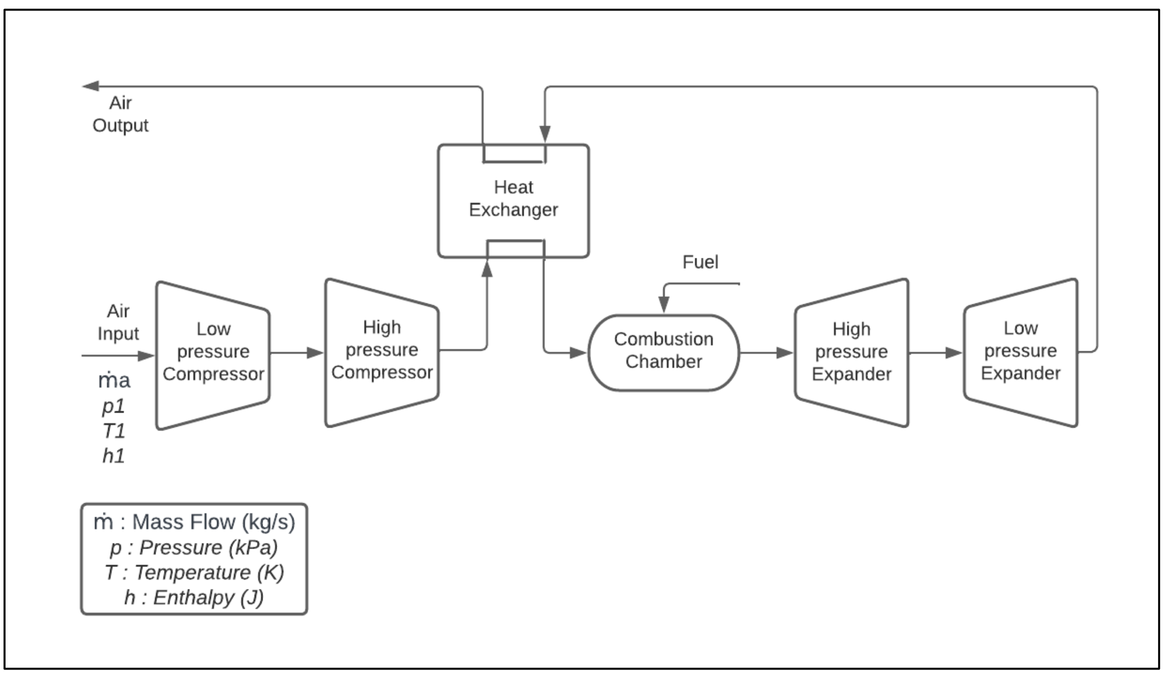


Figure 3.1 : Schematic illustration of a typical regenerative Brayton cycle based GT system consisting of multiple modules, here, two (2) compressors, two (2) turbines, including the different variables/flows

The MDA will follow this fundamental system to design the modular heat cycles. As illustrated in Figure 3.2, the MDA can handle and store two types of objects; modules and heat cycles.

The modules include compressors, turbines, or combustion chambers. Each module can be parametrized independently, e.g., the number of stages, the PR or the efficiency of the compressor can be configured automatically by the MDA. Each used module will have its proper configuration. The second object type includes the heat cycles. These cycles are composed of blank modules, e.g., a standard Brayton cycle will consist of a non-configured compressor, turbine, and combustion chamber. The MDA, when designing a cycle, will then associate user configured modules with heat cycles objects.

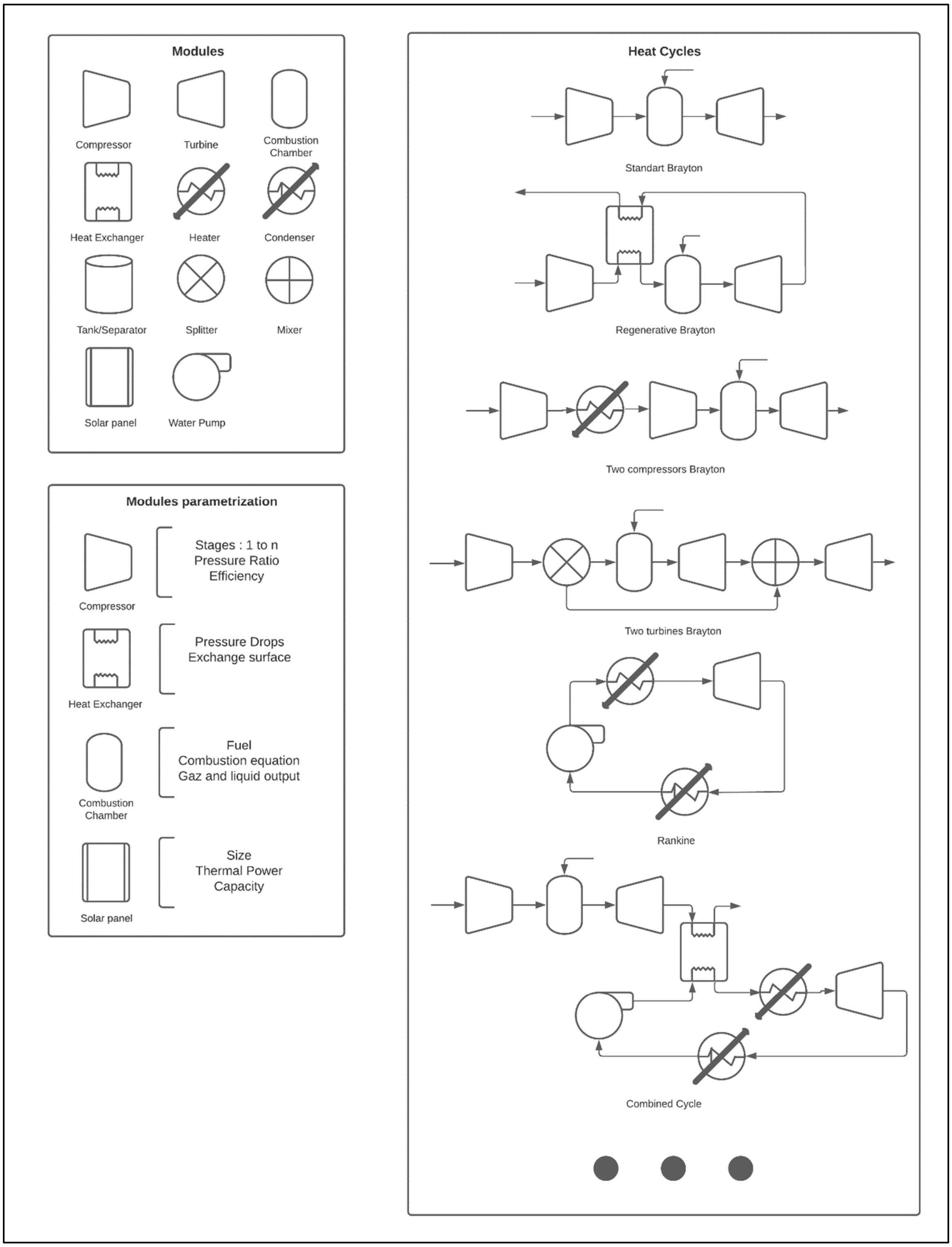


Figure 3.2 : GT system modules, including their parametrization options, and possible heat cycles available in the developed MDA

Each component is configured in Visual Basic for Applications (VBA) as an object with its proper characteristics. As Aspen HYSYS processes in a similar way, after configuration of each component object and their stream connection in Excel, this is transferred to HYSYS. Then, the cycle is created, simulated and the results are extracted to the same VBA object that supports configuration of the cycle.

The developed MDA has two modes of operation that are interconnected, and their functioning is summarized in a schematic overview illustrated in Figure 3.3.

The primary functionality of the MDA is the design of heat cycles (1). From a specific customers' requirement, the user will design the cycle of its choice with no restriction on components, fuel type, or cycles. In this step (Fig. 3.3 - 1.a), global system specifications (that applies to all types of heat cycles), such as ambient conditions, GT power output, maximum temperature, cost parameters, but also parameters specific to each type of heat cycle, such as components efficiency or pressure drops will be specified. The designed heat cycle will then be created in *Aspen HYSYS* (Fig. 3.3 - 1.b), and the different parameters are optimized to fit the customers' requirements (Fig. 3.3 - 1.c), e.g., power output and maximum temperature among others. Therefore, results are extracted in a second *Excel* sheet (Fig. 3.3 - 1.d), where the user can verify the detail of each component in the cycle (Fig. 3.3 - 1.e), as well as perform an evaluation of the global GT parameters, e.g., efficiency, power, cost, and fuel flow.

Certainly, when the user is satisfied with the designed cycle, it can be archived in a database (Fig. 3.3 - 1.f). This archiving process facilitates the cycle's reuse in the second mode of operation. Additionally, the user retains the flexibility to select different cycles stored in the database that can be used for experimental use or to serve as a foundational blueprint for designing an extended heat cycle. This allows a great design flexibility, allowing the combination of different cycle solutions, such as Brayton, Rankine, combined cycles, and the use of external components, e.g., solar panels or external heaters, to facilitate the comparison between classical cycles and less conventional solutions.

A second function of the MDA is the comparison of multiple cycles to find the optimum point of functioning (2). A database of heat cycles has been created including, e.g., Brayton cycles, multi-stage compressors, energy regeneration cycles, or solar heating. So far, almost 20 different cycles are available in the developed MDA.

First, the user must define the global specifications of the Turbine (see Fig. 3.3 - 2.a). Next, the selected cycles for comparison (Fig. 3.3 - 2.b) will be opened in different *Excel* sheets and updated to meet the global specifications. Then, the simulation of each cycle can be run for different PR (Fig. 3.3 - 2.c). The heat cycle creation and optimization in *Aspen HYSYS* is similar to the “Design One Cycle” (1) mode. After extraction of each cycle’s results, the optimum functioning point and cost of the cycle is calculated (Fig. 3.3 - 2.d). Once all cycles have been created and all optimum points found, the results are compared and the solution that accommodates best the clients’ requirements is selected (see Fig. 3.3 - 2.e). Subsequently, the user is granted access to the best-performing cycle from the "Find Optimum Point" (2) mode. Here, the cycle can be modified as desired within the "Design One Cycle" (1) mode, allowing for further fine-tuning and customization of the cycle to align it precisely with specific customers’ requirements and preferences.

The second operational mode of the application (2) significantly enhances the accessibility of the customer-engineer relationship. By implementing an easy-to-expand database, engineers gain the capacity to effortlessly conduct a variety of design tests, while concentrating on solutions tailored to specific customer needs. The database also streamlines the process of identifying the most suitable heat cycle, resulting in substantial time savings during the GT design and customer-engineer meetings. This functionality enhances efficiency and fosters a more streamlined approach to the design process, ultimately benefiting both engineers and customers alike.

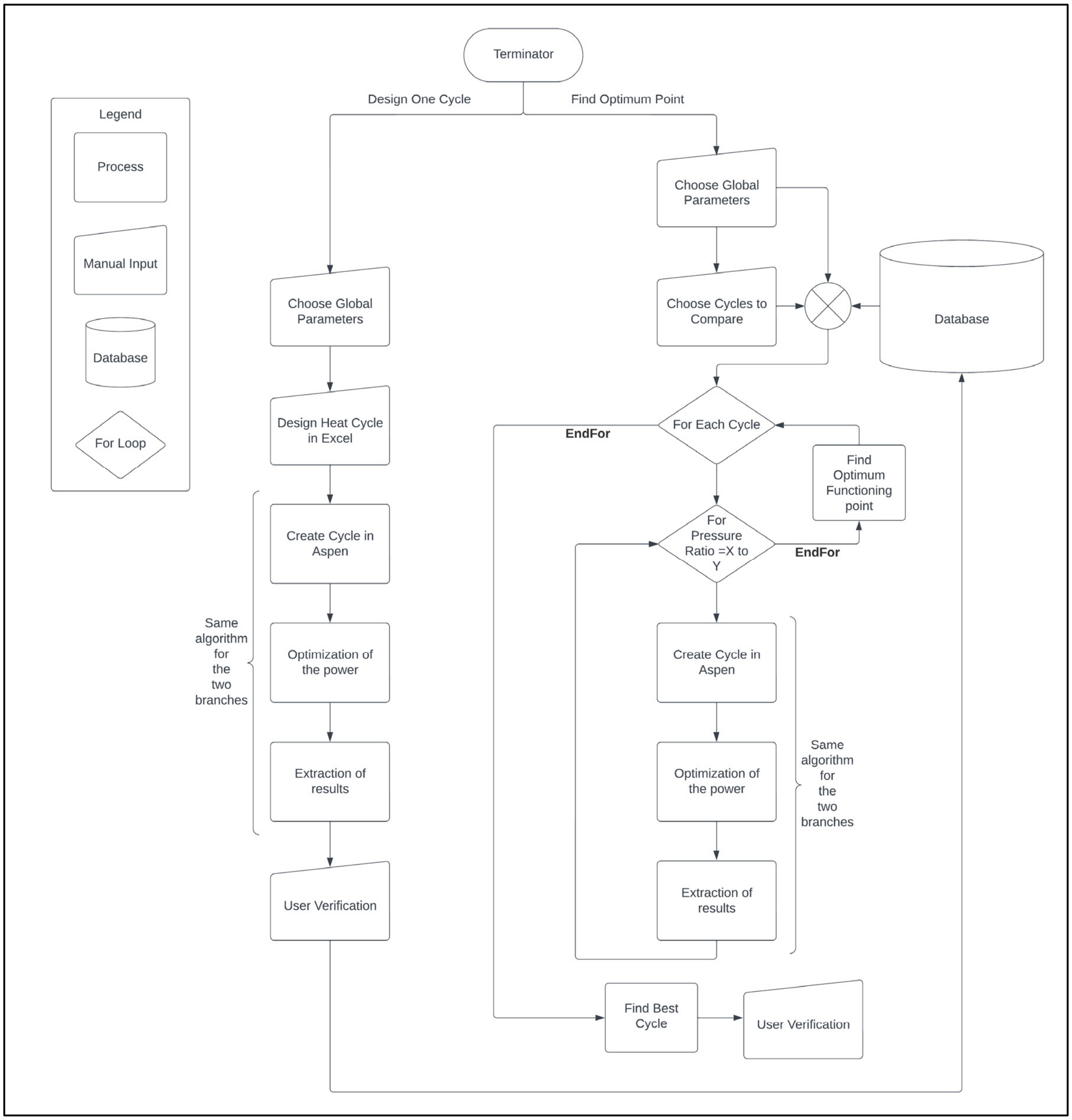


Figure 3.3 : Schematic overview of the GT Modular Design Application (MDA) functioning including two branches for the two modes of operation. The first branch (design one cycle) results in a database that subsequently feeds the second branch (find optimum working point)

It should be noted that the proposed MDA aims to provide an overview of the best solutions for a given use case to support the user in quickly assessing different heat cycle (and GT) scenarios. Hence, the obtained solution will not be necessary the most performing one for all case scenarios, nor the designed heat cycle will be fully optimized. Indeed, the overall performance of a specific configured heat cycle (GT) can be obtained using generic building blocks, i.e., modules. Once a satisfactory modular GT configuration has been achieved, the user can further optimize the selected cycle including its components (modules).

The proposed MDA aligns with the concept of I4.0 aiming to deliver a high degree of customization at economically viable costs, and here opening the possibility of accessible and rapid modular GT solutions, while including customer requirements and design flexibility.

3.3.2 Heat cycle (GT) variables

Multiple variables can be manipulated in the developed MDA, which is summarized in Table 2. In fact, these variables can be categorized in the following three (3) groups:

a) Global specifications, that affects all heat cycles. These include the customer requirements and constraints, such as the demanded power, the location of the GT, and the number of Operating Hours (OH) per year.
b) Heat cycle parameters, which are defined by the ”Design One Cycle” mode (1), and subsequently modified by the user or the MDA software when calculating the optimum functioning point. It includes the two main parameters of a GT i.e., the PR, and the FT, as well as components (modules) efficiency, connection to other components and the different pressure drops in the components.
c) Medium (e.g., working fluid) parameters, that can be defined by ambient conditions of the working environment or by the user.

With the exception of the global specifications (a), the remaining variables (b and c) typically do not require reconfiguration for the ”Find optimum point” mode (2) calculation, as they have already been defined during the ”Design One Cycle” mode (1). In fact, the PR varies during the mode (1) calculation, and the FT is constrained by the maximum temperature defined in the global specifications (a). This heat cycle design approach ensures that these parameters align with the customer's requirements, promoting efficiency and accuracy in the optimization process.

Table 3.2 : Parametrizable variables by the user for the simulation of a heat cycle in the MDA

Parametrizable Variables		
Global Specificationss	**Heat Cycle Parameters**	**Working Fluids**
Power Ouput	Pressure Ratio	Pressure
Maximum Temperature	Flaming Temperature	Temperature
Ambient Conditions	Pressure/Temperature Drops	Mass Flow
Cost of electricity	Components Efficiency	Composition
Operating/Maintenance Cost	Combustion Reaction	
Loan Characteristics	Components Disposition	
Operating Hours		

The parameter that will be considered for the choice of the optimum heat cycle is the cost of electricity, expressed in US dollar per kilowatt-hour ($/kWh). The MDA approach is oriented towards a customers' perspective. Variables such as TE or fuel flow are of interest to engineers but do not show what matters most for the customer; the financial aspect. Indeed, the cost optimization is of paramount importance from an industrial perspective (Aji et al., 2018). Furthermore, this cost of electricity can be readily compared to prevailing market prices, enabling a comprehensive assessment of competitiveness and cost-effectiveness in an industrial context. Therefore, the customer can readily discern whether the proposed solution is competitive and aligns with their budgetary constraints.

It is worth noting that the optimal operational point of a GT is often characterized by its TE. The TE plays a pivotal role in the calculation of fuel cost, a substantial component of the overall operational expenditure. Hence, TE serves as a critical determinant in achieving cost-efficiency in GT operation (Horlock, 1995).

Figure 3.4 illustrates the primary interface of a standard Brayton cycle in Aspen HYSYS. The components and the medium streams that connects them are represented as well (as the energy streams).

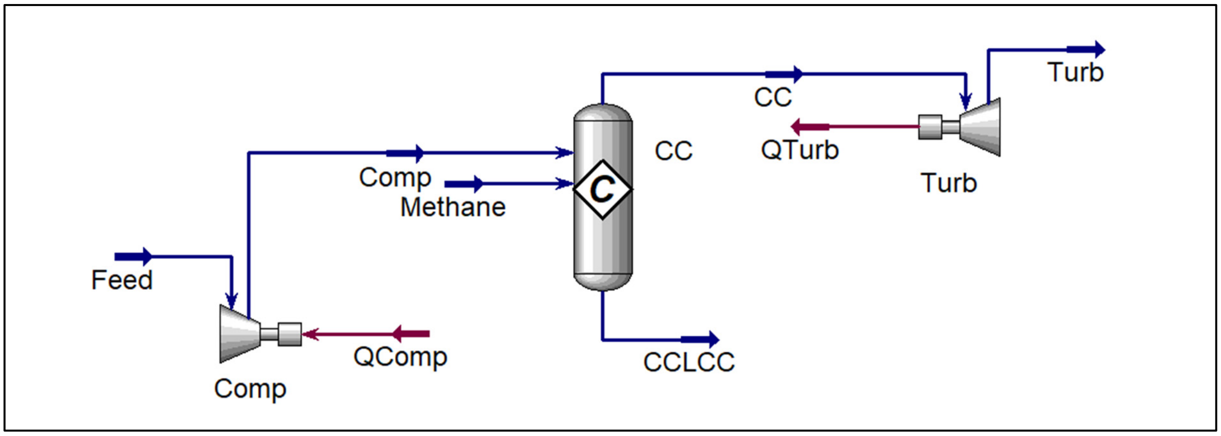


Figure 3.4: Standard Brayton cycle, its components, input streams and energy streams, created and simulated in Aspen Hysys via the developed MDA

3.3.3 Cost estimation

Table 3.3 summarizes the different costs considered in the MDA. This section will describe and detail the calculations of these costs integrated in the developed MDA.

Table 3.3 : Costs considered for the simulation in the MDA

Cost considered in the MDA
Purchased Equipment Cost (PEC)
Fuel Cost
Operating and Maintenance Cost
Loan and interest cost (CRF)

The electricity cost has been defined as the decision variable for heat cycle (GT) optimization. Therefore, an estimation of all costs related to GT operations is needed to ensure the validity of the proposed solution, i.e., GT configuration, to the customer.

First, the cost of the equipment, Purchased Equipment Cost (PEC), is among the most essential factors to consider (Gorji-Bandpy, Goodarzian et Biglari, 2010). This PEC includes the cost of each GT component and constitutes one of the major parts of the global GT cost.

Estimating the PEC in a modular application, as in this study, presents notable challenges. Indeed, the developed MDA approach being general, the GT components are not based on a specific commercial catalog, hence the multiple input variables are preventing to consider a fixed $/kW cost.

In reference (Gorji-Bandpy, Goodarzian et Biglari, 2010), the formulas for the 4 most important components of a GT i.e. compressor (ac), turbine (at), combustion chamber (cc) and heat exchanger (aph), have been expressed.

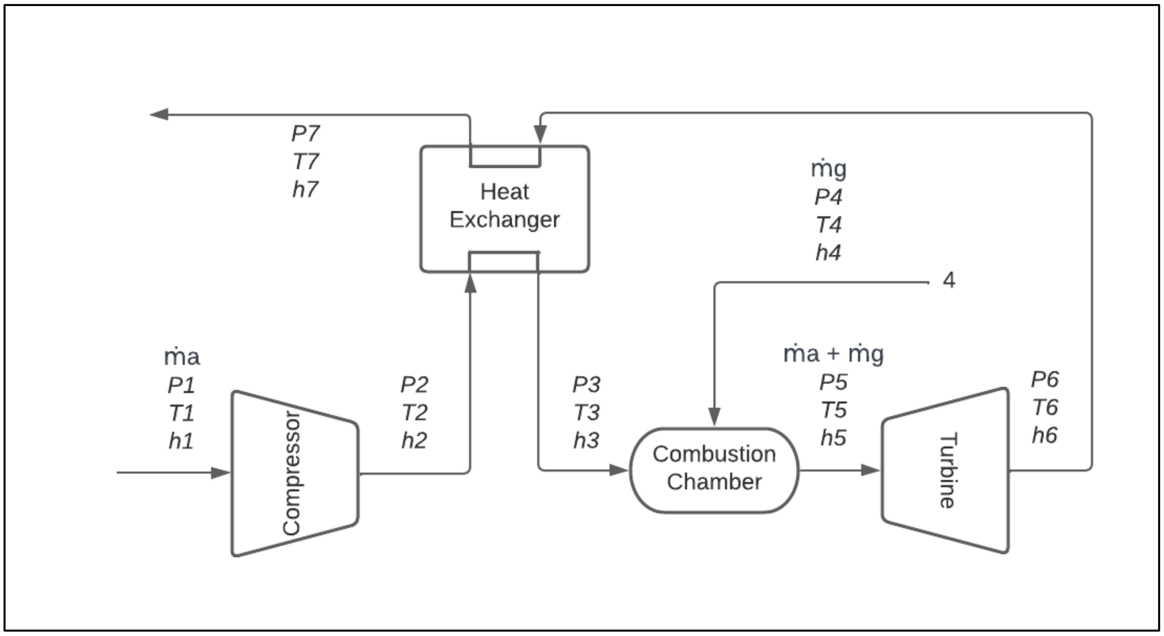


Figure 3.5 : Illustration of a regenerative Brayton cycle, including mass flow, pressure, temperature, and enthalpy noted for each input and output
Adapted from Gorji-Bandpy et al. (2010,p349)

Equations 3.2 to 3.5 (Gorji-Bandpy, Goodarzian et Biglari, 2010) can be used to estimate the PEC of these components from thermodynamic quantities. P is the pressure, T the temperature, $\dot{m}$ the mass flow, h the enthalpy, and η the isentropic efficiency Index correspond to Input and Output of components, noted in Figure 3.5.

$$PEC_{ac} = \left(\frac{71.1 * \dot{m}_a}{0.9 - \eta_{sc}}\right) * \left(\frac{P_2}{P_1}\right) * Ln\left(\frac{P_2}{P_1}\right) \tag{3.2}$$

$$PEC_{CC} = \left(\frac{46.08 * \dot{m}_a}{0.995 - \frac{P_5}{P_3}}\right) * (1 + exp(0.018 * T_5 - 26.4)) \tag{3.3}$$

$$PEC_{at} = \left(\frac{479.34 * \dot{m}_g}{0.92 - \eta_{st}}\right) * Ln\left(\frac{P_5}{P_6}\right) * (1 + exp(0.036 * T_5 - 54.4)) \tag{3.4}$$

$$PEC_{aph} = 4122 * \left(\frac{\dot{m}_g * (h_6 - h_7)}{18 * \Delta T_{lm}} \right)^{0.6} \tag{3.5}$$

Where, P represents the pressure, T the temperature, m˙ the mass flow, h the enthalpy, and η the isentropic efficiency. These variables are illustrated in Figure 3.5.

In the case of certain heat cycle components, e.g., centrifugal pumps, steam turbines, and fired heaters, graphical data and curves sourced from catalogs reported in literature (Loh, Loyns et White, 2002) have been methodically adapted. These characteristic curves have been transformed into polynomial equations using PlotDigitizer (PlotDigitizer, 2023) and integrated into the Excel part of the MDA. Figure 3.6 illustrates an example of the adaptation of a cost estimation curve, here presenting the purchased equipment cost in USD (including inflation correction (U.S BUREAU OF LABOR STATISTICS, 2023)) of a centrifugal water pump as a function of its mass flow entry (adapted from (Loh, Loyns et White, 2002)). this value.

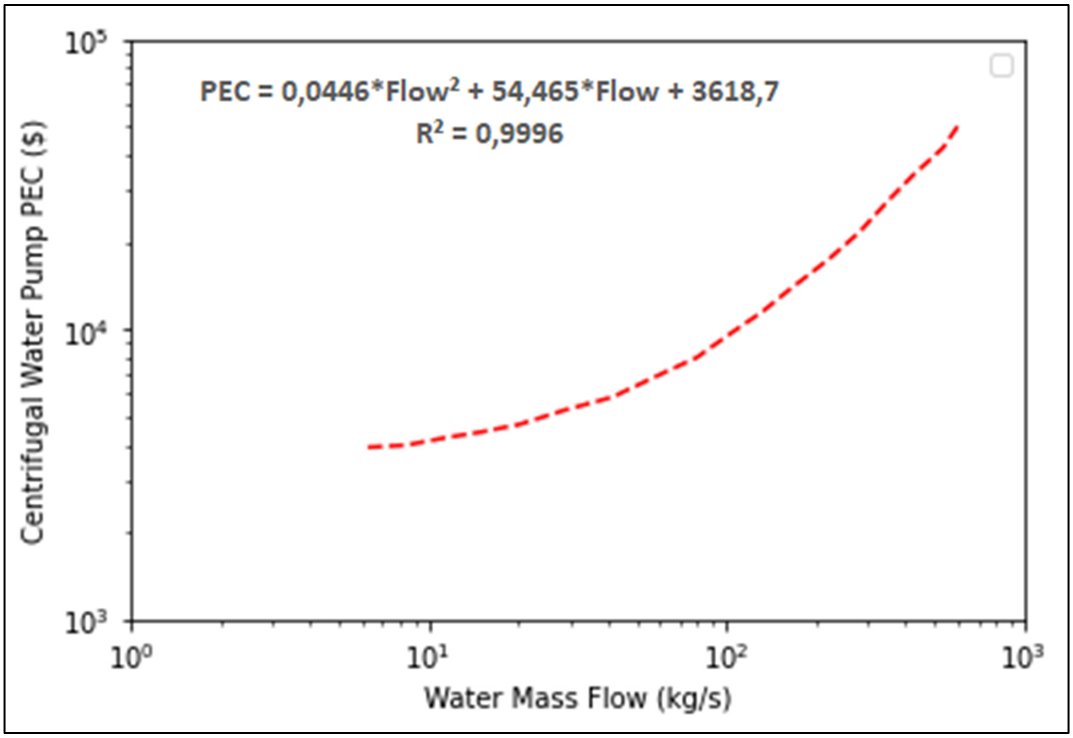


Figure 3.6 : Purchased equipment cost (PEC) in USD ($) of a centrifugal water pump in function of its mass flow entry
Adapted from Loh et al., (2002, p30)

In the context of solar water heaters, a distinctive approach was employed. Given the absence of a standardized method for cost estimation, a cost approximation for these heaters was chosen to be based on the electricity cost for solar heating, quantified in terms of dollars per kilowatt-hour ($/kWh). While these values are well-documented, to accommodate a diverse range of solutions, the cost can be selected as a configurable model input variable.

The second cost to consider includes the fuel cost. As illustrated in Figure 3.7, which plots the ratio of the calculated PEC over the fuel cost used in the MDA for two different cycles (Brayton and combined cycle) at varying PRs, both PEC and fuel costs must be evaluated simultaneously as their ratio varies significantly from 2% to 50%.

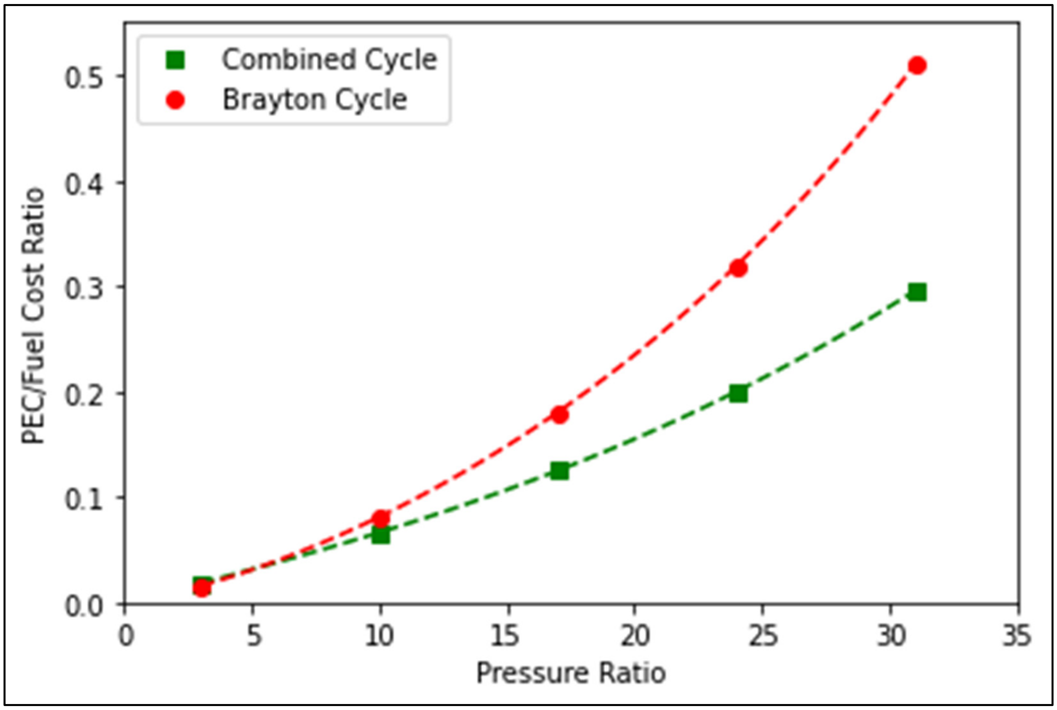


Figure 3.7 : Ratio of calculated PEC/fuel cost in the MDA for two different cycles (Brayton and combined (Rankine-Brayton) cycle) against varying pressure ratios (PR)

To estimate the fuel cost, the TE of the cycle is first calculated, by determining the ratio of the net work output to the heat input. (Short, Packey et Holt, 1995), and subsequently converted to the heat rate. Then, as the market price expressed in \$/MMBtu is widely accessible (MARKETWATCH, 2023), the fuel cost expressed in \$/kWh of each cycle can be deduced (Eq 3.6). It should be noted that the market price for energy has been defined as an input parameter in the MDA, due to its high volatility.

$$Fuel\ Cost_{\$/kWh} = \frac{Fuel\ Cost_{\$/MMBTu}}{HeatRate} \tag{3.6}$$

To consider needed investment loans and its amortization, the Capital Recovery Factor (CRF) has been considered as well to the cost calculation, where i denotes the interest rate and n the number of annuities (Eq 3.7).

$$CRF = \frac{\{i * (1 + i)^n\}}{\{[(1 + i)^n] - 1\}} \tag{3.7}$$

Once these three cost values (PEC, fuel and CRF) have been calculated, and considering the annual OH and the cost factor of Operating and Maintenance (O&MFactor)of the GT, the Simple Levelized Cost of Energy (SLCE) can be calculated (Eq 3.8) (Short, Packey et Holt, 1995). This SLCOE is also defined as the decision variable.

$$\begin{aligned} &Simple\ Levelized\ Cost_{\$/kWh} \\ &\qquad = \frac{PEC * CRF * O\&MFactor}{OH} + Fuel\ Cost_{\$/kWh} \end{aligned} \tag{3.8}$$

3.4 MDA validation

To establish the MDA's capability to yield results congruent with real GT behavior, a series of rigorous tests were conducted across various real-life GT configuration scenarios. These tests aimed at extracting and analyzing the influence of input parameters and subsequently comparing the obtained results to data available in literature. (Bouam et Aissani, 2008 ; Gorji-Bandpy, Goodarzian et Biglari, 2010 ; Rahman, Ibrahim et Abdalla, 2011 ; Ibrahim, Rahman et Abdalla, 2011 ; Maier, 2023). Nevertheless, literature only scarcely provides complete and detailed information on the required parameters to fully replicate a GT. Consequently, the modular GT configurations simulated within the developed MDA inherently exhibit slight variations from configurations described in the literature (Bouam et Aissani, 2008 ; Rahman, Ibrahim et Abdalla, 2011). Hence, this study concentrates mostly on relative comparisons of different modular GT configurations, considering GT performance curve trends and order of magnitude cost and efficiency estimations. Certainly, variations in variables such as TE may be evident between the simulated cycles and those referenced in the literature. However, such differences, remain sufficiently minor to allow for a meaningful interpretation of the prevailing trends and behaviors upon using the developed MDA tool. To complete the validation, two simulations have been executed using data from cycles reported in literature (Bouam et Aissani, 2008 ; Rahman, Ibrahim et Abdalla, 2011), offering a sufficiently detailed dataset to validate the precise creation of the heat cycles within the MDA. For comparison of the performance and costs curves derived from the MDA tool with typical GT data from literature, PlotDigitizer software and Python scripts using the Matplotlib library have been used to convert hardcopy curves from literature into digital curves(PlotDigitizer, 2023).

3.4.1 Process analysis and comparative study

As discussed in section 3, several parameters impact the GT efficiency, and consequently its cost. The key driver for GT performance is the PR, hence its value will be studied for each GT design parameter, such as the FT or the ambient temperature. The results presented in this section have been obtained deploying a Brayton cycle, as it is the most common heat cycle in industrial applications and most reported in literature. However, the same behavior has been noticed for the other type of cycles (e.g., Rankine and combined cycles).

One of the dominant parameters for GT operation is the turbine FT (Rahman, Ibrahim et Abdalla, 2011). As this includes the maximum temperature of a GT, this FT value characterizes the mechanical aspect and cost of the GT. Indeed, the higher the FT, the more resistant the GT materials are required (e.g., creep resistant), resulting in higher component costs. Hence, the importance to determine the impact of the FT on the TE to evaluate the balance between fuel cost and component cost. Despite some differences in efficiency, which can be explained by the differences in input parameter and solving solutions, Figure 3.8 demonstrates a similar trend of the impact of the PR on the thermal efficiency, at different FT.

The impact on the FT becomes increasingly pronounced as the PR escalates. At lower PR values, the TE tends to exhibit relatively minor differences among various FT values. However, as PR increases, the gap between TE and different FT values grows significantly (Fig. 3.8). The same behavior is noticed in both Fig. 3.8 a) Simulated in the MDA and Fig.3.8 b) adapted from (Rahman, Ibrahim et Abdalla, 2011).

Another noticeable trend emerges where low FT values at higher PR levels are associated with a substantial drop in efficiency. In contrast, the TE remains comparatively stable for higher FT values, even as the PR increases. This observation supports the sensitivity of TE to FT at higher PR levels and the distinct performance characteristics of gas turbines at varying operating conditions.

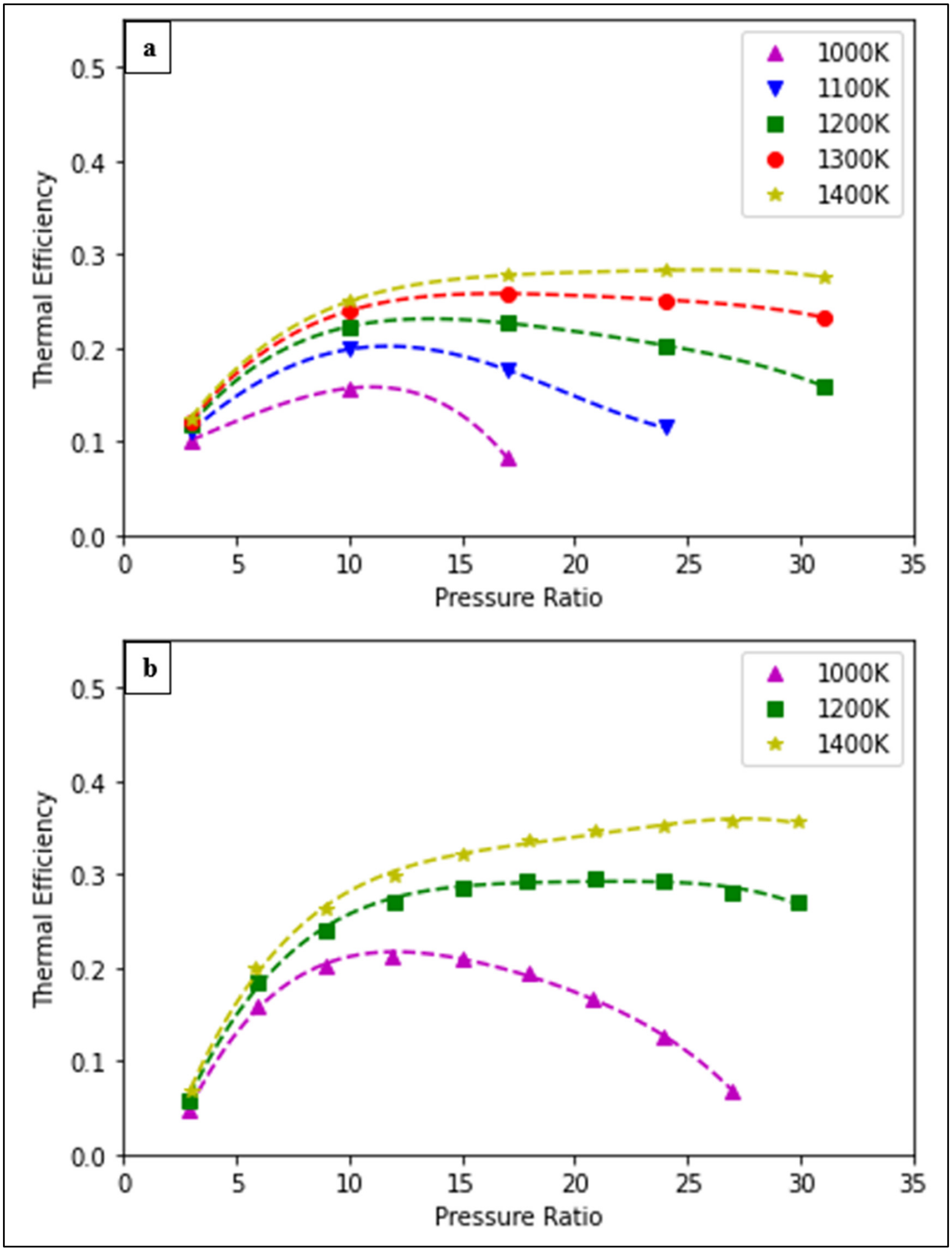


Figure 3.8 : Effect of the variation of the pressure ratio (PR) on thermal efficiency (TE) for multiple flaming temperatures (FT); a) simulated in the MDA for a standard Brayton cycle; b) for an optimized standard Brayton cycle
b) adapted from Rahman et al., (2011, p3544)

Another essential parameter of influence is the inlet temperature of the GT (Bouam et Aissani, 2008), typically the ambient temperature for open heat cycles. Certainly, this parameter is vital to consider because of the versatility of uses of a GT.

Gas turbines (GTs) offer remarkable versatility and can indeed be employed in a wide range of environmental conditions. They are well-suited for use in arid and hot regions, such as deserts, where they can efficiently generate power under extreme temperatures. Similarly, GTs can also function effectively in extreme cold environments ($T < 0°C$) , such as e.g., in Greenland (Li, Liu et Ye, 2021).

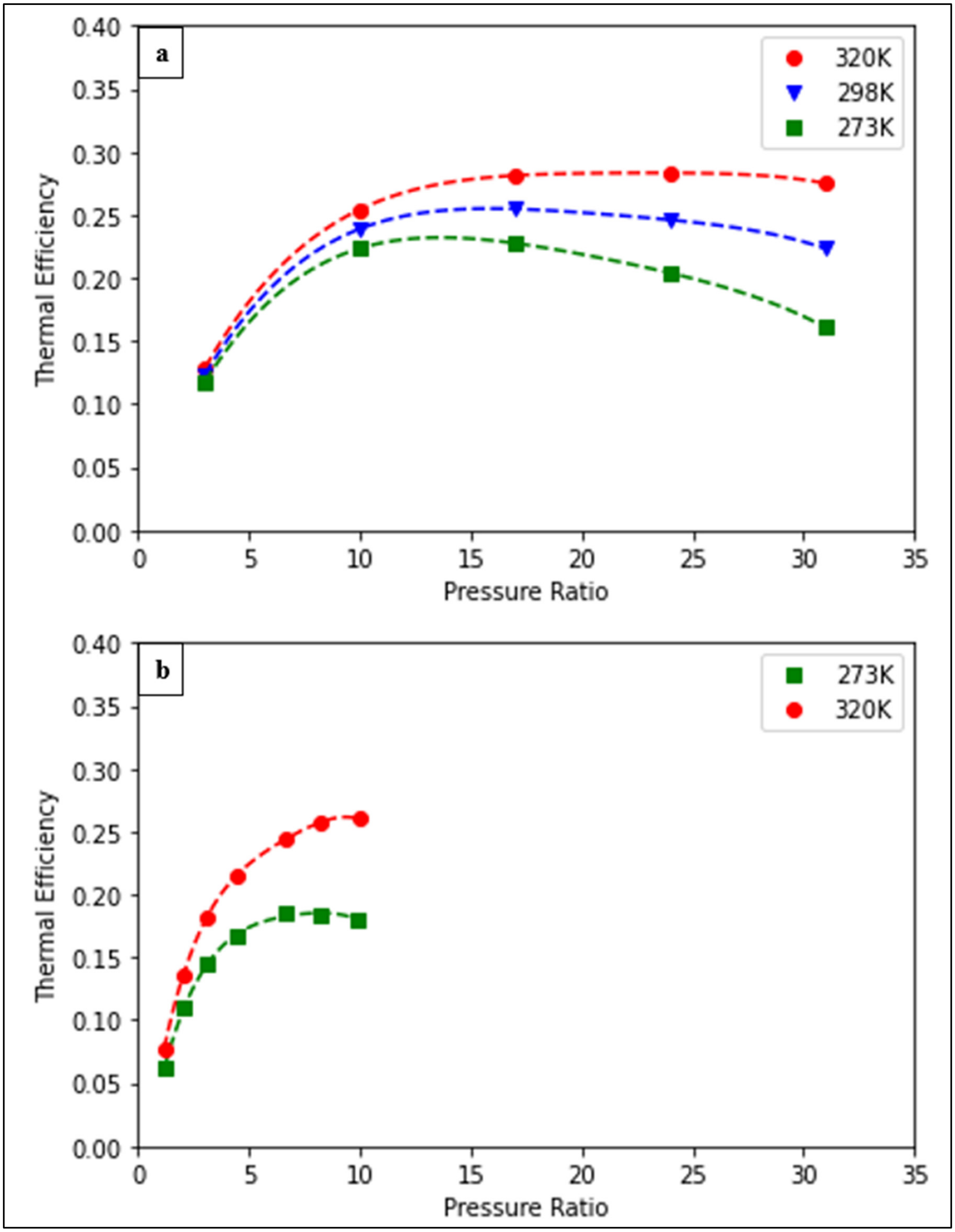


Figure 3.9 : Effect of pressure ratio (PR) on thermal efficiency (TE) for multiple ambient temperatures; a) simulated in the MDA for a standard Brayton cycle; b) for a standard Brayton cycle
b) adapted from Bouam & Aissani, (2008, p299)

As witnessed in Figure 3.9, for both curves, the TE is overall higher at higher ambient temperatures. Similarly, as for the FT, the TE deviations are much higher at high PR. In the use case illustrated in Figure 3.9. b (adapted from (Bouam et Aissani, 2008)), the PR is limited to 10. Therefore, the comparison between Figure 3.9 a and Figure 3.9 b cannot be extended beyond this value. However, as the behavior is similar for the two curves at lower pressure, the same can be expected for higher PR.

It can be concluded that the impact of input parameters on the behavior of the developed MDA simulation seems to be in adequation with the literature trends for most variables. efficiency could also be studied to make the study more exhaustive.

3.4.2 Behavior of different cycles

The developed MDA includes three (3) main types of cycles: Brayton, Rankine, and a Combined Cycle. Each type of cycles has its specific variations, with varying configured chains of compressors or turbines, regeneration, or external components, such as solar panels.

As illustrated in Figure 3.10, the behavior of different combined cycles from the MDA simulation are similar with equivalent cycles reported in literature. Indeed, efficiencies are different due to lack of detailed information on the literature derived cycles, but the same behavior can be observed for the classical combined cycles i.e., a TE increase with growing PR until a certain limit has reached. The hierarchy between the cycles is respected with the solution including two (2) turbines having a higher global thermal efficiency than the one (1) compressor solution. The regenerative cycles in both solutions have similar behavior, which is different from other cycles, demonstrating an efficiency peak at low PR, i.e., PR = 5 for the literature and PR = 10 for the MDA simulation. The GT efficiency drops after this peak, passing below the classical solutions. Also, the simulation curve (Fig. 3.10 a) stagnates from a certain PR onwards, while that of the curve reported in literature (Ibrahim, Rahman et Abdalla, 2011) steadily declines. This difference can be explained by differences in the generation of the cycles, and by the employed optimization algorithm of the simulation, which will prioritize the Brayton cycle and might differ from the method used in the documented study from literature.

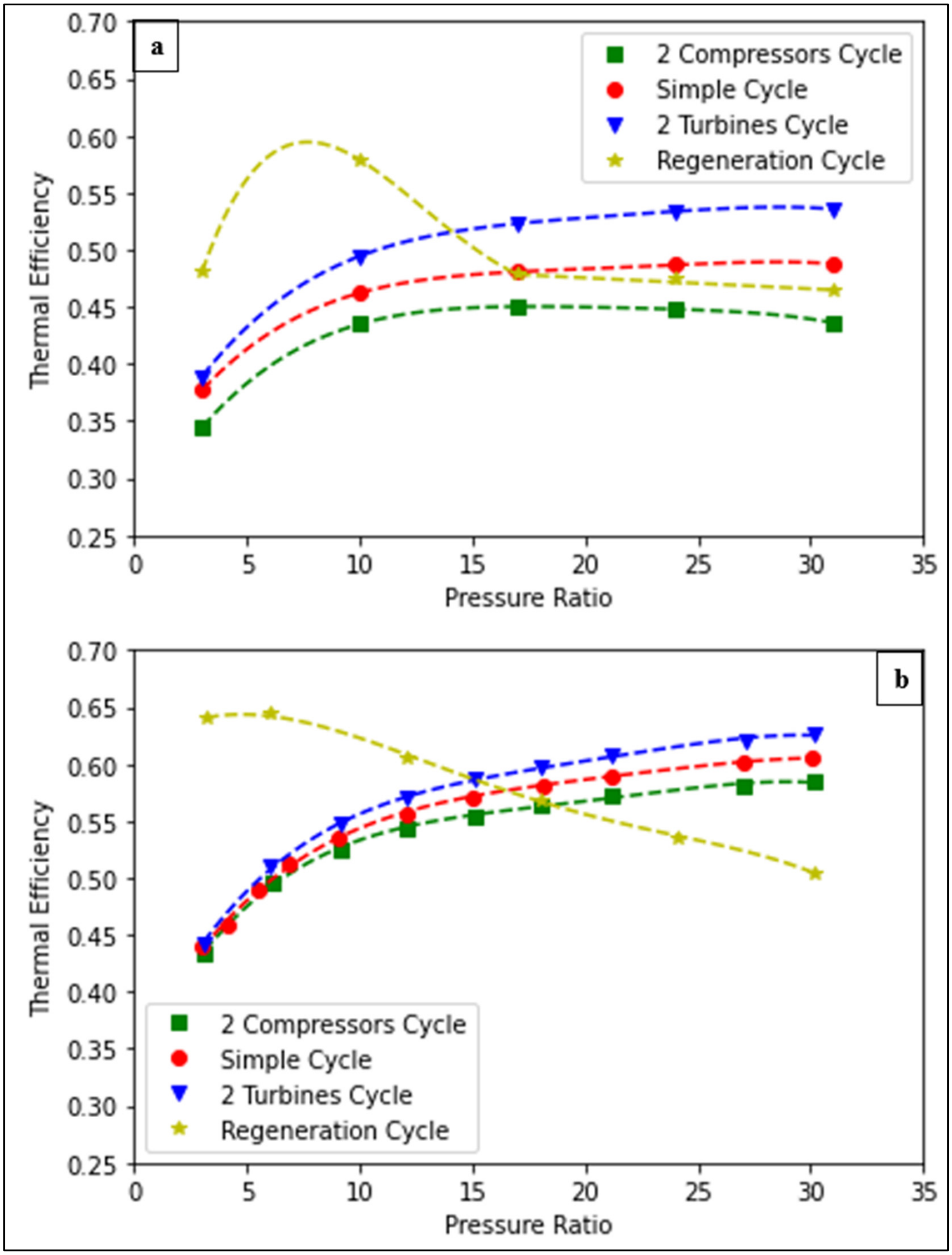


Figure 3.10 : Different combined cycles and their thermal efficiency for different pressure ratios; a) simulated in the MDA for multiple cycles: a 2 compressors Brayton cycle, a standard Brayton cycle, a 2 turbines Brayton cycle and a regenerative Brayton cycle; b) for multiple cycles: a 2 compressors Brayton cycle, a standard Brayton cycle, a 2 turbines Brayton cycle and a regenerative Brayton cycle
Adapted from Ibrahim et al., (2011, p4222)

Finally, comparisons were conducted between GT cycles sourced from literature (Gorji-Bandpy, Goodarzian et Biglari, 2010 ; Maier, 2023), where all relevant data were provided, and the behavior of these cycles when configured and analyzed within the developed MDA tool. Two cycles were studied, the first being a regenerative Brayton cycle including two (2) compressors and three (3) turbines (Maier, 2023). The comparison of the simulation results and the data from literature are summarized in Table 4. The second cycle is a standard regenerative Brayton cycle, derived from the work of Gorgi (Gorji-Bandpy, Goodarzian et Biglari, 2010). The results of the comparison are summarized in Table 5 and allow the verification of a proper implementation of the equations. 3.2 to 3.5.

Equation 3.9 was used to calculate the relative error (Er) between simulation results and data from literature.

$$Er = \frac{(LiteratureValue - SimulationValue)}{LiteratureValue} \tag{3.9}$$

The results of the relative error can be found in the last column of both Table 4 and Table 5. Some differences can be noted, notably in the flow of air and fuel, which can be explained by the used assumptions made for the calculation, such as the thermodynamic model (here the Peng-Robinson model (Eq 3.1) was adopted), and the optimizing method for the turbine. Table 4 presents the error (Er), which is relatively low for the FT and TE parameters (0.1% for power and FT and less than 5% for TE).

Table 3.4 : Comparative values and relative simulation error for a 2 compressors and 3 turbines regenerative Brayton cycle GT system, obtained by simulation using the MDA and data reported in literature
Taken from Maier, (2023, p1)

	Unit	Litterature Turbine	Application Turbine	Relative Error
Power	kW	6300	6300	0,00%
FT	K	1450	1453	0,18%
Fuel Mass Flow	kg/s	0,278	0,257	-7,72%
Entry Mass Flow	kg/s	18,72	15,41	-17,74%
TE		0,43	0,44	2,63%

For the second cycle, detailed in Table 5, the error (Er) is similar as the values documented in Table 4. The fuel and air flow error is still higher than 10% The simulation results indicate that this results in the turbine PEC that is similar as (Gorji-Bandpy, Goodarzian et Biglari, 2010), with an error (Er) of only 3%.

Table 3.5 : Values and relative error for a regenerative Brayton GT compared between the simulation of the application and data
Taken from Gorji-Bandpy et al. (2010, p353)

	Unit	Litterature Turbine	Application Turbine	Relative Error
Power (kW)	kW	140000	140184	0,13%
FT	K	1320	1321	0,08%
Fuel Mass Flow	kg/s	8,52	7,21	-15,41%
Entry Mass Flow	kg/s	510	564	10,62%
TE		0,29	0,30	4,60%
Cost ($)	$	35000000	35945762	2,70%

3.5 Case study

To illustrate the effective application of the MDA tool in an industrial context, a comprehensive case study has been conducted. This case study serves as a practical demonstration of the MDA's utility and its potential to address real-world challenges within the industry. It offers valuable insights into the application's operational feasibility and its capacity to provide solutions that align with industrial requirements.

Case study context:

- a customer from an industrial site based in Quebec, Canada, needs a 15MW GT to power its site. The installations that will be powered by the GT operates at 90% of the time, cumulating to an annual run-time of 8000 hours.
- The loan envisioned by the company to fund the needed investments has a 10% interest for 20 years of annuities.
- The location of the plant benefits from a substantial and mostly unused parcel of land. This advantageous land availability means that there are no constraints on the size of GT nor the potential incorporation of solar panels. Therefore, solutions, such as combined cycles, and solar heated sources will be evaluated in this case study.
- The mean sun radiation of the Quebec is around 4.7 kWh/m^2 (Hydro-Quebec, 2022), which combined to the surface available, and the market of Solar Water heater gives a maximum of 15 MWth Solar Heater. In Quebec, the average temperature over the year is of 278K (Gouvernement du CANADA, 2023). As the effect of ambient temperature

on GT Efficiency can be considered as linear, this value will be used as the ambient temperature of the cycle.

The GT customer has access to two different fuels:

- Pure Methane, which is a commonly used fuel in GT operations. It is a relatively low-cost and performant fuel, which cost around 3.7$/kWh (MARKETWATCH, 2023).
- Biomethane, a Renewable Natural Gas (RNG) with a composition as represented in Table 6 (Chen et al., 2015). This RNG is more expensive than pure methane. It costs around 7 $/kWh.

Table 3.6 : Composition of the renewable natural gas (RNG) used for the simulation.

Gas	Composition (%)
Methane	61,3
CO2	35
Nitrogen	0,79
Oxygen	0,21
H2	2
H2S	0,7

The company aims to reduce its carbon emissions. Therefore, if a solution using Biomethane is viable, they are ready to choose this solution even if its price is higher than a Methane fuel solution. This maximum price limit is fixed at 80% of the market price. In Quebec, the average cost of electricity is 0.073$/kWh (Hydro-Quebec, 2023), thus the company is ready to spend up to 0.0584$/kWh.

The operating and maintenance cost is evaluated at 6% of the total cost of the GT per year. All selected parameters are summarized in Table 7.

Table 3.7 : Input parameters for the study case simulations

GT Parameters	Units	Value
Power of the GT	kW	15000
Maximum Temp of the GT	K	1400
Ambient Temperature	K	278
Ambient Pressure	kPa	101
Cost of Electricity	$/kWh	0,073
Interest Rate	%	10
Number Of Annuities		20
Maintenance Factor		1,06
Operating Hours Per Year	h	8000

The customer requirements align with the conditions for each cycle contained in the database. Consequently, each cycle will undergo a thorough optimization process to identify the most optimal global solution. It is worth noting that the results for simple Rankine cycles are omitted from the case study to facilitate readability, nevertheless these results will be presented in the subsequent part of the case study. The findings from the simulation of the chosen cycles within the context of the case study (1) are summarized in Figure 3.11.

As expected, Methane GT solutions are less expensive than its equivalents sourcing biomethane (see Fig. 3.11) and more efficient (see Fig. 3.12). Nearly all solutions fit in the imposed budget margin except for the classical Brayton solution. However, for the biomethane option, only one solution respects the budget margin. The optimum solution found for both fuels is the solar regeneration Brayton cycle. This cycle, simulated in Aspen HYSYS, is illustrated in Figure 3.13. In line with the customer's specifications, the cost of the biomethane optimum solution has been confirmed to be under 80% of the prevailing market price, which was defined as \$0.058 per kWh. Consequently, this solution aligns with the customer's requirements and will be selected as the preferred choice. Thus, in this case study (1), the solution proposed to the customer is a regenerative Brayton cycle powered with a biomethane fuel, for a cost of electricity (including PEC and Fuel Cost) of 0.049\$/kWh.

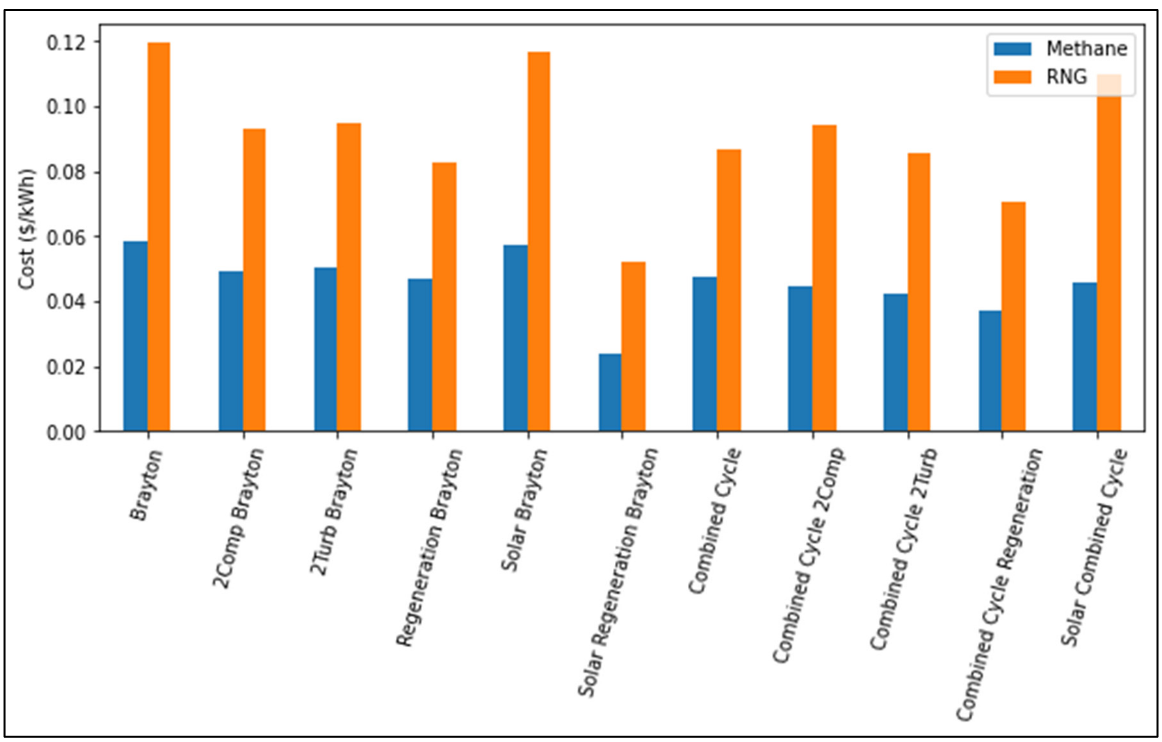


Figure 3.11 : Optimum cost comparison for multiple heat cycles using Methane and RNG fuels in case study (1), obtained by the MDA

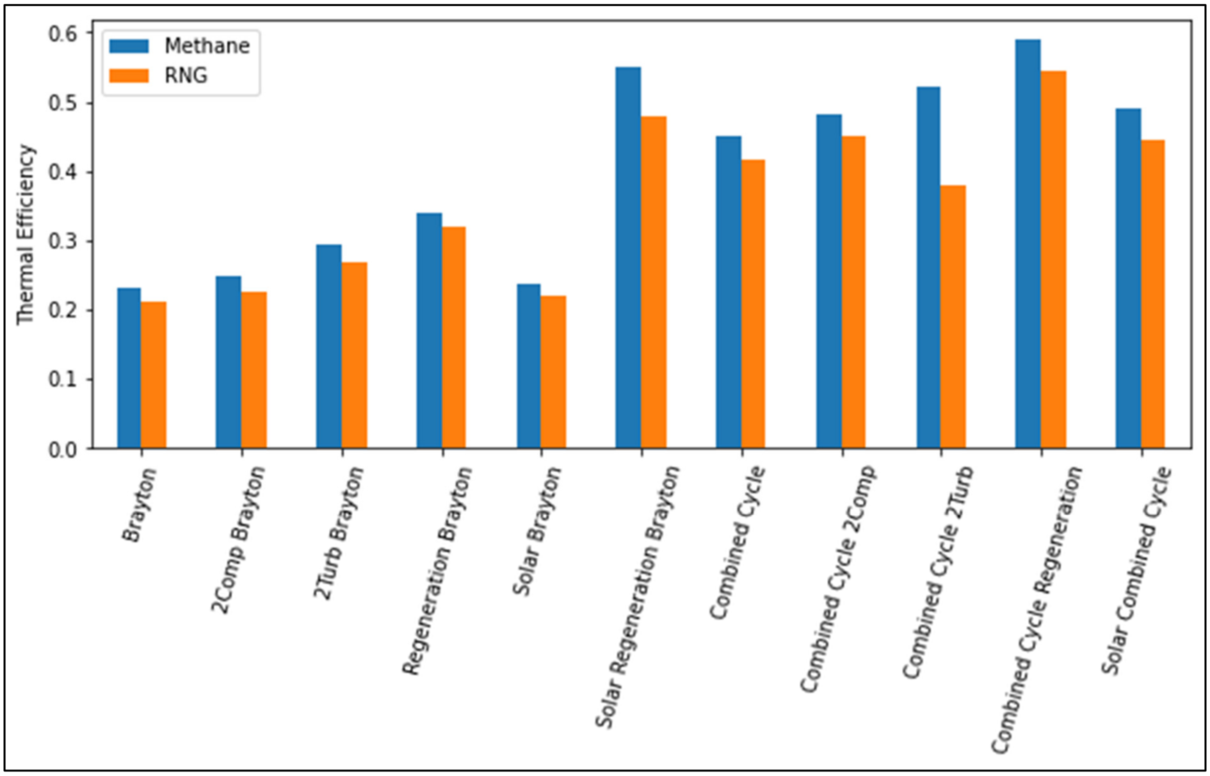


Figure 3.12 : Optimum thermal efficiency comparison for multiple heat cycles using Methane and RNG fuels in case study (1), obtained by the MDA

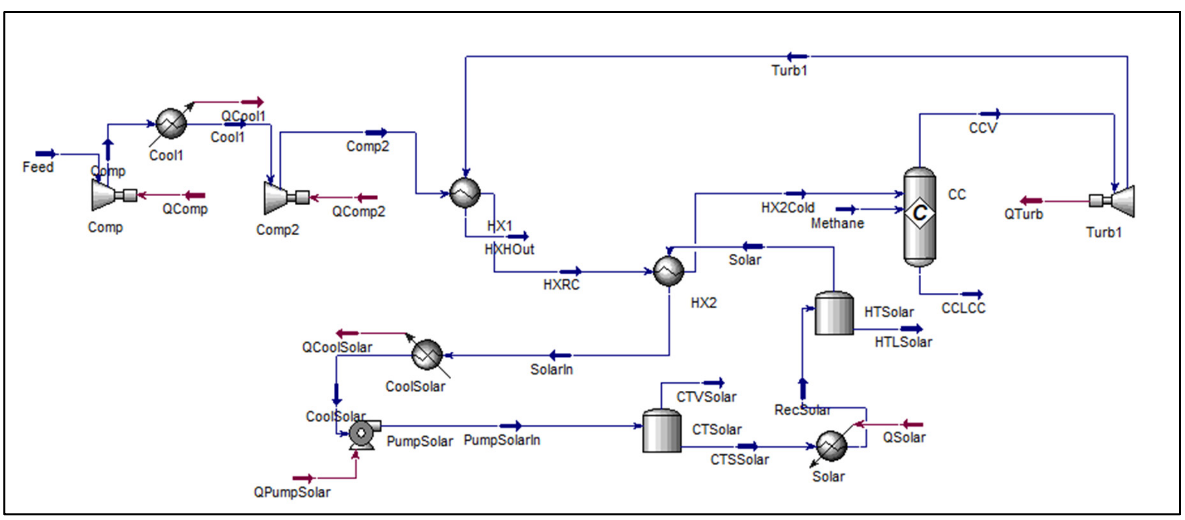


Figure 3.13 : Solar regeneration Brayton cycle created and simulated in Aspen HYSIS via the MDA

After some time, the customer returns to the GT provider. There have been some organizational changes in the company. It was decided to invest in the creation of a new warehouse next to the already existing factory, resulting in a modified context for case study (2).

As a consequence, the land available for the solar panels is now occupied by the warehouse and the company needs to dismantle the existing solution. They need a new solution that can, if possible, reuse some parts of the precedent solution (i.e., case study (1)). Even more, to power the new warehouse and its equipment, they desire to increase the available power from 15MW to 25MW. As the investment requirement for this new warehouse changes the initial budget, a loan for the GT has to be rediscussed. The new loan includes a 15% interest rate and 10 years of annuities. As the available space is now significantly smaller, the combined cycle or solar panels cannot be used anymore. Brayton and Rankine cycles are then the only cycles considered in this case study (2).

As the previously installed solution was a solar assisted regenerative Brayton cycle (Figure 3.13), the components that were part of the Brayton cycle can be reused as a basis for the new GT design. To increase the efficiency and power of this turbine, more compressors or turbines could be added.

The optimum solution for both fuels, outlined in Figure 3.14 and Figure 3.15, is a regenerative Brayton cycle including two compressors, and three turbines. This GT design (represented in Figure 3.14) results in a cost of 0.031$/kWh for Methane fuel and 0.057$/kWh for RNG as fuel.

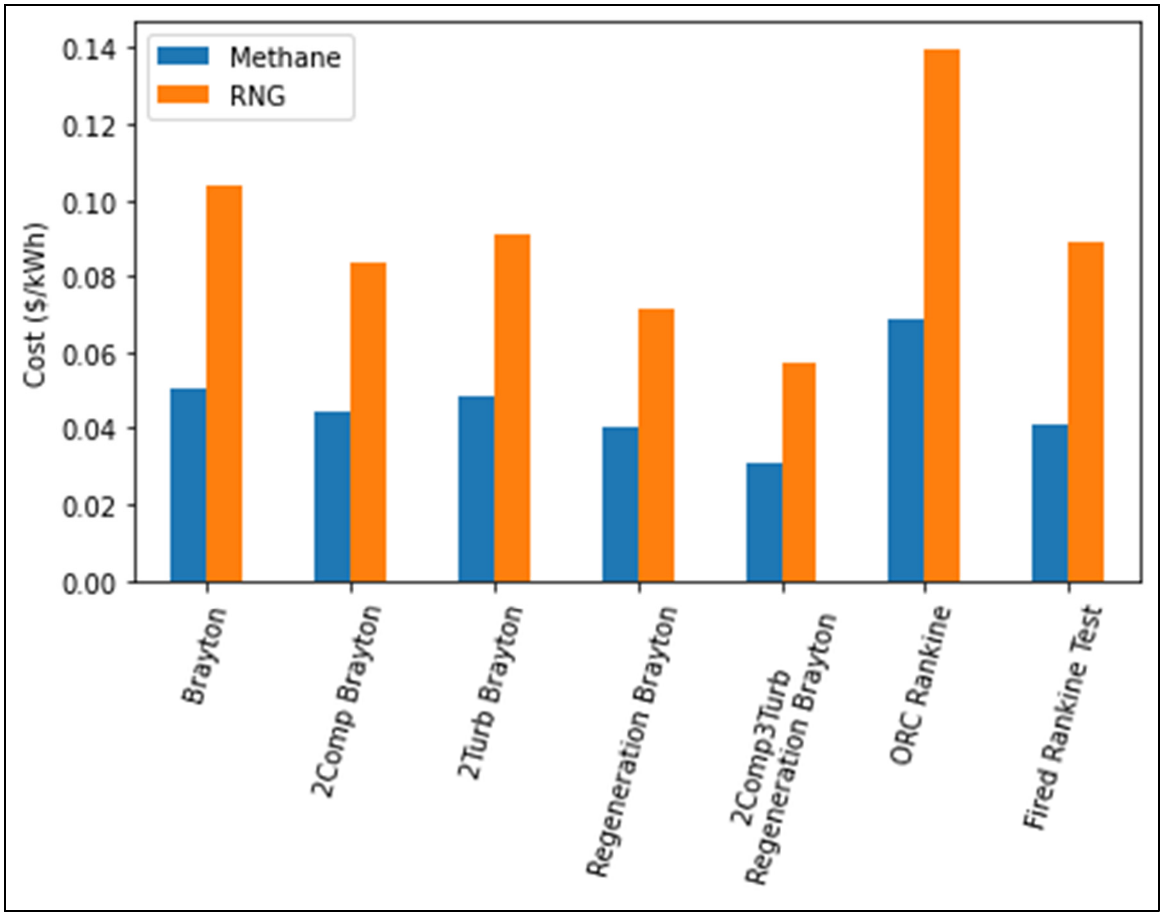


Figure 3.14 : Optimum cost comparison for multiple heat cycles using Methane and RNG fuels in the study case (2), obtained by the MDA

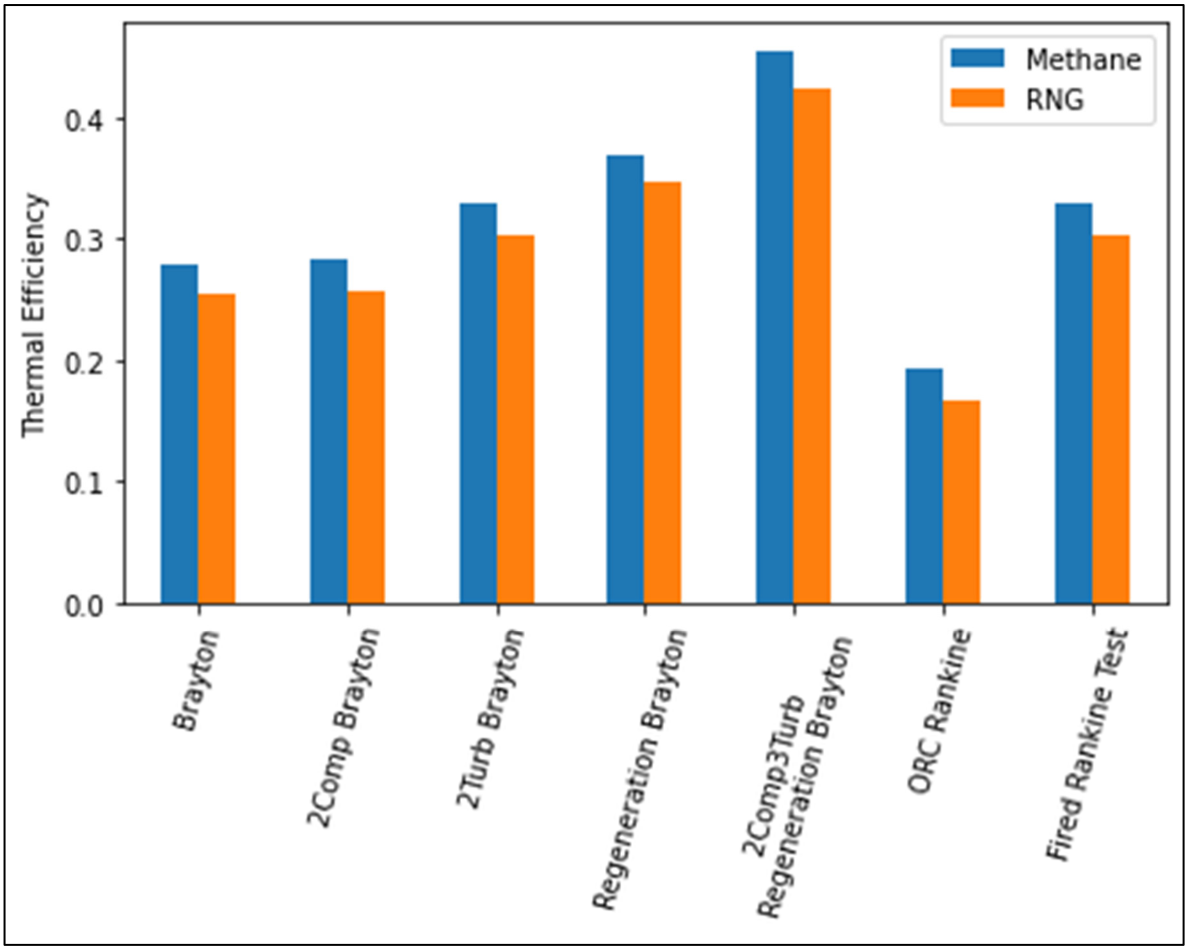


Figure 3.15 : Optimum thermal efficiency comparison for multiple heat cycles using Methane and RNG fuels in the study case (2), obtained by the MDA

Even if the RNG energy cost is under the maximum allowable limit, i.e., 0.058$/kWh, considering volatility in the global fuel market price, and the new investments performed by the company, this solution seems not the best in this case (2). The solution proposed to the company is therefore a regenerative Brayton cycle including two compressors and three turbines fueled with Methane. This solution allows the reuse of the core of the first solution (case study (1)), by reusing one compressor, the combustion chamber, one GT and the heat exchanger, hence contributing to a more sustainable GT design solution.

This solution allows the reuse of the core of the first solution, by reusing one compressor, the combustion chamber, one GT and the heat exchanger.

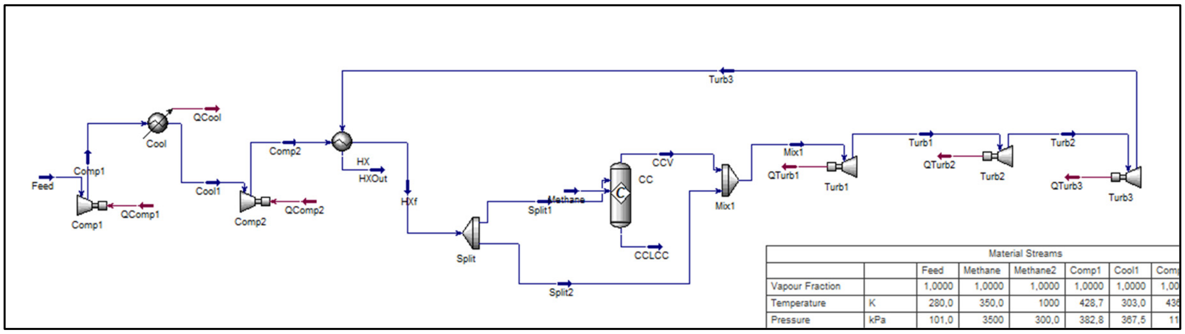


Figure 3.16 : A schematic overview of a 2 compressors, 3 turbines regenerative Brayton cycle based GT system, created and simulated in Aspen HYSIS via the MDA

3.6 Conclusion

This study on MDA development presents a valuable contribution to the existing body of knowledge related to GT cycle simulation and optimization. It provides insights into the advantages of modularity and its prospective applications, not only within the larger industrial sector but specifically within the GT sector. By exploring the possibilities and implications of modular design and optimization, this research study offers innovative solutions that can enhance both efficiency and cost-effectiveness in GT design and technology towards more sustainable GT solutions.

The operation of a novel developed MDA, facilitating the simulation, optimization, and cost estimation of a diverse range of GTs and, more widely, heat cycles, has been comprehensively outlined. The developed application serves as a pivotal contribution to the integration of Industry 4.0 principles within the realm of GT technology. It empowers users to address various customer requirements by simulating precise cycle configurations and evaluating the cost implications of these solutions. The user-friendly design and efficient storage of new solutions render this application an easily updatable tool, fostering rapid and effective decision-making within the GT sector. It embodies the future of GT design and optimization, aligning with the ever-evolving landscape of industrial technology.

The adopted simulation process appears to provide accurate and reliable results. The behavior of the simulated heat cycles aligns with expected thermodynamic principles, and the trends in the generated curves closely correspond to available data in academic and industrial literature. Furthermore, the inclusion of a detailed case study elucidates and exemplifies the MDA's practical utility. It demonstrates the extensive range of possibilities and potential applications, offering a clear and comprehensive illustration of how the application can address real-world scenarios and requirements.

While the developed application for modular GT design is currently functional and relevant, there remain numerous opportunities for further research. First, the scope of the design system could be broadened by incorporating a greater number of components, such as distillation columns and additional solar-derived heaters. Moreover, the database can be expanded to encompass a wider variety of heat cycles, potentially including configurations like the solar regenerative combined cycle. In terms of optimization, for the code can be refined to improve simulation efficiency and reduce processing time. Additionally, exploring the advanced functionalities of HYSYS could yield more precise and detailed simulations. Furthermore, the "Find Optimum Point" mode of the application can be enhanced to allow the variation of parameters like power output, ambient conditions, or fuel for a single run. Currently, users must adjust these parameters manually and initiate a new run, but streamlining and automating this process can simplify and expedite the optimization phase. These potential improvements will contribute to the MDA's evolution and its capacity to offer even more advanced and efficient solutions in the future.

CHAPTER 4

GAS TURBINE MODULARITY APPLICATION DETAILS

There is some pertinent information for the comprehension of the exact functioning of the MDA that did not have its place in the article. Therefore, they will be presented in this chapter. the algorithms used for the optimization of the power of the GT will be presented. Also, the parametrization of each module involved in the MDA will be described, with an emphasis on the creation of a solar water heater model. Finally, the functioning of the Compressor and Turbine Design algorithm will be explained, which calculate the optimum Diameter and rotating speed for each pressure ratio and mass flow.

4.1 Optimization programs

The GT output power and entry mass flow are correlated parameters. Therefore, at fixed parameters, diminishing the value of one will decrease the other value.
As a result, the easiest way to control the value of the Output Power, a value depending on many variables, as PR, FT, Component's efficiency, is to fix every variable and to vary the value of Entry Mass Flow. It makes sense at a physical scale, as it is one of the easiest parameters to control. This optimization will therefore not be exhaustive and is lacking some precision to find the optimum point. However, as the MDA aims to propose a solution that can propose results quickly, the optimization of the GT considering all parameters would take too long. Therefore, it has then been decided to focus only on mass flow.

The optimization process, schematized in Figure 4.1, is divided in two branch, one mode for simple cycles (Brayton, Rankine, with multiple components.) and the other for combined cycle.

The power optimization works the same way for both type of cycles. The relative error between the Wanted Power and the Simulated Power is calculated. If the error is superior to 1%, we divide the Mass Flow by the ratio of Simulated Power over Wanted Power. After a recalibration of components, to ensure that the other parameters as Flaming Temperature, Fuel Mass Flow, or Pressure Drops are still correct. The operation is done while the error limit is not respected. The difference made for Combined Cycle is that it is needed to adjust both cycles. Therefore, the Rankine cycle will first be modified, to ensure that this cycle is the minority cycle (less than half of Output Power). If Rankine cycle has too much power compared to Brayton cycle, then the cycle will not be able to converge as Rankine Energy comes from Brayton exhaust gas. If Brayton generates too less power (meaning small entry Mass flow), the Heat exchanger between the two cycles will not be able to furnish the great amount of energy. Therefore, the Rankine power must be kept below a certain level for the GT to work.

Then, the Brayton Power is adjusted, the same way as in the first option, until a relative error of less than 1% is reached.

For every iteration, all components are recalibrated, and the compressor and turbine method is called to redesign these components. All the code associated with this research can be found on a Github presented in Annex I.

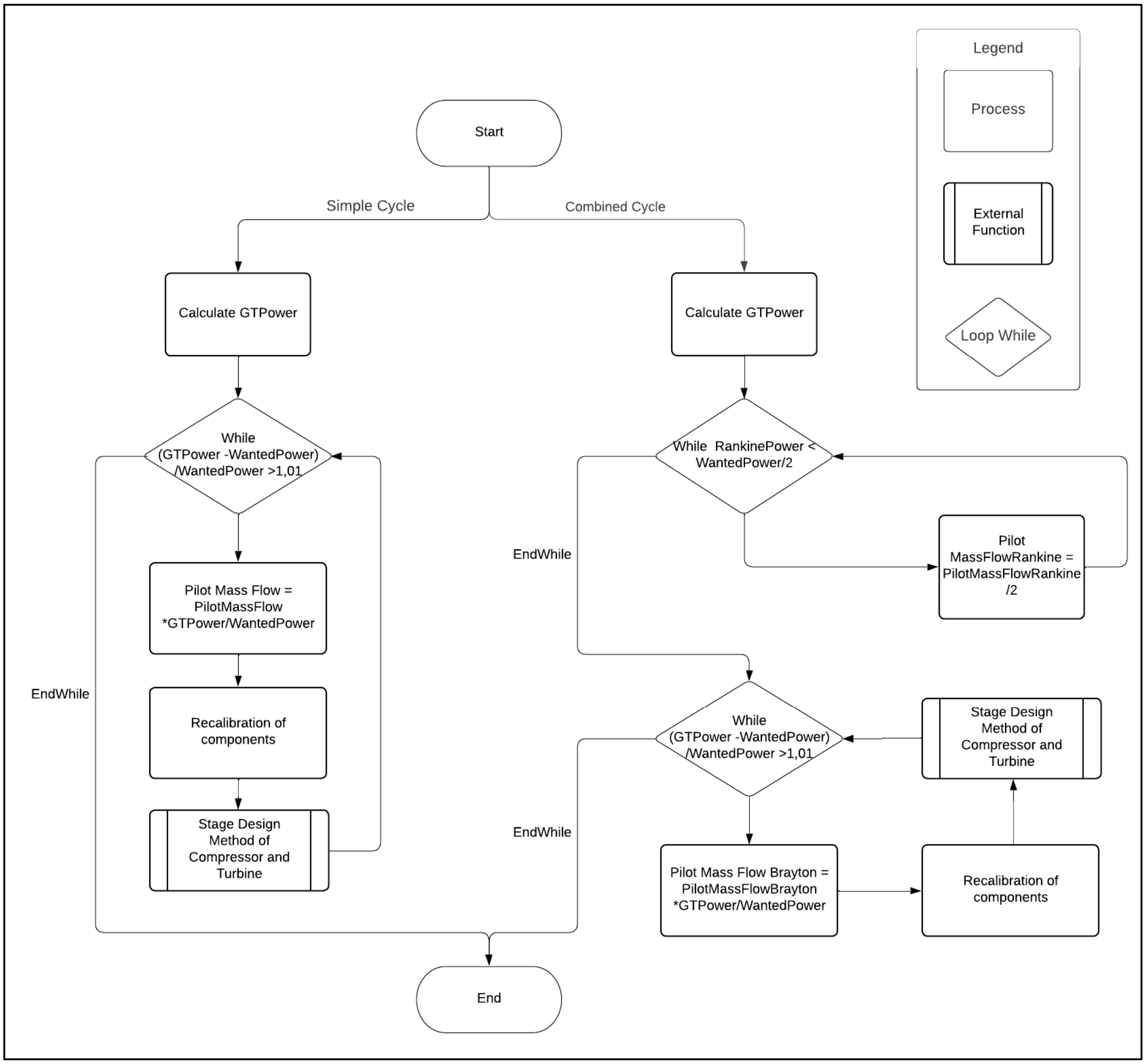


Figure 4.1 : Power Optimization Algorithm

4.2 Components configuration

One important part of the MDA is how to design modules and what parameters to configurate in each one.

Aspen is not a permissive software and has a list of parameters needed to make component converge. This list varies with components. However, for each component, the Input Stream must be fully parametrized (Pressure, Temperature, Mass Flow and Composition)

The parametrization of some of the major components will be described in this part. The other components can be found in Annex II.

4.2.1 Compressor and turbine

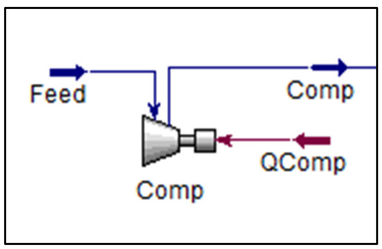


Figure 4.2 : Compressor component in Hysys

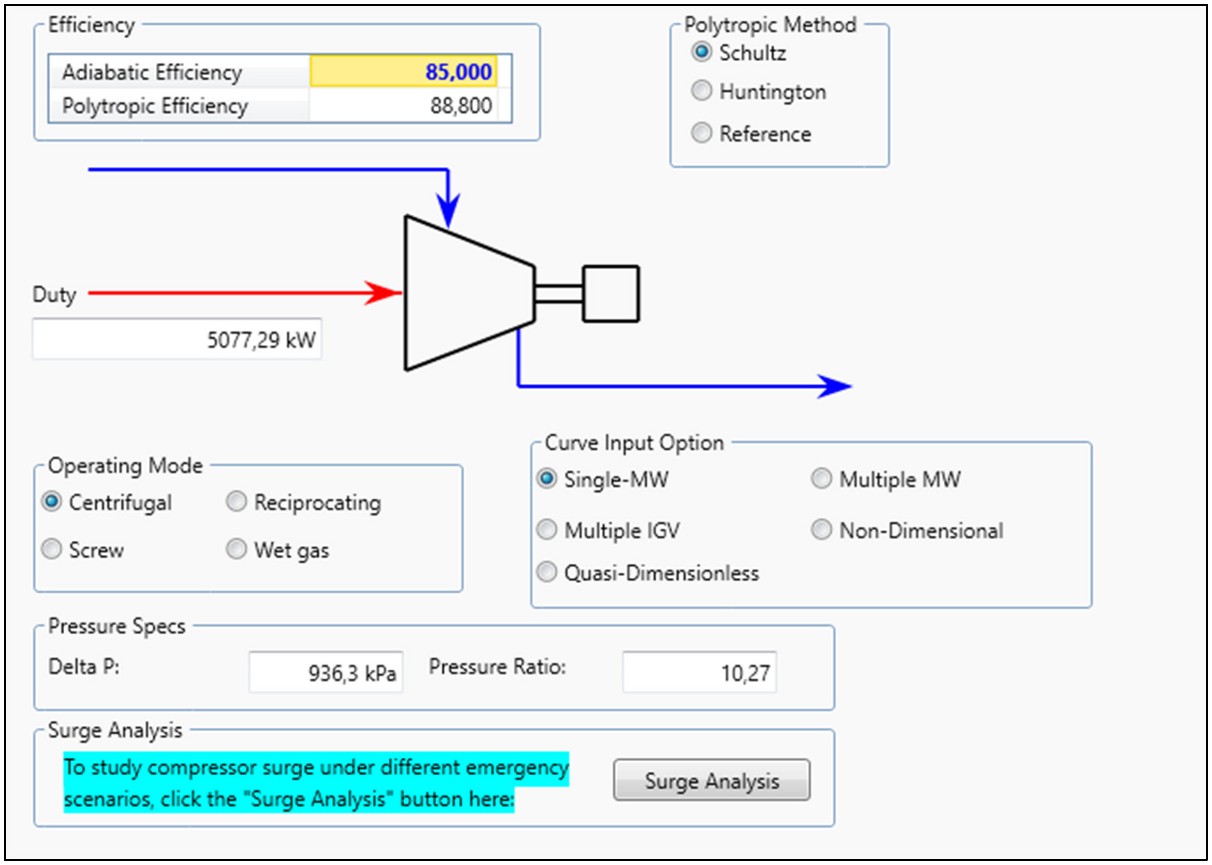


Figure 4.3 : Compressor configuration in Hysys

Compressor and Turbines, as the most important component of Brayton Cycle, are interesting cases to study.

Its parametrization is simple, as there isn't a lot of parameters to evaluate. Its configuration is illustrated in Figure 4.2 and Figure 4.3.

Except for the stream input, there is only two components required to evaluate : The pressure Ratio and the Efficiency. Other parameters can be inputed, as behavior curves, operating modes etc..

The Pressure Ratio can't be modified by an excel command, therefore it's the Output Pressure which is calculated. This led to the integration of security mesures in the code, as recalibration of components and construction verification. If the Entry Pressure is modified, the algorithm will need to modify Compressor/Turbine Output pressure as Aspen Hysys won't do it by itself.

Construction errors can be caused if the component is created in Hysys before the component which is supposed to precede it in the cycle. In this case, the input stream is not parametrized, therefore the output pressure cannot be calculated. Security and recalibration have been added to avoid these errors. These errors can be caused in each components.

Pressure Drops, Temperature Drops; and Fuel Flow functions the same way as pressure ratio and are to be recalibrated.

4.2.2 Combustion chamber

The combustion chamber, which serves as the primary heating process for the Gas Turbine, poses a greater challenge in terms of parameterization compared to preceding components. Indeed, as seen in Figure 4.4, a fuel input is required, that will complicate the parametrization.

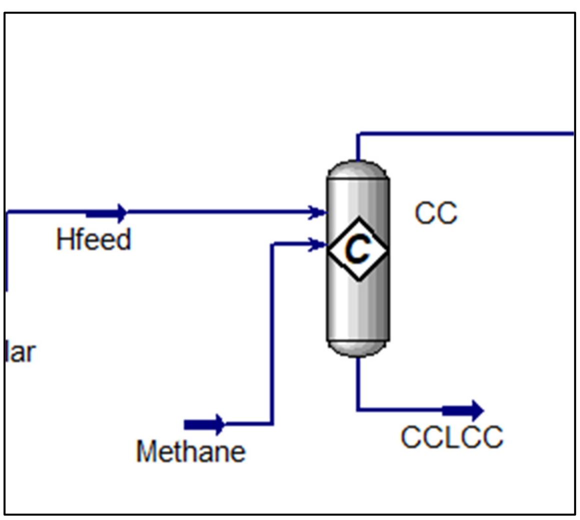


Figure 4.4 : Heat Exchanger in Aspen HYSYS

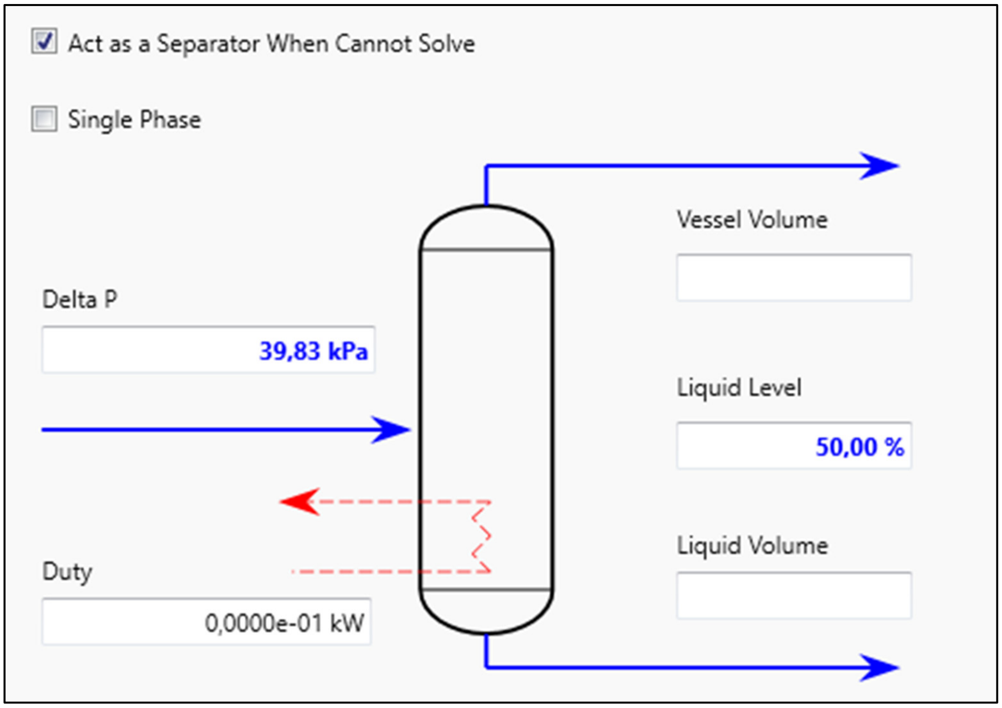


Figure 4.5 : Combustion Chamber Configuration in Hysys

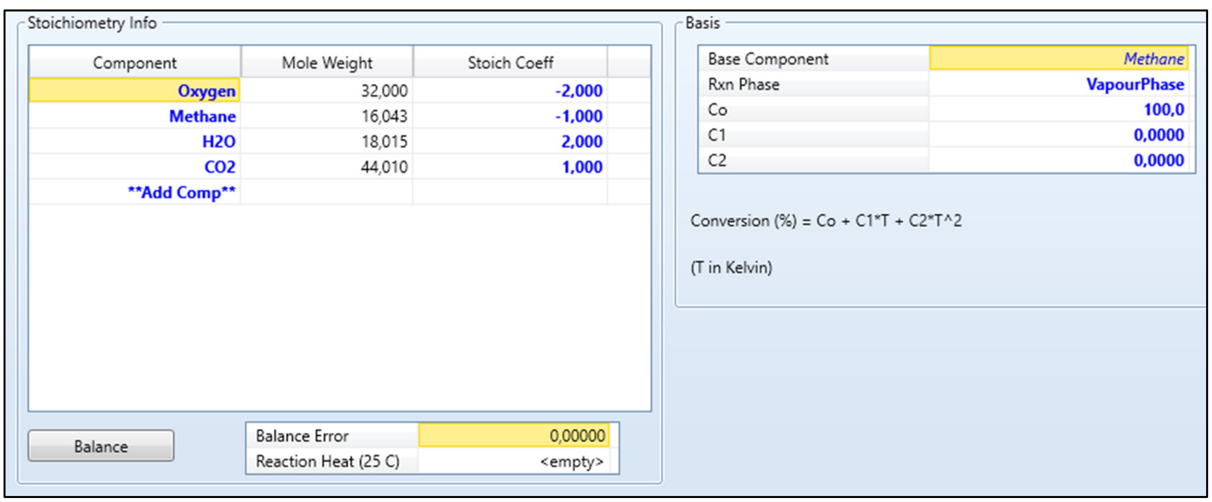


Figure 4.6 : Chemical reaction configuration in Hysys

This component has two inputs and two outputs. The inputs are composed of the input stream, the compressed fluid (generally air) and the Fuel Stream. The output consist of Liquid and Vapor Output. In the context this research is placed, only the vapor output is used.

The stochiometric reaction, described in Figure 4.6, that takes place in the combustion chamber needs to be parametrized. As for Gas Turbine, the air is in excess , (the component that is fully consumed must be parametrised too. The main Parameter for Combustion Chamber is the Output Temperature. This Temperature is refered as Flaming Temperature. If the input is the Flaming Temperature, he component will not converge, as the Fuel Mass Flow will not be calculated. Therefore, it is the Fuel Mass Flow that is set up by the application. An approximate Fuel Flow is set. Then, a loop adjust the Fuel Flow until the Flaming Temperature reach 99% of the wanted Flaming Temperature. Pressure Drop also needs be parametrized.

4.2.3 Heat exchanger

The last important component is the heat exchanger.

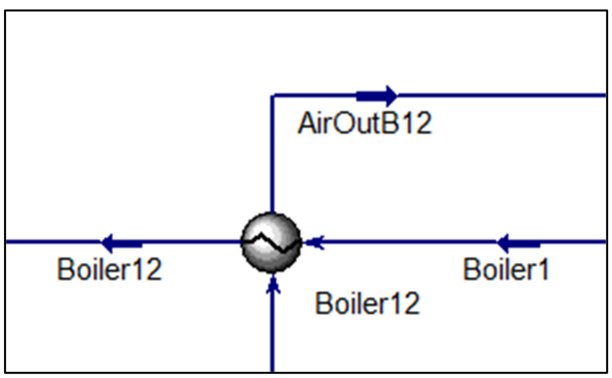


Figure 4.7 : Boiler in Aspen HYSYS

It is the main component used for regeneration cycles and for Rankine cycles. The heat Exchanger has many variations of configuration depending on its use. It is not possible to configurate a Heat Exchanger efficiency in Hysys, therefore the main parameter to input will be output Temperature (of the main stream).

To help Hysys converge in loop cycle (Rankine), there is three stages of heat exchanger to use. Below are the three stages and how they are configurate.

- Saturated Liquid: Vapor Percentage = 0
- Saturated Steam: Vapor Percentage = 1 (can be less than 0 if a separator is used)
- Superheated Steam: Temperature Outlet

These stages correspond to the heating process of water.

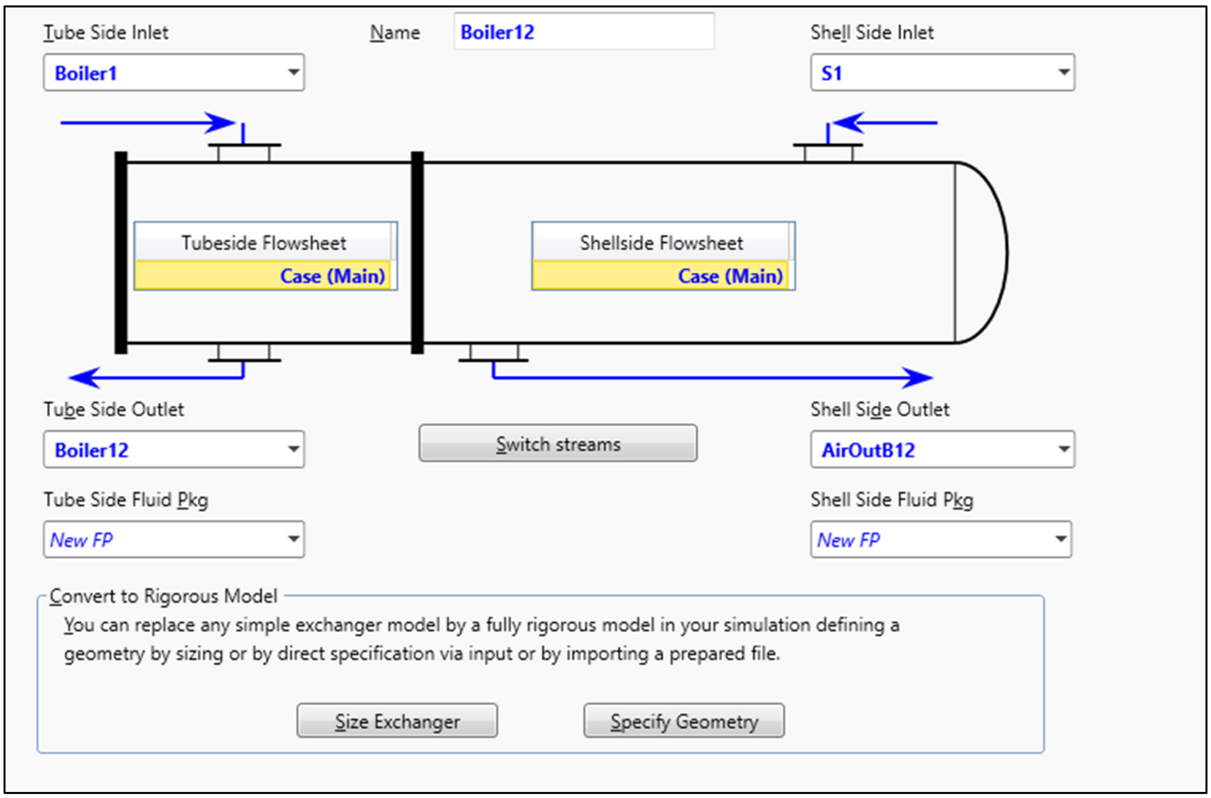


Figure 4.8 : Heat Exchanger configuration in HYSYS part.1

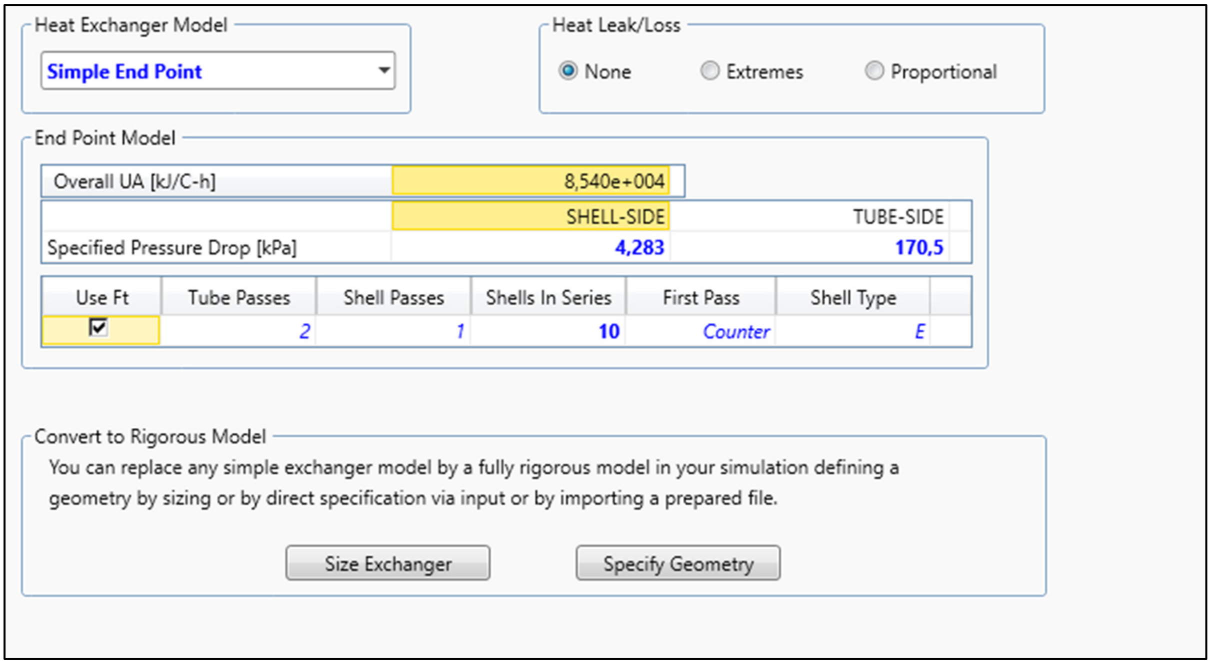


Figure 4.9 : Heat exchanger configuration in Hysys part.2

The size of the heat exchanger can also be configurate. It has not been implemented in the application yet.

4.2.4 Solar panel

There is no solar panel component currently available in Aspen HYSYS. Therefore, a new model has been created and added to the MDA. The solar panel model created for this application is composed of multiple components that will simulate a part of the integral process. For the application, a solar water heater has been modelized and is illustrated in Figure 4.10. This module have been inspired from the work of (Nshimyumuremyi et Junqi, 2019 ; Alwan *et al.*, 2022).

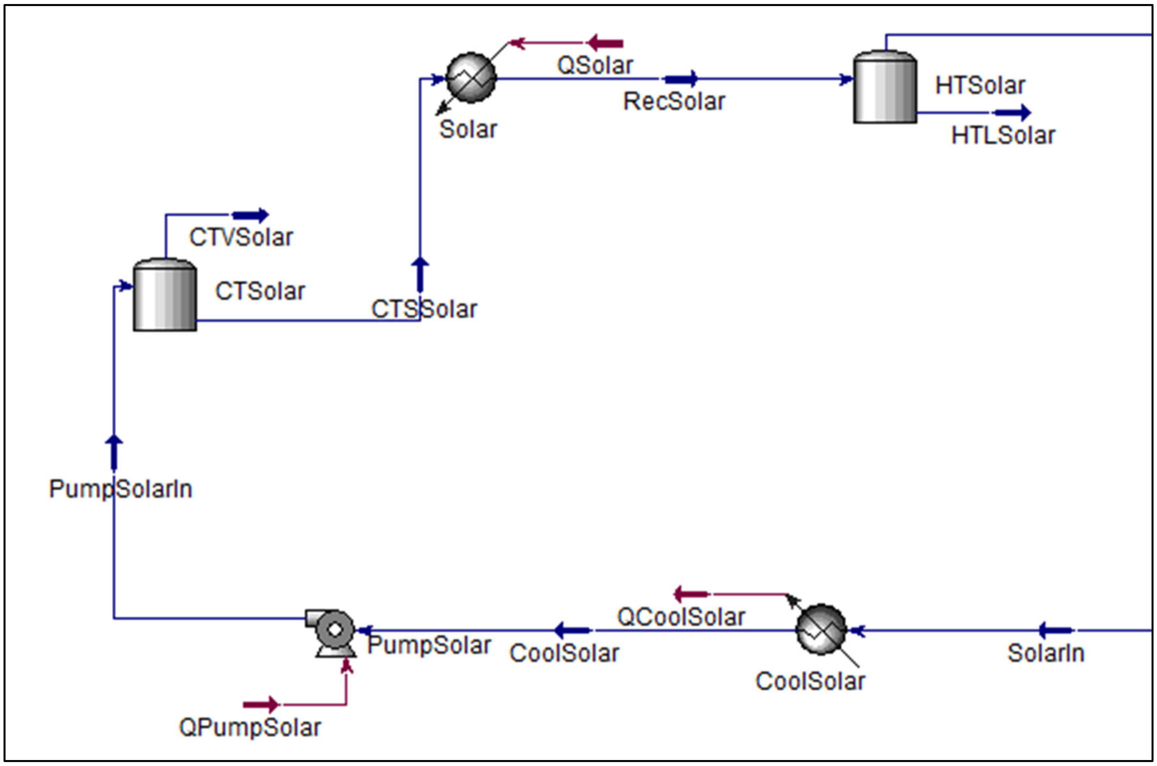


Figure 4.10 : Solar Water heater Components in Hysys

It is composed of a pump, one cold tank for storage, one heater, which will be assimilated to the solar receiver. Then, another tank for the storage of hot water/steam.

A heat exchanger, connected to the hot water tank and the cooler modules ensures the transmission of the generated heat to the main heat cycle. This component will provide the heat created through the solar panel to the associated heat cycle. The connection will be made afterward to create a loop for the water stream.

The other components are simple to configurate and can be found in Annex III.

4.3 Turbine and compressor design

As seen previously, compressor and turbine are the most important components of the gas Turbine. They are also the more costly component. Therefore, to push the design further, it is interesting to calculate some design characteristics of these components, as Diameter, Rotating speed, flow coefficient. These calculations are the basis for the implementation of a Component Database, where the different components available in the company are stored. Therefore, with the calculation of these parameters, fitted available components could be identified easily. This would improve the precision of the application, as the exact behavior of Compressor and Turbine would be known. This method can also apply to every component, depending on Company Production.

4.3.1 Compressor

Different methods have been used for the calculation of Compressor Design and Turbine.
The method used for Compressor is inspired of the Fullerman Design Method (Fullerman, 1967).

The idea is to calculate values as Tip Speed (tangential speed at the tip of an impeller), Mean Diameter and Rotating Speed of the Compressor impellers. To do so, two coefficients are used: Flow Coefficient φ and Stage Loading Coefficient λ. The user parameters these two-coefficient depending on the geometry wanted and the efficiency targeted. The user uses the Smith Chart Figure 4.11 (Coull et Hodson, 2013) to determine these values.

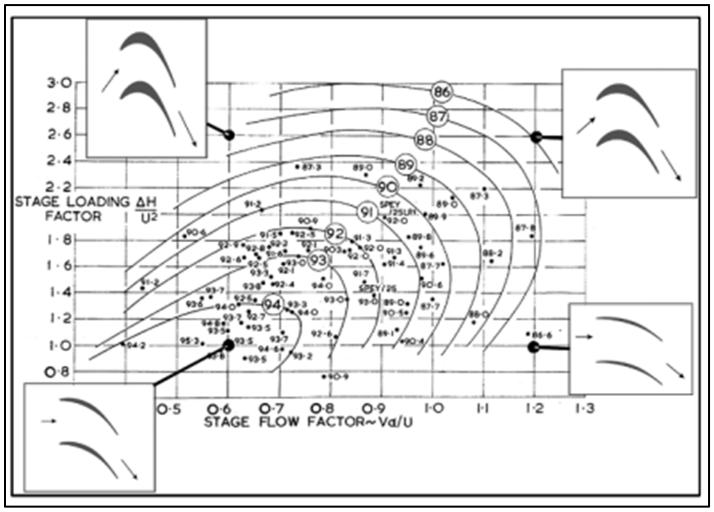


Figure 4.11 : Smith Chart
From Coull et Hodson, (2013, p2)

Once the efficiency is known, the pressure coefficient ψ is calculated from flow coefficient φ using the Flow/Pressure curve presented in Figure 4.12.

Therefore, as data from aspen HYSYS e.g., Pressure Ratio, Mass Flow Input Temperature, have been extracted, it is possible to determine the Head (*Hmax)* needed to compress the fluid. (Head is a variable used to measure work in compressors, expressed in N*m/K).
User has configured a maximum tip speed allowed (Physical limit of the Compressor). From this value, it is possible to calculate the Maximum Head per Stage ($\frac{H_{max}}{stage}$) as described in Eq (4.1)

$$\frac{H_{max}}{stage} = \frac{\psi}{32.2} * TipSpeed \qquad (4.1)$$

Where Tip Speed is expressed in ($\frac{ft}{s}$)
Therefore, with the Required Head, *Hmax* of the compressor and the maximum head per stage $\frac{H_{max}}{stage}$, it is possible to deduce the number of stages required in the compressor. From there,

actual tip speed, mean diameter (2*r) and Rotating Speed are calculated. Tip speed and mean diameter are illustrated in Figure 4.13.

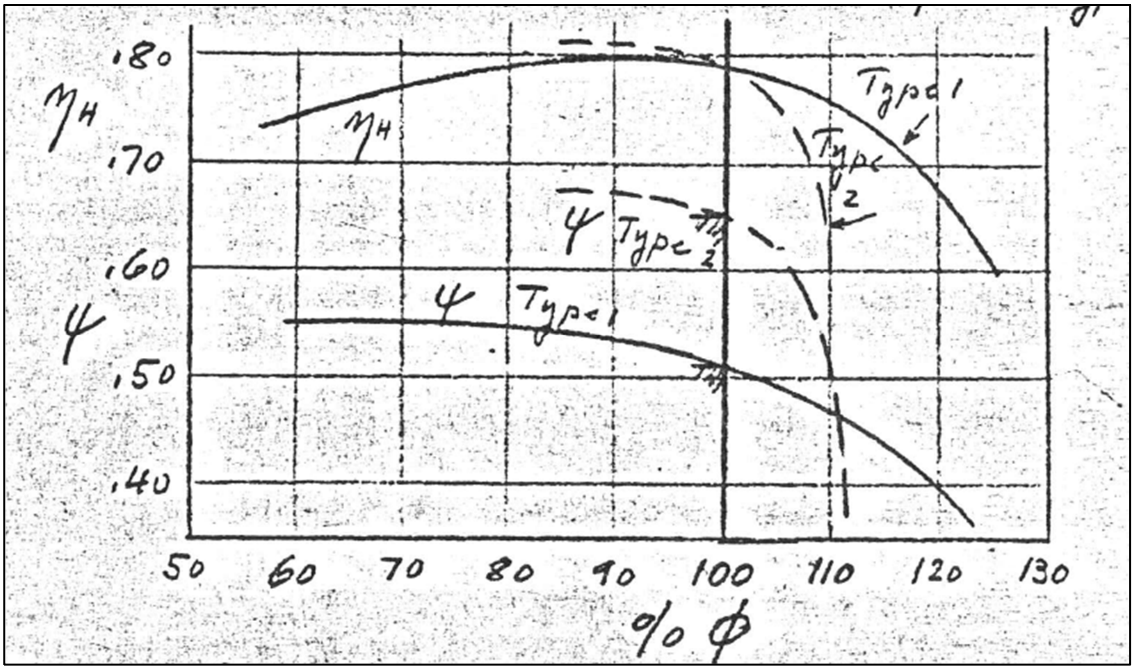


Figure 4.12 : Curve Flow/Pressure Coefficients
From Fullerman, (1967, p4)

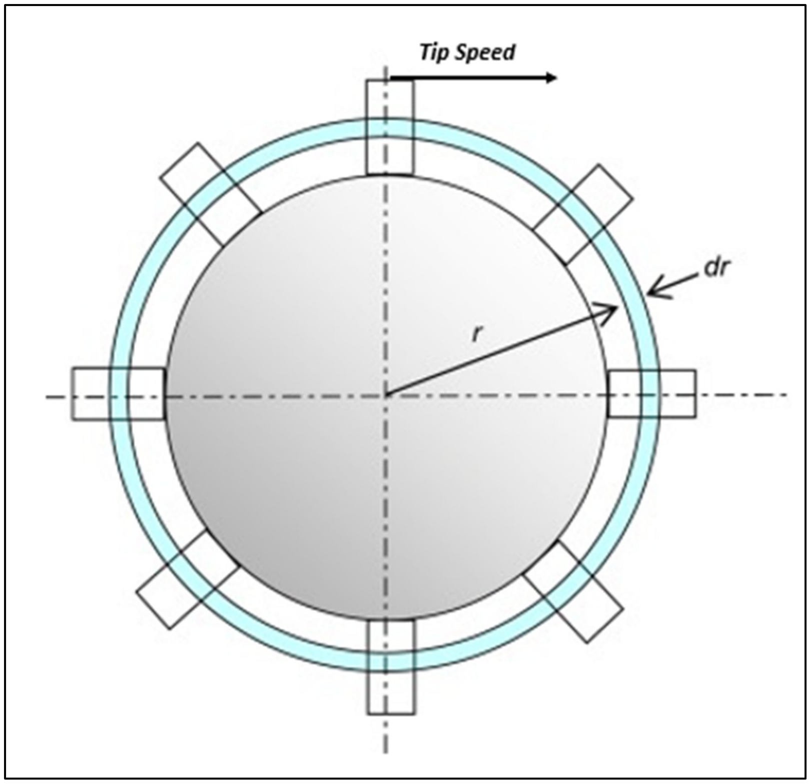


Figure 4.13 : Compressor schematic and representation of tip speed and mean diameter

4.3.2 Turbine

The principle is slightly different for Turbines, as the impellers are not powered, but are moved by the working fluid. Therefore, the calculation will be different and more axed on Blades geometry. This method is partially based on (Tournier et El-Genk, 2010) Method.

Multiple Parameters must be defined by the user. Flow Coefficient and Loading Factor as for compressor, The degree of reaction and the Hub tip ratio as well as the Max Tip Speed.

Degree of Reaction correspond to the part of pressure drop effectuated in Rotor (the other drop happens in stator part). The hub/tip ratio correspond to the difference between total Diameter of a pale versus Diameter of the rotor axe. These variables are very important parts of the blade

geometry and are to be fixed by the user. Depending on the values, the Turbine behavior can change drastically.
For now, only means values have been used, but a stage per stage design should be considered and implemented for more precise

By calculating Geometrical values as Blades angles (Alpha2) and from Values specified previously, it is possible to calculate the Temperature and pressure drop of each blade. Therefore, by running the calculation until we reach the proper pressure ratio, we can obtain the needed number of stages. From there, similarly to the compressor calculation. From there, tip speed, mean diameter and rotating speed can be deduced. (See Figure 4.13)

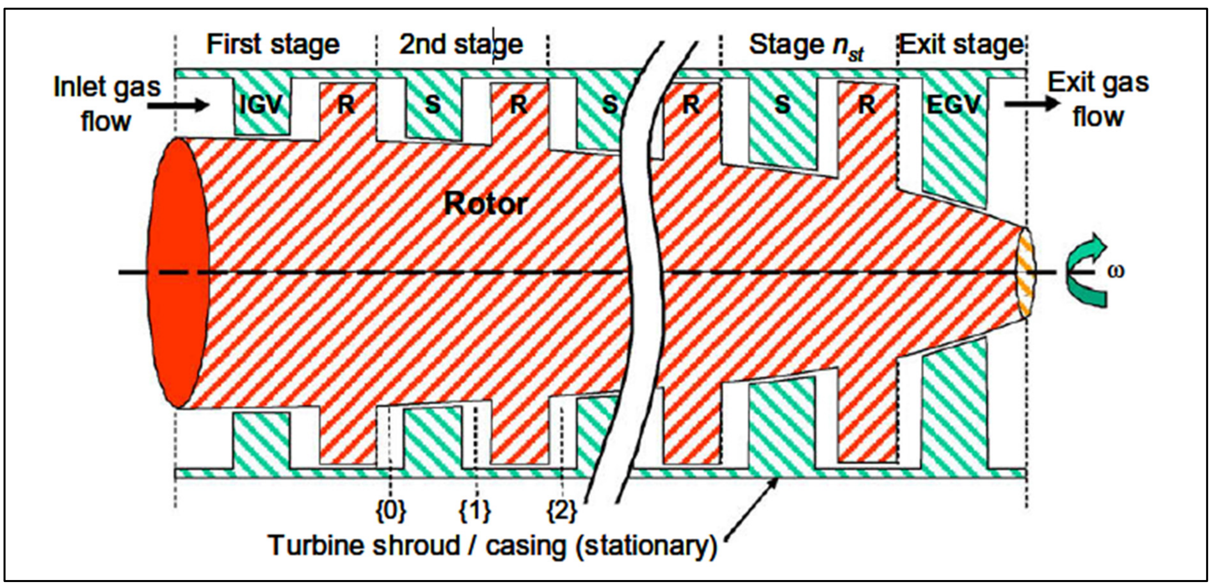


Figure 4.14 : Schematic of a turbine system
From Tournier et El-Genk, (2010, p18)

CHAPTER 5

DISCUSSION

5.1 Application upgrades

Even in the MDA gives great results and can function on its own, there is still a lot of improvement that can be made, either to increase the precision of the simulations or to improve the user experience and the interface accesibility.

First, as explained in Chapter 2, the application only runs the "Optimum Cycle" for one set of entry parameters. If the fuel is to vary, or ambient temperature for example, the user will need to rerun another simulation after the modification of said parameter.
An even more intuitive interface could be programed, with the integration of more userforms. The Results sheets can also be redesigned to allows easier read of results, and the automatization of cycles comparison graphs.

For the Simulation part, a lot of things could be added. First, as seen in Chapter 3, the methods for Compressor and turbine Design are basics, with the use of mean variables. It could help the cycle designs to improve these methods. Moreover, there is a lot of cycles and components that could be added into the system. The Solar Combined Cycle is one of the most important cycles which is missing. Other Solar-Derivate Heater could be integrated, with a more precise model for Solar receiver, with for example the model of a solar tower. Also, there are still some variables to take into account, e.g, the pressure and temperature drops that can occur between modules. The optimization process could also be extended to more variables to make the simulation more precise.

Storing each result in a large database would be helpful to reduce calculation time.

5.2 Towards a higher degree of modularity

The MDA gives a great overview of how to implement modularity into the design of Gas Turbines, by the design of different cycles, with many components, and modifiable inputs. But also, by the comparison of different stored cycles for different inputs, allowing to furnish the customer a quick solution which matches its specific requirements.

However, there is lot to implement to reach a full modularity in the application.

First, a solution suggested in Chapter 3 would be to implement a database of components. Like for compressors, it would help calibrate the simulation to the exact behavior of compressor available in the company. Therefore, the company could propose to their customers results for a solution that would be the same as the real one.

Another addition that could be interesting would be the integration of recycling components. This approach has been observed at the end of chapter 2, in the study case, where the core of the first solution were reused. However, it was not considered into the solution. Therefore, the price of reused components was not taken into account. It would then be very interesting to incorporate the idea of reused components. It could be done by selecting components of a cycle that are reused, enter cost parameters of thus components (if investment done, how much paid already etc…).

A possibility would be to open the application to a customer use. It could be made into an add-on in the company website, where the customer enters it specifications and gets a quick overview of the price available for him. It would fasten the discussions between company and customer as if there is no solution fitted for the customer, he will not have to engage discussions.

CONCLUSION

With the aim of improving the design and optimization of gas turbines, this research explored the principles of modularity within the context of Industry 4.0. It has uncovered the profound impact of modularity on the gas turbine sector, revolutionizing the way engineers and designers approach the complex task of gas turbine cycle development, while involving customers.

Throughout this research, modularity ease to allow engineers to create custom gas turbine cycles tailored to meet specific customer requirements was highlighted. By selecting from a diverse range of components and configuring inlet temperatures, gas turbine engineers can now navigate a dynamic landscape of possibilities, adapting their designs to suit unique operational constraints and performance objectives. This level of customization not only ensures the optimization of gas turbine cycles but also promotes an environment of innovation and adaptability within the industry.

Moreover, the integration of advanced simulation algorithms and optimization techniques has demonstrated the ability to predict cycle efficiency with precision, facilitating the identification of cost-efficient solutions. Our research has highlighted the potential for significant gains in operational excellence and cost competitiveness, setting a new standard for gas turbine cycle performance.

The gas turbine sector, like many others, is at the intersection of technological advancement and sustainability imperatives. By embracing modularity and Industry 4.0 principles, we are not only advancing the efficiency and cost-effectiveness of gas turbine technology but also contributing to global efforts to reduce carbon emissions and secure a sustainable energy future.

The application developed in this research comes to fill a need in the gas turbine sector and brings a solution to design, optimize and store multiple heat cycles, made up of several components. Components are not restricted to classical Compressors and turbines but are extended to newer components as solar water heater. This allows way more flexibility for the engineer to design a gas turbine most fitted to the customer requirements.

This research therefore focused on the creation of a modular design application. Using Excel and Aspen Hysys, it was possible to create a reliable application. This application has two operating principles. The first is a heat-cycle-free design. The operator can arrange the various components as he wishes, change input parameters, and output requirements, and test these cycles at will. Tested and approved cycles are then stored. The second principle uses these stored cycles to make rapid comparisons between existing cycles. For the same input request, meeting the customer's requirements, the application will compare the different cycles and calculate the optimum cycle and its operating point. This provides a highly accurate initial estimate, enabling engineers to concentrate on refining a single solution.

Looking forward, the prospects are promising. The application met the different objectives fixed, of modularity, design, optimization, and comparison. Results are consistent and in line with literature, and the study case realized demonstrate the powerness of this application. This research lays the foundation for continued innovation and progress within the field of gas turbine. As new technologies emerge and data-driven decision-making becomes increasingly prevalent, the role of modularity will only grow in significance.

In closing, this thesis represents more than just a culmination of research; it signifies a commitment to a sustainable and technologically advanced future. It invites gas turbine engineers, designers, and stakeholders to embrace the potential of modularity, harness the capabilities of Industry 4.0, and marks the beginning of continuous improvement in gas turbine technology. Together, we have unlocked the door to a new era in the gas turbine sector, one marked by efficiency, adaptability, and environmental responsibility.

RECOMMENDATIONS

The modular design application is working properly and giving decent results. Its use has been illustrated trough a study case. However, this application is not perfect and could be granted multiple upgrades.
First of all, the application could be made more autonomous. For now, it is not possible to run simulations with different fuels to compare their results. It has to be made in two simulations. A great way of amelioration would be the integration of crossed simulations with different inputs.
Interface could also be redesign, to be cleaner. The results page, which is only a table needs to be worked on to improve the readability of the results. A result extraction process could be considered to ease the creation of graphs.

Modularity is already well-implemented in the application but can also be pushed forwards. A component database, with existing, in-house components, would be interesting to have simulations fitted to solutions the company is truly able to provides.
The integration of a life-cycle system could be pertinent. The reuse of existing components could facilitate the end of life of several components, reduce the global cost for both customer and company.

ANNEX I

CODE OF THE APPLICATION

You can find the Excel Application, all the VBA code, and the principal results of the simulations (comparison, study case, multiple cycles…) at this address: https://github.com/LucasChavanel/ModularGTExcel.git

- ModularGTApplication : The Excel application which connects to Aspen, store cycles and optimize the cycles.

- StudyCaseGT : The Excel where are isolated the results obtained in the study case discussed in the article.

- ValidationResults : The Excel where is stored all other results used in the study

ANNEX II

HYSYS CONFIGURATION OF COMPONENTS

In this annex, screenshots of the configuration of several components integrated in the application are displayed.

a) Fired Heater

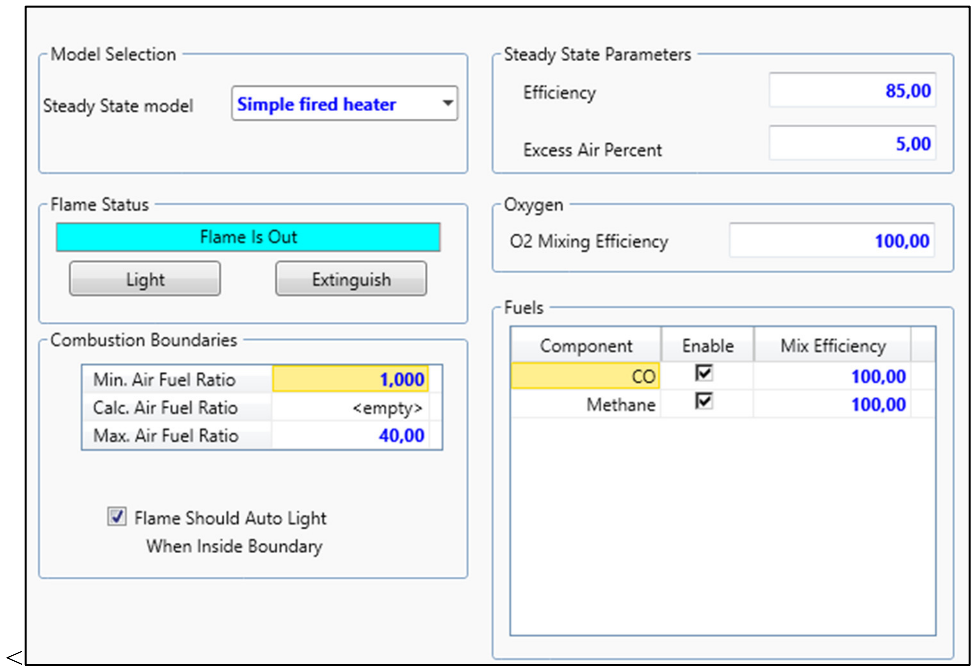


Figure A2.1 : Fired Heater configuration

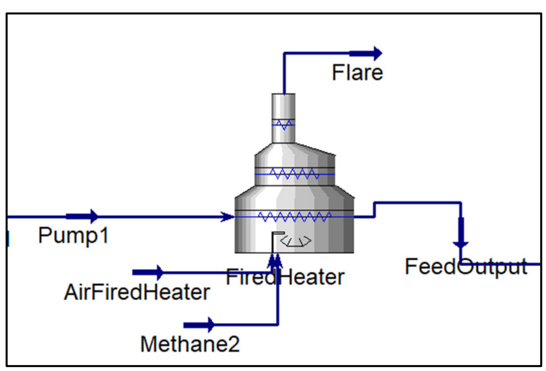


Figure A2.2 : Fired Heater icon

b) Pump

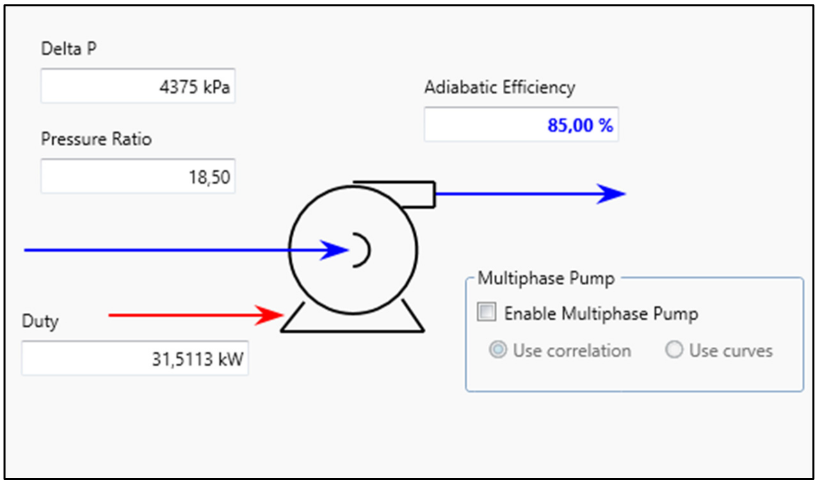


Figure A2.3 : Pump configuration

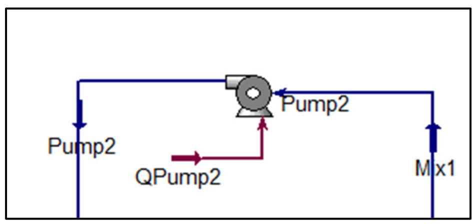


Figure A2.4 : Pump icon

c) Tank/Separator

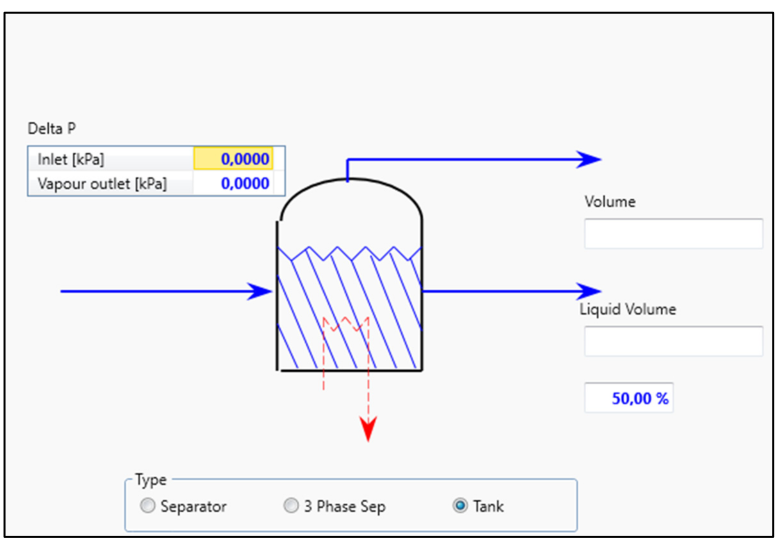


Figure A2.5 : Tank/Separator configuration

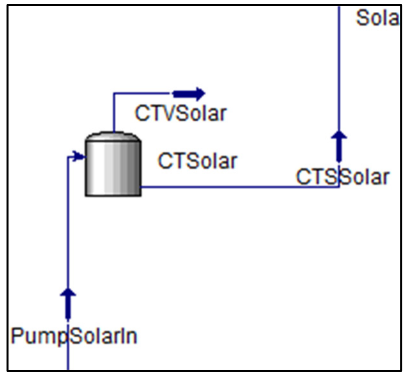


Figure A2.6 : Tank/Separator icon

d) Splitter

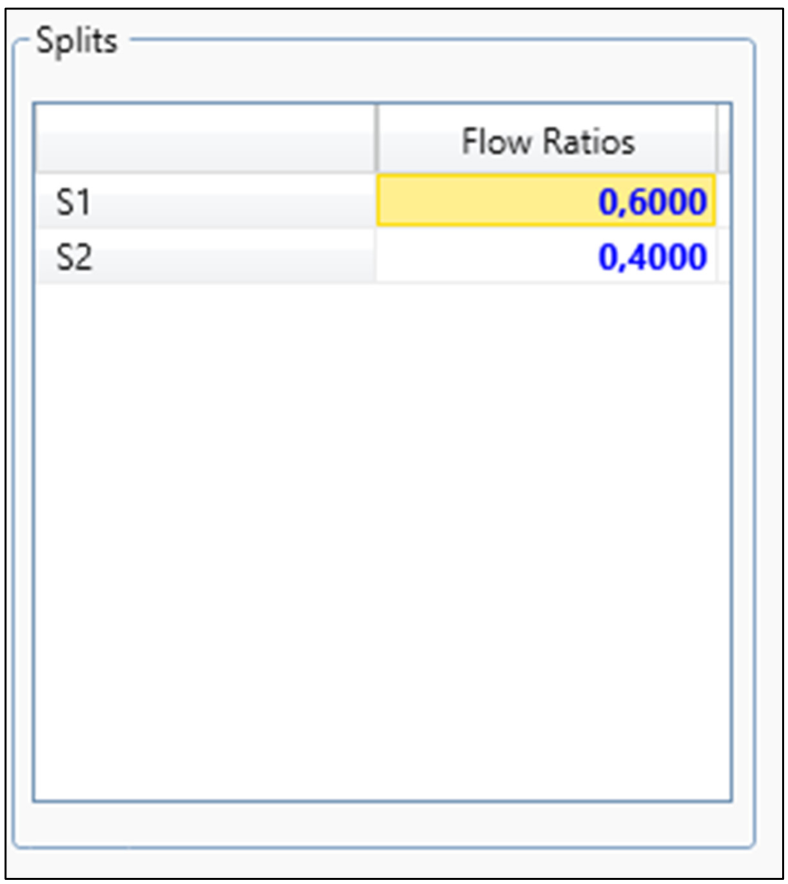


Figure A2.7 : Splitter configuration

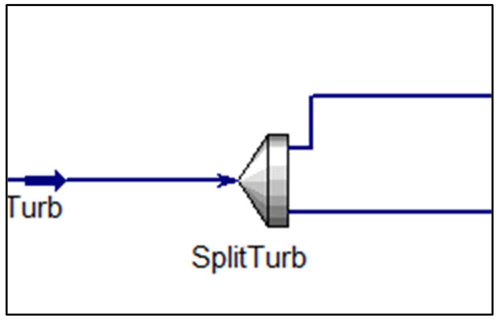


Figure A2.8 : Splitter icon

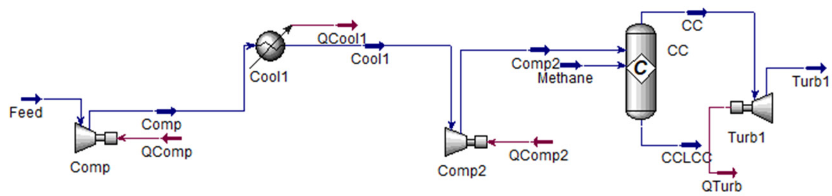
Components like Steam Turbines, Condenser, Heater, mixer are not shown as they are derivate components from the previous ones.

ANNEX III

HYSYS SIMULATION OF HEAT CYCLES

This annex contains the heat cycles calculated, and the different values calculated by HYSYS for one set of parameters

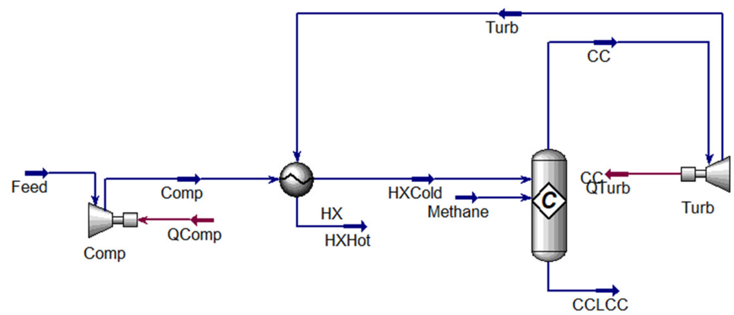
a) 2 Compressors Brayton



Material Streams										
		Feed	Methane	Methane2	Comp	Cool1	Comp2	CC	Turb1	CCLCC
Vapour Fraction		1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	0,0000
Temperature	K	280,0	350,0	1000	408,4	330,0	479,2	1320	844,5	1320
Pressure	kPa	101,0	3500	300,0	323,2	310,3	992,9	953,2	106,8	953,2
Molar Flow	kgmole/h	1,014e+004	374,2		1,014e+004	1,014e+004	1,014e+004	1,052e+004	1,052e+004	0,0000
Mass Flow	kg/s	81,28	1,668		81,28	81,28	81,28	82,95	82,95	0,0000
Liquid Volume Flow	m3/h	338,3	20,05		338,3	338,3	338,3	350,7	350,7	0,0000
Heat Flow	kW	-1513	-7635		9122	2567	1,509e+004	7453	-4,070e+004	0,0000

Figure A3.1 : Compressors Brayton cycle calculation

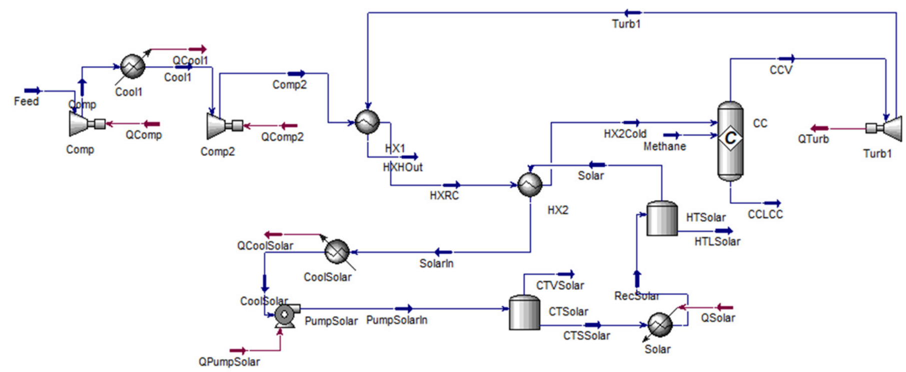
b) Regeneration Brayton



Material Streams									
		Feed	Methane	Comp	Turb	HXCold	HXHot	CC	CCLCC
Vapour Fraction		1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	0,0000
Temperature	K	280,0	350,0	581,2	849,8	849,0	592,3	1335	1335
Pressure	kPa	101,0	3500	1037	107,1	995,8	103,1	955,9	955,9
Molar Flow	kgmole/h	1,130e+004	248,3	1,130e+004	1,155e+004	1,130e+004	1,155e+004	1,155e+004	0,0000
Mass Flow	kg/s	90,54	1,107	90,54	91,65	90,54	91,65	91,65	0,0000
Liquid Volume Flow	m3/h	376,8	13,31	376,8	385,0	376,8	385,0	385,0	0,0000
Heat Flow	kW	-1686	-5067	2,664e+004	-5114	5,328e+004	-3,175e+004	4,821e+004	0,0000

Figure A3.2 : Regenerative Brayton cycle calculation

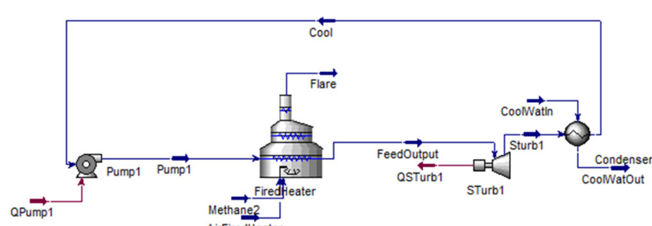
c) Solar Regenerative Brayton



Material Streams										
			Feed	Methane	SolarIn	Solar	Comp	Cool1	Comp2	Turb1	HXRC
Vapour Fraction		0,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Temperature	K	280,0	288,0	350,0	688,1	893,0	419,7	330,0	479,2	678,6	500,0
Pressure	kPa	101,0	101,0	3500	92,39	96,23	323,2	310,3	992,9	99,41	953,2
Molar Flow	kgmole/h	1199	3100	44,71	3038	3038	3100	3100	3100	3145	3100
Mass Flow	kg/s	6,000	24,84	0,1992	15,20	15,20	24,84	24,84	24,84	25,04	24,84
Liquid Volume Flow	m3/h	21,64	103,4	2,396	54,84	54,84	103,4	103,4	103,4	104,9	103,4
Heat Flow	kW	-9,580e+004	-262,0	-912,2	-1,924e+005	-1,857e+005	3081	784,7	4612	-718,1	5160
		HXHOut	HX2Cold	CCV	PumpSolarIn	CoolSolar	CTSSolar	CTVSolar	RecSolar	HTLSolar	
Vapour Fraction		1,0000	1,0000	1,0000	0,0000	0,0000	0,0000	1,0000	1,0000	0,0000	
Temperature	K	658,9	750,0	1085	280,0	280,0	280,0	280,0	893,0	893,0	
Pressure	kPa	95,41	915,0	887,6	101,3	88,39	101,3	101,3	101,3	96,23	
Molar Flow	kgmole/h	3145	3100	3145	3038	3038	3038	0,0000	3038	0,0000	
Mass Flow	kg/s	25,04	24,84	25,04	15,20	15,20	15,20	0,0000	15,20	0,0000	
Liquid Volume Flow	m3/h	104,9	103,4	104,9	54,84	54,84	54,84	0,0000	54,84	0,0000	
Heat Flow	kW	-1266	1,188e+004	1,097e+004	-2,427e+005	-2,427e+005	-2,427e+005	-0,0000	-1,857e+005	-0,0000	

Figure A3.3 : Solar regenerative Brayton cycle calculation

d) Rankine Cycle



Material Streams										
		Cool	CoolWatIn	Methane2	Pump1	FeedOutput	Flare	Sturb1	CoolWatOut	AirFiredHeater
Vapour Fraction		0,0000	0,0000	1,0000	0,0000	1,0000	1,0000	1,0000	0,0113	1,0000
Temperature	K	300,0	288,0	1000	300,2	1200	1214	650,1	371,9	280,0
Pressure	kPa	101,0	101,0	300,0	4040	4040	101,0	106,3	96,96	101,0
Molar Flow	kgmole/h	991,1	7993	158,5	991,1	991,1	1744	991,1	7993	1585
Mass Flow	kg/s	4,960	40,00	0,7065	4,960	4,960	13,41	4,960	40,00	12,71
Liquid Volume Flow	m3/h	17,89	144,3	8,495	17,89	17,89	58,13	17,89	144,3	52,88
Heat Flow	kW	-7,876e+004	-6,373e+005	-1609	-7,874e+004	-5,716e+004	-2,343e+004	-6,318e+004	-6,217e+005	-236,6

Figure A3.4 : Rankine cycle calculation

e) Combined Cycle

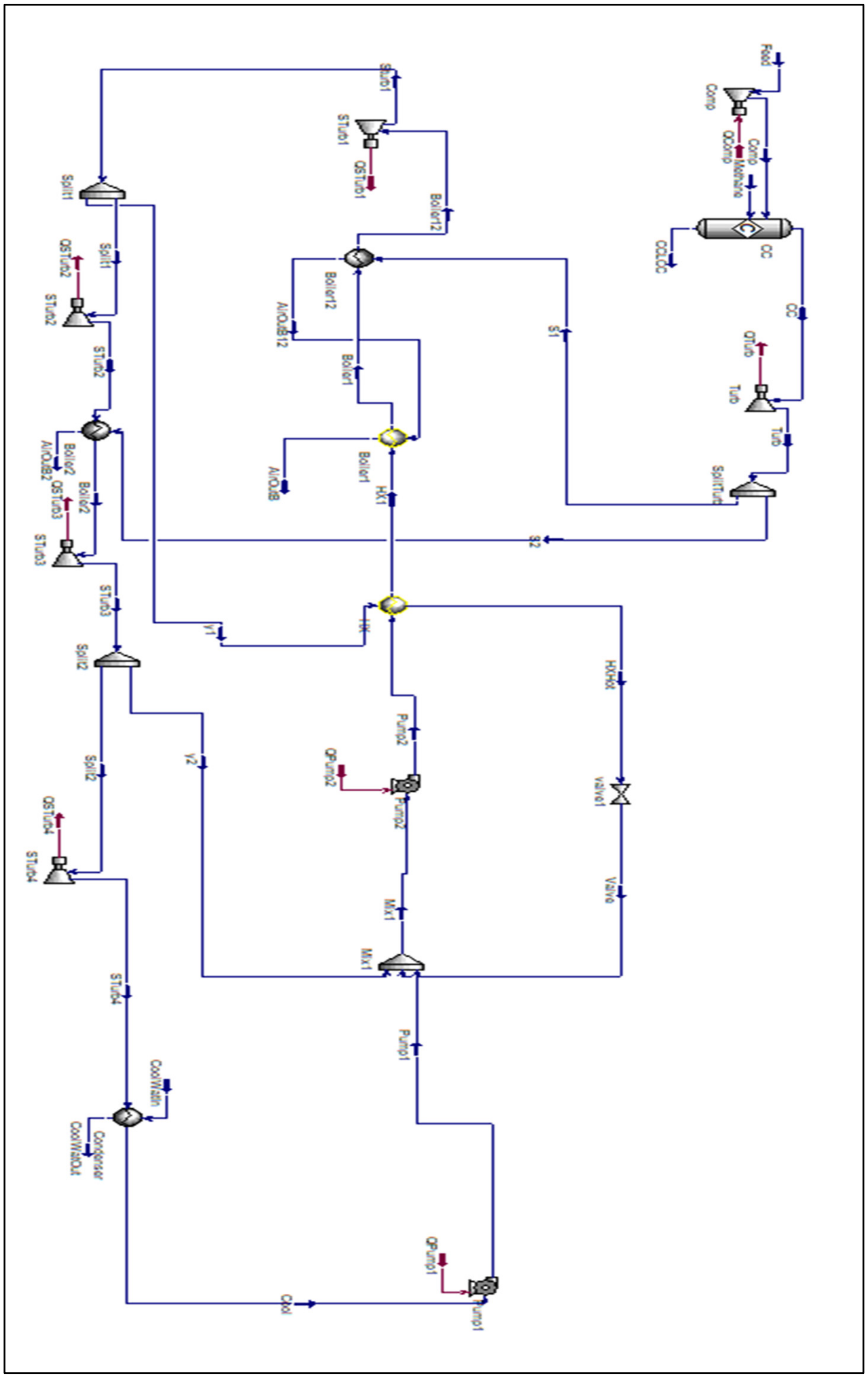


Figure A3.5 : Combined Cycle in Aspen Hysys

Material Streams												
		Mix1	Feed	CoolWatIn	Methane	Comp	CC	Turb	S1	S2	Cool	Pump1
Vapour Fraction		0,0000	1,0000	0,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	0,0000	0,0000
Temperature	K	280,0	288,0	288,0	350,0	596,8	1251	794,7	794,7	794,7	300,0	300,0
Pressure	kPa	250,0	101,0	101,0	3500	1037	995,8	111,5	111,5	111,5	101,0	262,6
Molar Flow	kgmole/h	1199	1881	7993	53,86	1881	1935	1935	1161	773,9	479,6	479,6
Mass Flow	kg/s	6,000	15,07	40,00	0,2400	15,07	15,31	15,31	9,188	6,126	2,400	2,400
Liquid Volume Flow	m3/h	21,64	62,73	144,3	2,886	62,73	64,52	64,52	38,71	25,81	8,657	8,657
Heat Flow	kW	-9,580e+004	-159,0	-6,373e+005	-1099	4689	3590	-4774	-2864	-1910	-3,811e+004	-3,811e+004
		y2	Valve	Pump2	y1	HX1	HXHot	AirOutB12	Boiler1	AirOutB	Boiler12	Sturb1
Vapour Fraction		1,0000	0,0000	0,0000	1,0000	0,3492	0,0000	1,0000	1,0000	0,9089	1,0000	1,0000
Temperature	K	460,9	138,2	280,2	495,9	530,8	137,9	696,4	528,3	137,3	600,0	495,9
Pressure	kPa	291,0	250,0	4625	1719	4440	1715	107,1	4262	103,1	4092	1719
Molar Flow	kgmole/h	119,9	599,5	1199	599,5	1199	599,5	1161	1199	1161	1199	1199
Mass Flow	kg/s	0,6000	3,000	6,000	3,000	6,000	3,000	9,188	6,000	9,188	6,000	6,000
Liquid Volume Flow	m3/h	2,164	10,82	21,64	10,82	21,64	10,82	38,71	21,64	38,71	21,64	21,64
Heat Flow	kW	-7873	-4,981e+004	-9,577e+004	-3,928e+004	-8,523e+004	-4,981e+004	-3897	-7,857e+004	-1,056e+004	-7,753e+004	-7,855e+004
		Split1	STurb2	Boiler2	AirOutB2	STurb3	Split2	STurb4	CoolWatOut	CCLCC		
Vapour Fraction		1,0000	0,9706	1,0000	1,0000	1,0000	1,0000	1,0000	0,0000	0,0000		
Temperature	K	495,9	439,4	550,0	672,3	460,9	460,9	429,0	325,5	1251		
Pressure	kPa	1719	721,8	692,9	107,1	291,0	291,0	206,0	96,96	995,8		
Molar Flow	kgmole/h	599,5	599,5	599,5	773,9	599,5	479,6	479,6	7993	0,0000		
Mass Flow	kg/s	3,000	3,000	3,000	6,126	3,000	2,400	2,400	40,00	0,0000		
Liquid Volume Flow	m3/h	10,82	10,82	10,82	25,81	10,82	8,657	8,657	144,3	0,0000		
Heat Flow	kW	-3,928e+004	-3,972e+004	-3,886e+004	-2765	-3,937e+004	-3,149e+004	-3,164e+004	-6,308e+005	0,0000		

Figure A3.6 : Combined cycle calculation

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