AN ARCHITECTURE-BASED GROWTH APPROACH FOR INDUSTRIAL GAS TURBINE PRODUCT DEVELOPMENT

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AN ARCHITECTURE-BASED GROWTH APPROACH FOR INDUSTRIAL GAS TURBINE PRODUCT DEVELOPMENT

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To my greatest family: Your unconditional love and unwavering support serve as my strongest reinforcement to finally win this uphill battle! You are my true heroes! I love you so much! Wo Ai Ni Men!

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I can hardly recollect how and when exactly my Ph.D. journey started. What it matters to me is that it's a crusade I'm committed to accomplishing once the stopwatch starts to tick. The Odyssey is neither easy nor short of frustrations or setbacks. But I believe this is the only way to truly become a respectable scholar. Every step of the way forward, I was offered the unwavering and generous support from my beloved ASDLers and family. Nonetheless, I never take it for granted. I feel so much obliged to them from the heart. Rain or shine, they keep me grounded and motivated.

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LIST OF SYMBOLS AND ABBREVIATION

AC	Alternating Current
ANN	Artificial Neural Network
CTQ	Critical-To-Quality
DLN	Dry Low NOx
DOE	Design of Experiment
ERD	Entity Relation Diagram
FOM	Figure of Merit
GA	Genetic Algorithm
MG	Maximum Growth
GP	Gaussian Process
GR	Growth Range
GT	Gas Turbine
IGV	Inlet Guided Vane
IPPD	Integrated Product and Process Design
MHPS	Mitsubishi Hitachi Power Systems
LTU	Long Term Uprate
NASA	National Aeronautical and Space Administration
OEC	Overall Evaluation Criteria
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
RFP	Request for Proposal
RPM	Revolution per Minute
STU	Short Term Uprate

TBP	Thermal Barrier Coating
TIES	Technology Identification, Evaluation, and Selection
TIF	Technology Impact Forecasting
TIT	Turbine Inlet Temperature
TL	Technology Level
TRL	Technology Readiness Level
UTE	Unified Trade Environment

SUMMARY

Gas turbine development projects present difficult and complex design decisions for turbomachinery manufacturers. A successful product growth program must prove itself in the engineering field as well as in the business arena. Within the past seven decades, the industrial gas turbine has undergone continuous performance improvement in terms of thermodynamics, emission, reliability, maintainability, etc. However, the enablers behind this glory remain to be uncovered as the decision-making mechanism on product development is highly proprietary and subjective to change from one manufacturer to the other. In this research, an architecture-based methodology has been developed to understand and interpret the ascending performance trajectory of industrial gas turbines from a growth perspective. Historical data depicting the product evolvement are examined to reveal trends and features that can be tied to the published design philosophy and practices in this industry. Quantifiable growth metrics are introduced and deployed in an established framework that offers a scientific product development environment to emulate the prevalent product development practices. Furthermore, the capability established by this methodology is expected to support performance prediction and planning for future gas turbine products.

Within the context of the industrial gas turbine, it is well-observed that there are two common avenues of conducting product development. The first one is known as Product Improvement Program (PIP), which intends to improve the overall performance of an existing product architecture incrementally via technology infusion and partial redesign. This path enables products to “grow” with minimized product life cost and risk by recycling the existing design and production resources. The built-in growth is the amount of growth included in a given PIP. The capability to quantify this part of growth serves as a key decision factor upon future product architecture. An existing technology-based

design approach is augmented to gauge the built-in growth of a gas turbine architecture as well as to conduct enabling technology selection and prioritization. Once top technology candidates are identified, valuable resources are allocated accordingly to tap into the built-in growth for the most performance improvement. New Architecture Introduction (NAI) provides another route to "grow" industrial gas turbines. This program expands the existing product variety by unveiling a different architecture with substantially performance improvement. The new architecture typically features a redesigned flow-path and a more advanced technology class. The designed-in growth is introduced as the amount of growth intentionally implanted into the first product of a new architecture to be fulfilled later when the corresponding technologies mature. It assumes that emerging technology's impact can be predicted at a reasonable confidence level during its development stage. The product growth is designed into the new architecture by sizing the gas turbine technologies at a future level and then "adjust" its performance to the current technology level. Once the initial design and the fully-grown design are determined, the planned product development path for the new architecture is obtained.

To test the individual enabling steps within the architecture-based growth approach, two case studies are performed. The first case study is designed to demonstrate the capability of using Technology, Identification, Evaluation, and Selection (TIES) methodology to conduct built-in growth quantification for existing products and technology prioritization for subsequent development. The second case study focuses on the performance comparison of products developed using the two different product growth paths, i.e. PIP and NAI.

In addition to experiments, a case study is designed and carried out to demonstrate the full scope of capabilities equipped by this growth framework. The first part of the case study investigates the PIP options for an existing gas turbine architecture. The impact of each technology option is modeled so that built-in growth is quantified for the product as well as the architecture. The second part of the case study combines the designed-in growth concept with the prevalent gas turbine design techniques to generate a product development path for a new architecture. The thermodynamic performances of both initial and ultimate products are obtained using forecasted technology inputs.

Through development, testing, and implementation of the methodology, the objective of this research is achieved. Built upon the concept of architecture-based growth, this established framework puts built-in growth to use for existing architecture evolvement and utilizes designed-in growth to sketch the roadmap forward for new architecture development. The structured growth approach provides an alternative way for industrial GT designers to make informed design decisions upon developing industrial gas turbine products of the next generation and beyond.

CHAPTER I

INTRODUCTION

Gas turbines (GTs) see a broad range of applications in land, sea, and air usage. Ground-based GTs commonly operate as power sources to electrical generators. Since the end of the 1980s, they have emerged as a core component of modern power plants. Power output and efficiency are two major figures of merit (FOM) for this particular type of turbomachinery. Depending on specific applications, this simple-cycle GT can have an output power ranging from single-digit megawatts (micro-turbine) up to 400+ megawatts (heavy duty) with current maximum operational efficiency exceeding 40%. Amazingly, this machinery can also be operated along with steam turbines and thus forming an advanced cycle (such as combined cycle) to achieve a total plant efficiency above 60%. In this work, the focus is placed on the conceptual design practice dedicated to simple-cycle industrial GTs used for electricity generation.

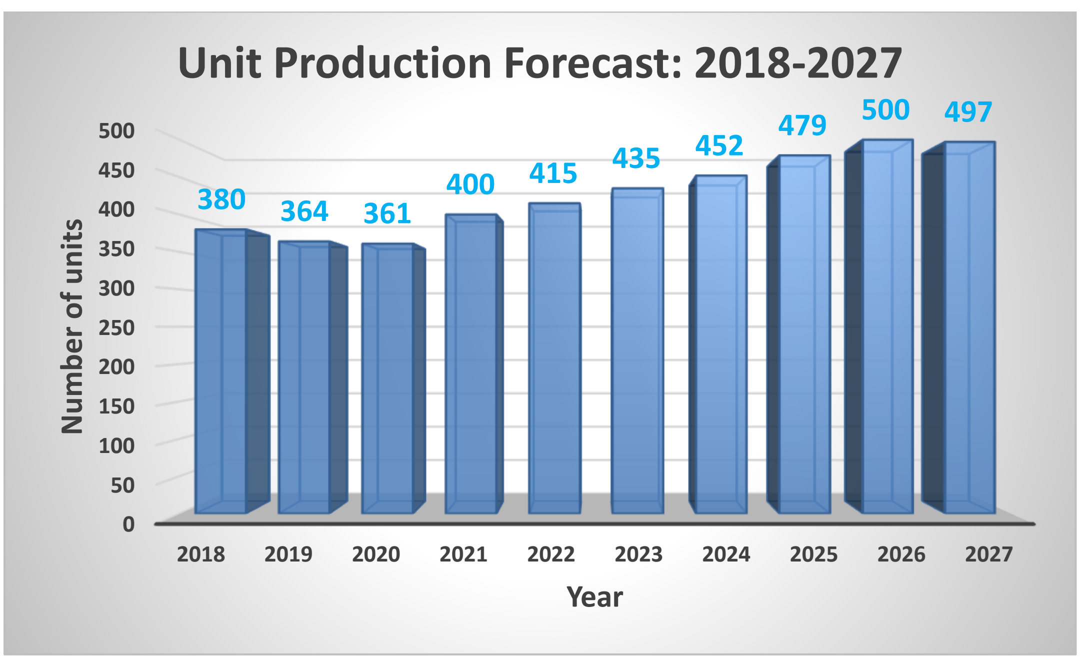


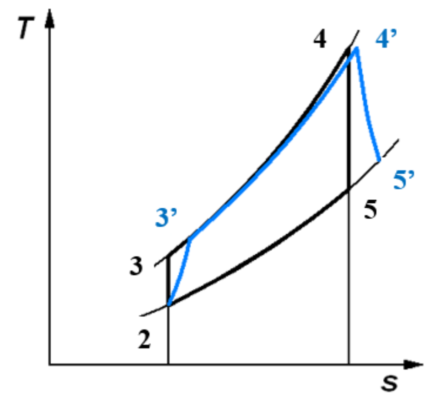
Figure 1.1 Gas Turbine Unit Production Forecast (2018-2027) [1]

Based on the data provided in the International Turbomachinery Handbook published in 2018, the total number of GT unit production used for power-generation has a forecast of 380 in 2018 as shown in Figure 1.1. This value is expected to fluctuate slightly during the upcoming years and will stand at 500 in the Year 2027[1], which is about a 30% increase from 2018.

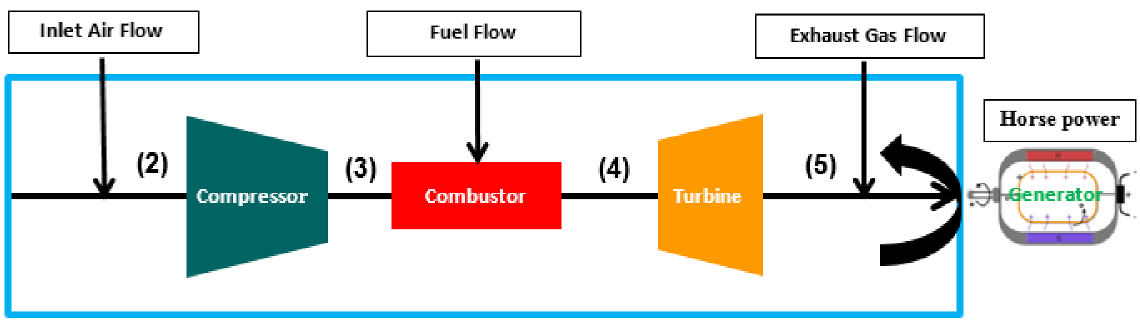
On the other hand, regrouping and consolidation processes among major manufacturers have never come to an end. The most recent case took place at the end of 2015 when General Electric completed its acquisition of Alstom's power business after years of tough negotiation. Amidst such a growing and yet competitive market, there's no doubt that GT companies are confronted with various challenges, and they constantly looking for better ways to maintain their competitive advantage in gas turbine products by constantly improving their internal product design and decision-making process.

1.1 *Simple-Cycle Gas Turbines*

Just like aircraft engines, simple-cycle gas turbines follow a cycle with constant addition of heat, which is commonly referred to as the Brayton cycle after George Brayton. The temperature-entropy (*T*-*s*) diagram for an ideal Brayton cycle (in black) and a real Brayton cycle (in blue) are illustrated in Figure 1(a). Each vertex in this subplot is a correspondent to a different stage number located in Figure 1(b). The station number is in compliance with SAE AR 755A standard published in 1994. For an ideal Brayton cycle, the lower pressure $\boldsymbol{p_2 = p_5}$ represents ambient pressure, and the upper pressure $\boldsymbol{p_3 = p_4}$ represents the air pressure after compression. The ideal Brayton cycle operates as follows: air is compressed from **state 2** to **state 3** in an axial flow compressor, while heat is added between **state 3** and **state 4** in a combustor. Work is then derived from the expansion of the hot combustion gases in a turbine from **state 4** to **state 5**. Since the expansion from **state 4** to **state 5** yields more work than that required to compress the air from **state 2** to **state 3**, useful work is produced to drive a load such as an electricity generator. In real practice, the whole thermodynamic cycle is not isentropic, and entropy is generated due to factors such as losses in the compressor or turbine, stagnation pressure decrease in the combustor, and heat transfer.



(a)



(b)

Figure 1. Gas Turbine: Theory of Operation

(a) *T-s* Diagram for Brayton Cycle; (b) Simple-cycle, Single-shaft Gas Turbine

Figure 2 shows how a typical simple-cycle power plant looks. The industrial GT draws the filtered air from the ambient and makes it pass through a series of Brayton cycle stages as shown in Figure 1. The exhaust gas is then treated and returned to the atmospheres via a vertical exhaust stack to be environmentally compliant. The GT's main axle is connected to the shaft of an electricity generator via a load gear box. The resultant rotation speed of the generator determines the frequency of alternating current (AC) produced. Power generated is then transported to the end-users via distributed stations and the power grid.

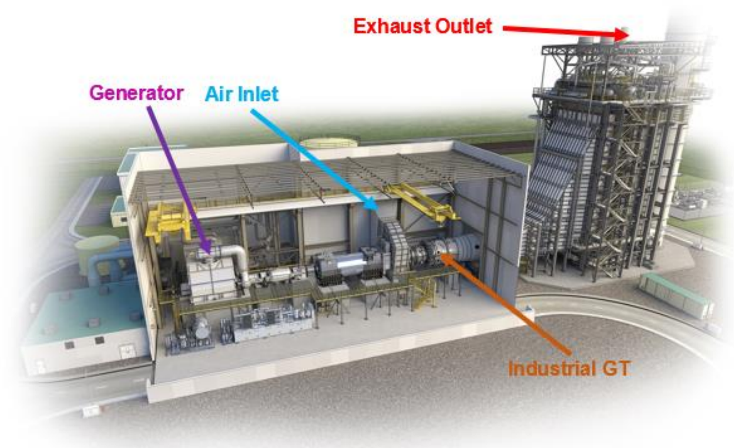


Figure 2. A Simple-cycle Power Plant [2]

1.2 *Aero-derivative and Industrial Gas Turbines*

Two categories of GTs are of prevalent interest nowadays for major gas turbine manufacturers such as GE and Siemens in power generation: aero-derivative GTs and industrial GTs. Despite the fact that both types follow a Brayton cycle, they are different in many other aspects. The former is derived from an aircraft engine and its features include lightweight, higher firing temperature, and better operational efficiency. Industrial GTs can be more powerful with less emission despite lower efficiency and firing temperature. Table 1.1 summarizes a more detailed comparison for both categories. It's again noteworthy to point out that industrial GTs for power generation are of major focus within the scope of this research work.

Table 1. A Comparison of Two Different Types of Gas Turbines

	Aero-derivative	Industrial
Compression Ratio	Low	High
Acquisition Cost	Low	High
Efficiency	39 ~ 42%	35 ~ 40%
Emission	High	Low
Firing Temperature	High	Low
Maintenance	More	Less
Power	<100 MW	Up to 400 MW
Air Flow	Low	High
Shaft Speed	High	Low
Weight	Light	Heavy

1.3 *Trending of Gas Turbine Products*

With the ongoing development of the competitive electricity and gas market, there are increasing demands for better-engineered GTs. In today's world, powerful output and superior efficiency are not the only prevalent product requirements. GTs with higher operational flexibility (capability to operate under multiple modes or fuel types), availability, and reliability are also of great interest because those help clients lower service cost under a variety of supply-demand conditions and hence rack up more profits. Certified emission compliance is undoubtedly requisite due to mounting attention to environmental protection.

The past three decades witnessed the significant performance improvement of turbomachinery. A typical example to be shown here is GT fleet SGT6-5000F, designed and manufactured by Siemens Energy [3]. The first version of this fleet was rolled out in 1990 with an output of 150 MW and operational efficiency at 34.9%. Since then, this product has been evolving through at least 7 different generations. In 2015, the newest frame of this fleet was able to push the output boundary up to 242 MW with efficiency standing at 39% (Figure 3). These monotonically ascending trends reflected in power and efficiency observed cannot serve a better instance of upcoming expectations for this type of GTs.

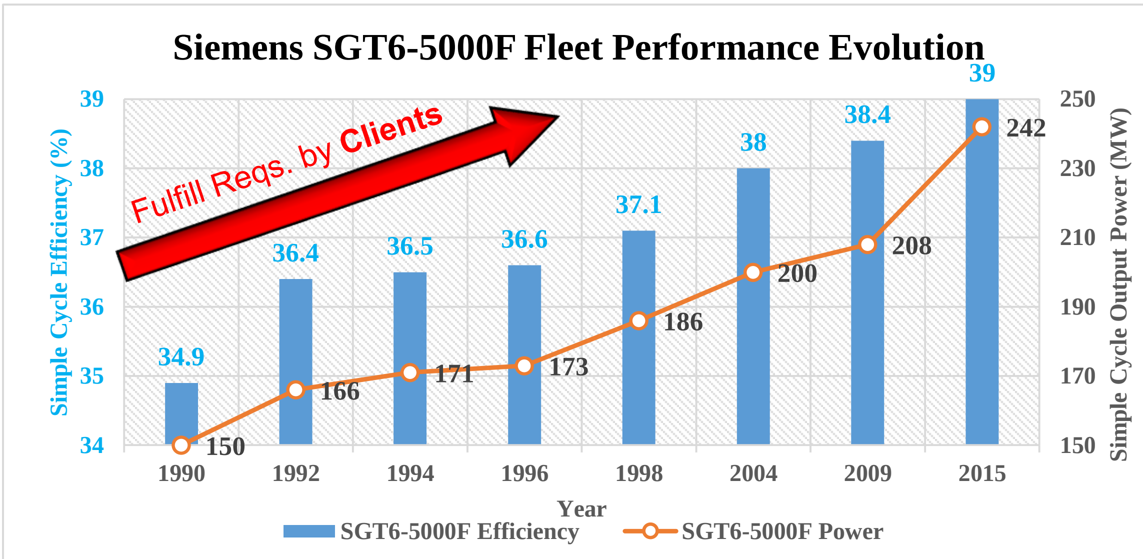


Figure 3. Advanced SGT6-5000F Development (1990 – 2015) [3]

One more example: combustors inside GTs produce various pollutants during operation. Depending on what kind of fuel is used, emissions may include carbon monoxide (CO), carbon dioxide (CO2), unburnt hydrocarbons (CHx), oxides of nitrogen (NOx), and sometimes oxides of sulfur. Federal or state government and various environmental organizations hold the responsibility to introduce stringent laws to regulate pollutant levels for various exhaust gases from GTs. This keeps manufacturers to stay ahead in developing and deploying innovative emission control technologies. Take NOx as an instance, in the past four decades, the reduction of NOx has come to fruition by either using water injection in the traditional diffusion combustors or installing a dry low NOx (DLN) combustor. Both types of burners can be used in conjunction with catalytic converters to further reduce the NOx emissions to around 10 ppm as presented in Figure 4.

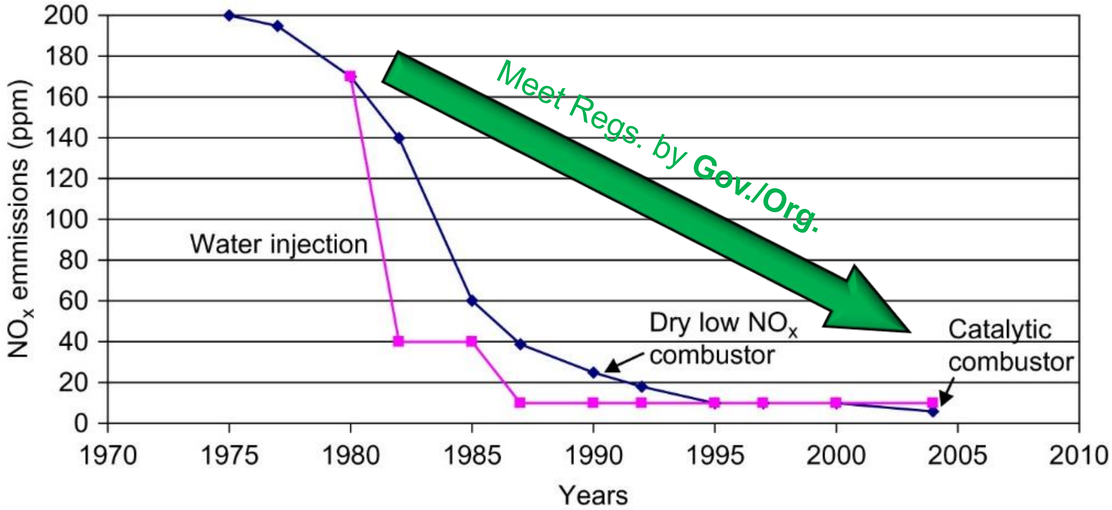


Figure 4. NO_x Emission Reduction in Two Gas Turbines (1975-2005) [4]

The two examples lead to the following observation on development trends of industrial GT product performance.

Observation 1: GT manufacturers face a diverse and yet dynamic business environment. Requirements for a competitive GT product performance are defined and pushed to become more powerful and green, less costly to operate, and still environmentally friendly.

1.4 *Industrial Gas Turbine Product Design and Development*

Successes of industrial GTs cannot be achieved without any well-established product design philosophies. Even though these ideas can be formulated differently from company to company, there are still some common thoughts which guide the development of the entire GT industry. Before diving into them, it is considered necessary to get a clear status quo of the industrial GT market.

In this research, Industrial GT **product series** is an evolving group of industrial products targeting a specific electricity market sector. In the electricity market, GTs are manufactured under different utility frequencies and duties. **Utility frequency** is the nominal frequency of the oscillations of AC in an electric power grid transmitted to the end-user. 50 and 60 Hz are the two dominant AC frequencies on this planet. Industrial GTs are classified as either heavy-duty or light-duty based on their power output ranges. However, there has been no consensus in the industry yet in terms of the exact number to differentiate the two classes.

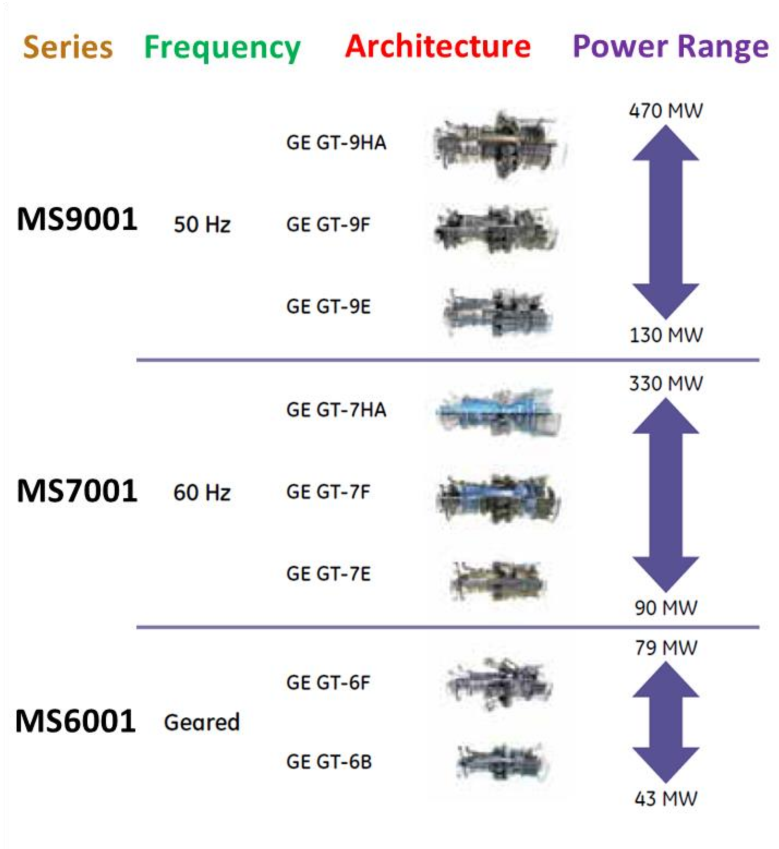


Figure 5. GE Industrial GT Products [5]

Take GE's industrial GT products manufactured in 2014 as an example (Figure 5): MS9001 and MS7001 are two heavy-duty GT series targeting 50Hz and 60Hz utility frequency markets respectively. MS6001 is a geared light-duty GT, which means this series can operate in either 50Hz or 60Hz utility frequency market. These product series combined cover the complete spectrum of the electricity market in the world. In a similar fashion, the product series for Siemens and MHPS segment the market as shown in Table 2. Siemens has 3 distinct series targeting different duty and power markets while

Mitsubishi Hitachi Power Systems (MHPS) possesses four such series, with each designed for a different market segment.

Table 2. Industrial GT Architectures for Siemens and MHPS [6,7]

Manufacturer	Architecture	Duty	Hz
Siemens	SGT-100~800	Light	50/60
Siemens	SGT5	Heavy	50
Siemens	SGT6	Heavy	60
MHPS	H-25	Light	50/60
MHPS	H-100	Light	50/60
MHPS	M501	Heavy	60
MHPS	M701	Heavy	50

Technology class in Figure 5 is defined as a collection of breakthrough technologies in material, cooling, and combustion that contribute to the step-change in GT firing temperature. Different technology class is thus categorized per GT firing temperature. **Firing temperature** is the highest temperature attained in the whole turbomachinery system. It usually occurs at the turbine inlet. So, it is also called the turbine inlet temperature (TIT). Firing temperature is also an indicator of technology advancement level of the product as the increasing temperature cannot be realized without substantial progress in materials, combustion, and cooling technology. Per GE's terminology in [8], E-class technology was introduced in 1972 and the corresponding firing temperature ranges from 2,000 ºF to 2,300 ºF. F-class technology was introduced in 1986 and its corresponding firing temperature is from 2,300 ºF to 2,600 ºF. The latest technology class is H-class, which was introduced in 2003 for steam-cooled GTs and later in 2014 for air-cooled GTs. This state-of-the-art technology further pushed the firing temperature to 2,900 ºF.

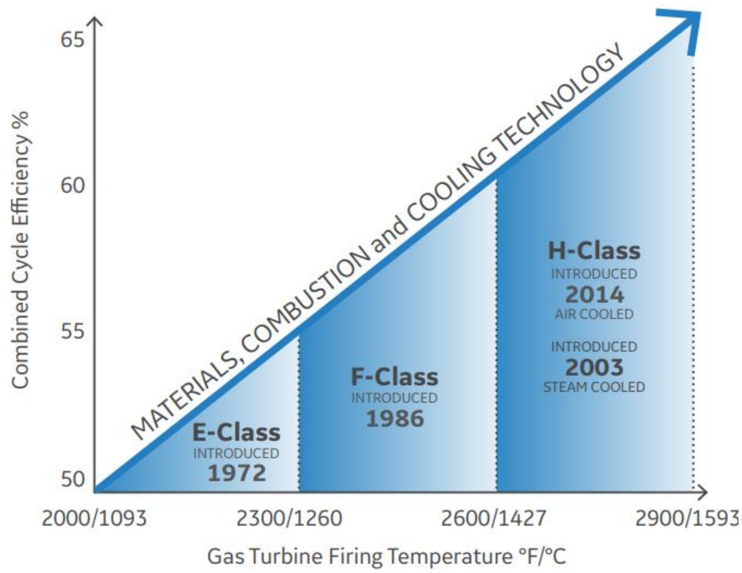


Figure 6. Different Technology Classes Defined by GT Firing Temperature [86]

Flow-path design includes specification of geometry and dimension of the entire GT flow-path. Using the concept of both technology class and flow-path, **industrial GT architecture** is thus a group of GT products sharing (almost) the same flow-path design and technology class. The research subject of this work is focused on GT architecture.

Figure 7 gives a picture of 50 industrial GT products, showing GE's product evolution history from 1957-2005. Within almost half a century, there have been four major product series designed and developed. Note that MS5001's market niche gave way to MS6001 in the 1980s as the later branched from MS7001 with better performance and potential technology capability. One interesting observation from this evolution plot is that a new series almost always is obtained by considerable geometrically scaling from an existing series and then followed by some appropriate redesign work. This applies to MS7001 (scaled from MS5001), MS9001 and MS6001 (both scaled from MS7001) [12].

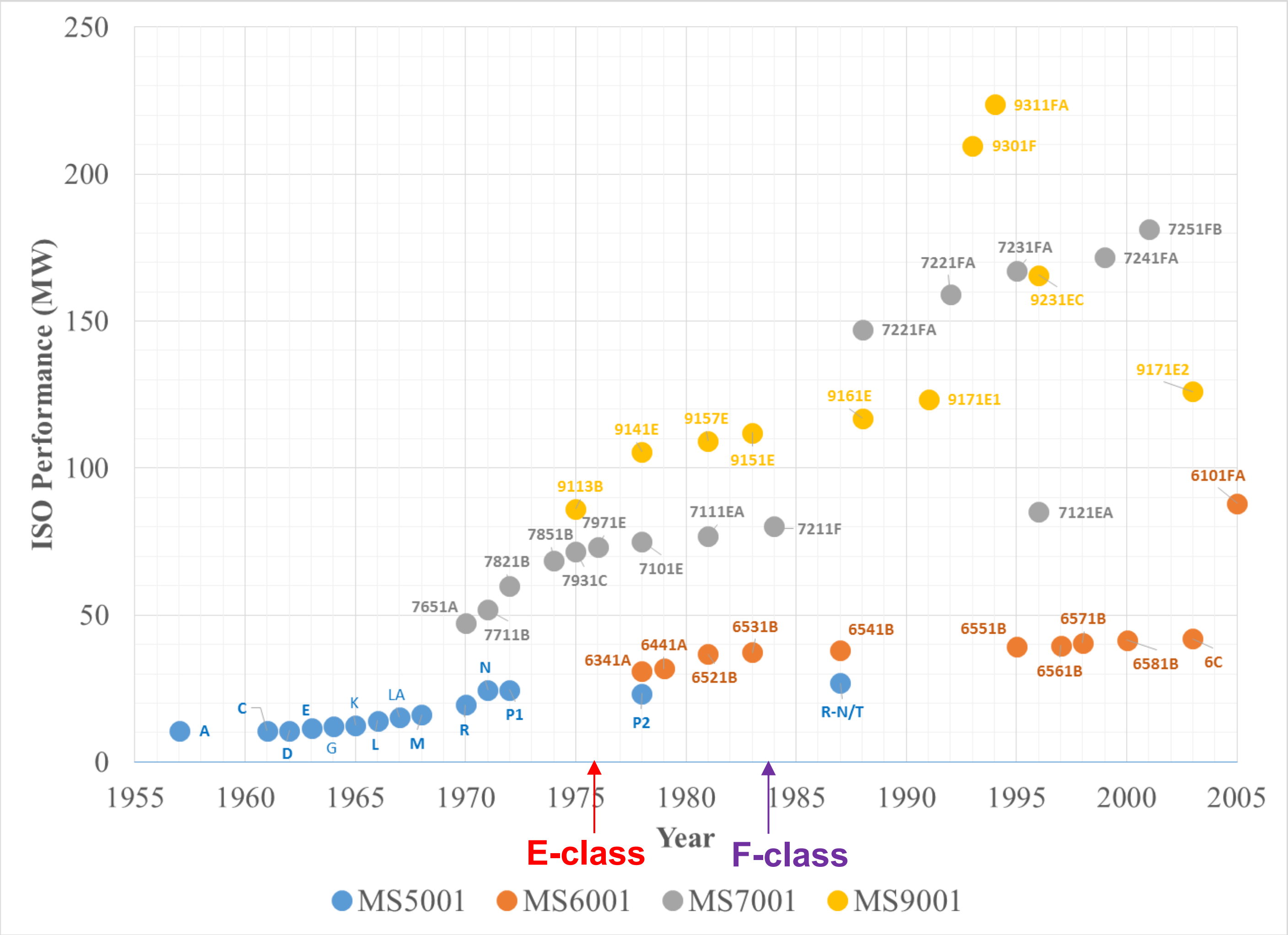


Figure 7. GE Industrial GTs Evolution History (1957-2005) [9-11]

Another observation is that products within the same architecture follow an incremental performance trajectory until a step-change enabled by a new technology class introduction accompanied by substantial design improvement. This is usually indicative of the beginning of a new GT architecture. A good example from the plot is the surge in performance from 7E architecture (7971E, 7101E, 7111EA, and 7121EA) to 7F architecture (7221FA, 7221FA, 7231FA, 7241FA, and 7251FB). The impact of F-class technology is unprecedented as it almost doubles the power output compared to the E-class technology for the same product series. The same trend can be observed in MS9001 series when this step-change occurred.

Geometric scaling is a popular and useful design technique when launching a new gas turbine architecture or even product series [12,13]. It is applicable to both compressors and turbines. This technique eliminates the need for reinventing the wheel by recycling the available technical knowledge from previous products. The existing production line can still be utilized for the new GT with minimum alternation, which dramatically reduces the required product cycle time. It is stated in [12] that scaling existing GTs has been used to "produce similar designs that range from 25 to 200 MW" at GE. Note that components such as combustors are not suitable for scaling and thus a thorough redesign and analyses processes are still to be carried out. Other design philosophies practiced by manufacturers include the use of proven design structural features and proven materials as well as extensive verification testing [14], which aims to maintain desirable reliability for new products.

"High on the priority list of every gas turbine manufacturer is continuous improvements." [13] There are two common ways of doing product development for GTs: Product Improvement Programs (PIPs) and New Architecture Introductions (NAIs). PIPs are often known GT uprates (interchangeably in this research), which intend to improve the overall performance of existing product architecture via partial redesign and technology infusion. They are given the name of "Flange-to-Flange (F2F) Replacement" [15] at GE

Power, "Performance Enhancement Program" [16] at Siemens Power and Gas, and "Upgrades & Modification Services" [17] at Mitsubishi Hitachi Power Systems. "Regardless of what name they go by, these programs have always been and will continue to be a major part of the gas turbine engine business." [13].

A GE PIP example is illustrated in Figure 8 for PG7231FA to be uprated to PG7241FA. This package includes 11 options and covers improvement in both hardware and software. On the hardware side, better cooling, sealing, and coating options are implemented throughout the flow path to make the system more efficient. On the software side, the extra combustor tuning kit enhances the real-time capability of monitoring/diagnostics when operating the gas turbine. As a result of this PIP, the improved PG7241FA is able to reach a higher firing temperature of 2,420ºF compared to 2,400 ºF in PG7231FA, generating 4 more MW of power and achieving 20 less BTU/kW-hr of heat rate compared to its previous version. Note that the entire uprate does not engage any flow-path design change and the performance improvement is incremental.

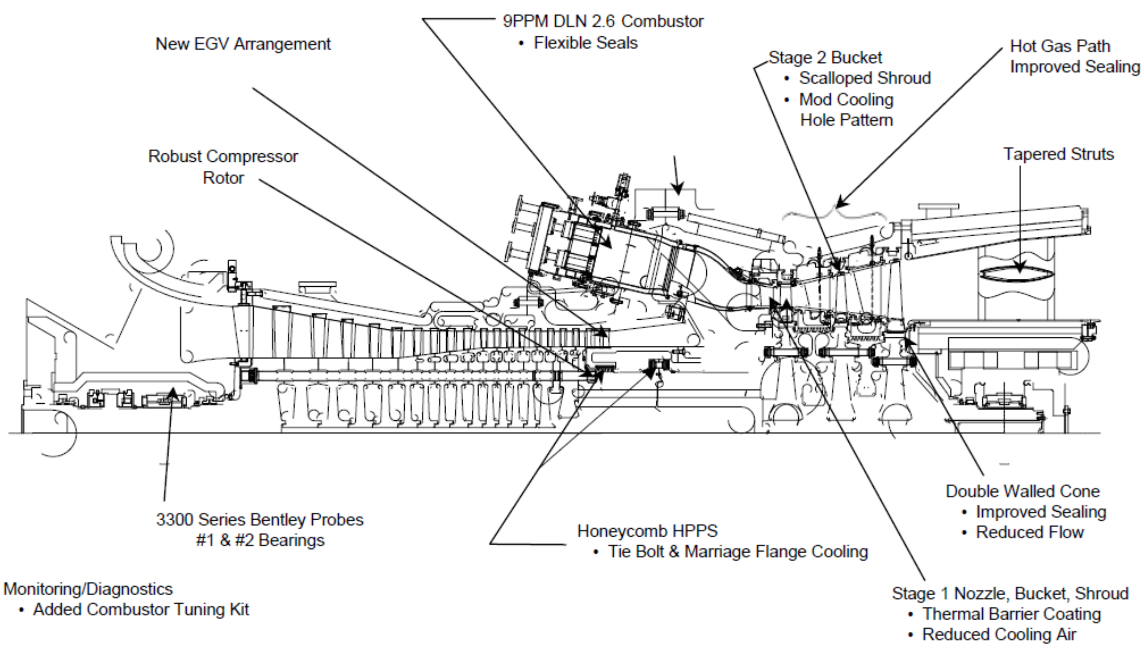


Figure 8. PIP Example for GE PG7231FA to PG7241 FA [18]

In contrast to PIPs, NAIs expand the existing architecture by bringing in a different architecture of GT with a significant redesign triggered by new technology class infusion. The reconfiguration work that comes with new architecture typically involves a change in flow-path design. This may be flow-path geometry redesign or scaling, zero staging for a compressor, etc. Zero staging adds an axial compressor stage in front of an existing compressor. This intends "to increase the output of an existing engine with few or no changes to the center core of the engine" [13], which is achieved by increasing compressor pressure ratio as well as mass flow rate. Take a look at the redesign conducted within compressors for various GE's product series. For MS 5001, 5001N is different from 5001M in flow-path geometry as well as zero staging. As a result, the newer compressor has a larger inlet capturing area and an additional rotor stage. These changes uptick mass flow rate as well as compressor pressure ratio. Between MS7001E and MS7001FA, on top of geometric change and zero staging, 7001FA's flow-path is scaled up from 7001 by a factor of 1.122 and radially shifted to enable a larger cross-section area. Those design changes are necessary with the infusion of F-class technology as the higher firing temperature enables processing more flow at a given duration to produce more power.

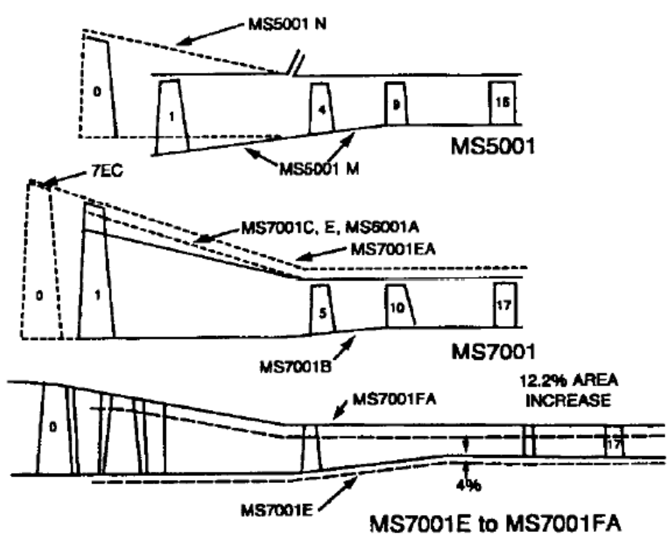


Figure 9. Compressor Flow-path Change for NAI [12]

The evidences present in this section lead to the following observation on industrial GT product development.

Observation 2: The majority of newer GT products are the updated versions of previous generations within the same architecture while the new GT architecture almost always develops from an existing architecture via technology infusion accompanied with additional redesign efforts.

1.5 *Summary of Findings*

Gas turbine development projects present very difficult and complex problems for turbomachinery manufacturers. A well-designed product must prove itself in the engineering field as well as the business arena. As such, any decision made throughout the development stage should factor in inputs from both sources. The design and development of gas turbine products are driven heavily by continuous technology evolution and redesign. Product Improvement Program and New Architecture Introduction are the two commonly observed paths GT manufacturers follow to augment the overall performance of their product portfolios. These two development paths are the subjects of research interest throughout this work.

1.6 *Dissertation Structure*

In this work, existing GT design philosophy and practices are used to understand the product development for industrial GTs from the perspective of product growth. The notion of growth will be defined and elaborated in the next chapter. The approach to be presented is used to quantify the built-in growth for existing architectures and to design in growth for future architectures. Given the forecasted demand from the market, this approach enables the GT manufacturer to effectively predict and evaluate performance information for new design concepts, prioritize technology development for smart resource allocation, and make informed decisions upon product development roadmaps.

Chapter 2 encompasses the complete research formulations about the present work. The concept of growth is construed in the context of observations of existing industrial GT products. The literature review section includes necessary background information about classic gas turbine product design & development method and contemporary system engineering design methodologies to be used for approach development. The architecture-based growth approach is elucidated in Chapter 3, including relevant sets of research questions and posed hypotheses. Test cases are constructed to testify the proposed hypothesis formulated. The result of the testing will support the formulation of step-by-step methodology. Chapter 4 develops a specific implementation of the entire approach on the product design and development of industrial GT products. Both PIP and NAI paths are demonstrated in the set of experiments. Based on the result, a thesis statement is formulated to address the overarching research question posed for this research. Chapter 6 summarizes the contribution enabled by this work in the context of GT product design and decision-making.

CHAPTER II

RESEARCH FORMULATION & LITERATURE REVIEW

In today's turbomachinery industry, informed decisions cannot be made without adequate knowledge from both engineering and business fields. This is evidenced by almost all recent acquisitions of various power station projects. The GT conceptual design capability and product development strategy are the top two elements to ensure a successful procurement and completion of those assignments. Every time a potential challenge emerges before, or during the existence of a GT development program, innovative alternations to current design and decision practices become requisite. This chapter starts with two examples that help define motivation and scope of this research work.

2.1 *Research Motivations*

As the first of two motivating examples from the real world, in January of, 2016 the Glendale City Council in California posted a Request for Proposal (RFP) for its "Glendale Water and Power Proposed Grayson Power Plant Repowering Project" (Specification No. 3595). As the city's existing 238 MW power generation was nearing the end of its useful life, the city would like to take this opportunity to replace it with a new system to:

1. Maintain reliable power supply services for local communities
2. Keep electrical rates affordable to Glendale taxpayers
3. Comply with state regulations regarding renewable energy supplies and greenhouse gas emissions

A 250 MW replacement system using a more efficient and cleaner natural gas-fired generation, such as the integration of a combined cycle and a simple cycle gas turbine technologies, was a necessity for the city's future needs. The pre-bid meeting held in February 2016 had a long list of attendees, including GE Power, Siemens Energy, Mitsubishi Hitachi Power Systems, Man Diesel & Turbo North America, Fairbanks Morse Engine, and Wartsila. In other words, this project has drawn attention from almost all the major gas turbine manufactures worldwide, and ultimately, it was interesting to see whose proposal would stand out in this fierce engineering competition.

In the GT industry, RFPs are typically issued prior to a bidding process in the following instances: 1. when a current GT user is looking for a performance improvement for existing products; 2. when a user wants replacement of extant fleets of GTs; 3. when a plant operator shows interest in acquiring gas turbine fleets for a new power plant. The RFP specifies key information regarding the upcoming project, such as plant location, desired plant performance, available project funding, and expected delivery schedule. Once this document becomes available, GT manufacturers must quickly decide how to respond to the posted need. In either situation, the management only has a short timeframe (usually a month) to decide whether pursuing the project is worthwhile or not. If deemed worthwhile, manufacturers will only have an additional three to four months to submit a detailed proposal. In Glendale's case, the final date to submit a notice of intent to propose was February 2016, meaning the detailed proposal was due in May of 2016. Participants then only had one month to decide whether the project is a go or no-go and roughly three months to layout their preliminary design plans.

Table 3. Typical Technical Information Requested in a GT Project RFP

Equipment	**Operation**
Configuration and Technology	Operational Availability
System Performance	Operating Schedule
System Life	Maintenance Plan
Emission Data	Spare Parts
…	…

Table 4. Typical Capital Cost Information Requested in a GT Project RFP

Site and Project Development	Equipment and Operation
Design	Gas Turbine and Generator
Permits	Construction
Consulting	Annual Operating Expenses
Project Management	Balance of Plant
…	…

Situated in a highly competitive arena, each participant must be well-equipped to tackle a variety of challenges. Management must make a series of prompt decisions, all while under significant pressure from rivals. Using their best estimates, they additionally need to assure that critical product and project information is present in the proposal (Table 2.1 and Table 2.2). In the early stages of the project acquisition process, a majority of the proposal's critical points are naturally more difficult to address. Nevertheless, one critical question would be whether one or more GT(s) in the production line would be able to entertain those requirements in a competitive context. If the answer is affirmative, less effort will be necessary to figure out the details. However, in the instance that "No" is the answer, it would be initially considered more natural to improve existing products with applicable technologies in hand. Based on the amount of gap, a substantial amount of redesign work might be involved in technology infusion to bridge that difference. Sometimes this gap, along with the required amount of effort, may justify the establishment of a new architecture of GTs that target a different market segment. However, it is ultimately up to higher management to make this challenging decision. Considering that this type of GT product development decision process is highly proprietary and occasionally subjective, the proposed approach in this work alternatively provides a structured and transparent way to quantify the performance potential for each gas turbine series. This information may then be used as an argument to justify whether launching a new gas turbine production line is feasible or not. This work is expected to lead to improved decision-making methods and competitive product development strategy for GT manufacturers.

Another motivating point arises from the observation of the ascending trajectories of industrial GTs in Figure 7. Both the incremental performance changes within the same architecture and step changes between different architectures coexist in product series MS6001, MS7001, and MS9001. Those noticeable trends and features can be understood if a thorough investigation is conducted to look into what actually happened behind the scene. Once the connection between those phenomena and the design practices is established, a rationale can be formulated to support the future product development and decision-making of industrial GTs.

2.2 *Research Objectives*

This research uses the perspective of growth to understand and interpret the historic performance evolution path of several prominent gas turbines series. The concept of growth is considered to be a key metric that drives the development path of GT products forward via one of the two common avenues introduced in CHAPTER I: Product Improvement Program and New Architecture Introduction. In this context, t**he growth of a GT product** is defined as the potential amount of improvement in GT performance for a given set of technologies at a certain technology level. **The growth of a GT architecture** is the maximum room of performance improvement that the product under that architecture is expected to achieve with all compatible and available technologies. The notion of growth provides a unique angle to shed lights on the typical black-box style GT product design and decision-making process, and it is treated as a useful metric to support an informative product development strategy for decision-makers in a competitive environment. There are two types of growth formulated in this research, corresponding to PIP and NAI respectively:

(a) **Built-in growth** - for the existing architecture, it includes an improved way to select technology solutions for each product as well as architectures of interest so that the growth for an individual product and the entire architecture can be quantifiable for efficient product down-selection in various project acquisition scenarios and smart resource allocation for technology development.

(b) **Designed-in growth** - for the new architecture, the approach demonstrates a way to infuse designed-in growth into the very first new product configuration so that as the architecture evolves, and new technology matures, this part of the growth can be expected to gradually be fulfilled and converted to performance gains in the upcoming products within that architecture.

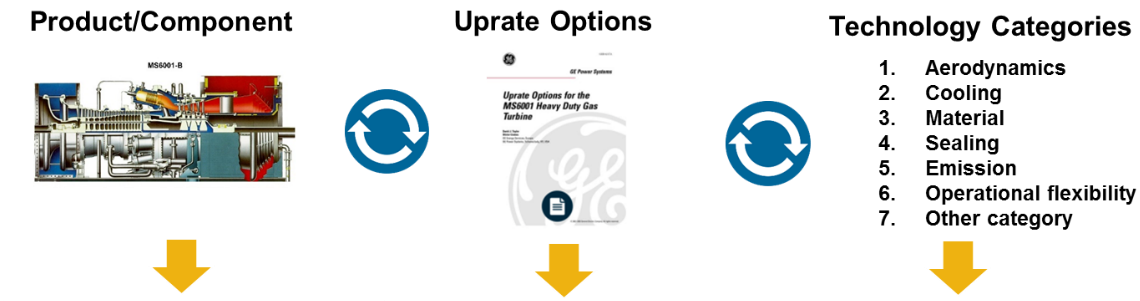
Observations made in CHAPTER I, and motivations formulated in this chapter are used to induct three objectives for this research:

Research Objective 1:

Extend the capability of existing conceptual-level technology integration and selection procedure applicable to GT product design and development so that the new framework is anticipated to quantify the built-in growth exists in the current architecture.

The purpose of the first objective is to present a procedure to quantify existing growth and to prioritize technologies to be developed for PIP. The concept of PIP is construed as a means to tap into the growth already incorporated in the existing architecture. This amount of growth is ready to be converted into performance improvement with the maturity of corresponding technologies. Therefore, quantifying this portion of growth to ensure that the potential room of improvement can be gauged, and later fulfilled, remains a challenge.

On the other hand, it is observed that each uprating option is enabled by one or more technological improvements. In serving as elements to shape uprating options tailored to individual GT, technologies are the fundamental drivers for PIP. Take GE's uprating manual as an example [9], those options shown in Figure 10 target different components of the system and each of the option is driven by one or more enabling technologies from a wide spectrum of areas, including aerodynamics, cooling, material, etc. In traditional conceptual design, these technologies are typically selected to maximize a particular product's performance with affordable add-on cost. This type of consideration is within the scope of single product design and optimization. Evidently, this approach no longer holds in the context of GT uprating. The manufacturer would expect broader impacts from selected technologies upon its existing products, i.e., a technology that improves the performance of a dozen different products from an architecture is naturally more preferred over technology that only influences a couple of products. To be more concise, "common beneficiary" types of technology are being embraced. As such, the selection criteria must consider the entire product architecture, and the technology solutions to be unveiled are anticipated to be robust and justifiable for future resource investment.



Component	Option (ID)	Technology
Compressor	Add High Flow Reduced Camber GTD-450 IGV (FT4C)	Advanced Aerodynamics + Material
Combustor	Uprate Combustion System to Dry Low NOx 1.0+ (FG2L)	Dry Low NOx
Turbine	Uprate Stage 2 Shrouds to Honeycomb Seal (FS2T)	Advanced Sealing

Figure 10. A Subset of Uprate Options for GE MS6001 [9]

Research Objective 2:

Formulate a way of using designed-in growth concept for GT New Architecture Introduction path by leveraging both GT traditional design techniques and product growth consideration, and prove its technical feasibility, as well as potential added-value to current design practice.

The second objective focuses on another path of product development for industrial GTs: NAI. It is already comprehensively observed that the majority of newer GT designs are derivatives of previous generations. As introduced in CHAPTER I, different architecture under the same product series are used to target different market segments, and each architecture may expand and enrich existing GT frames to create new products (derivatives). For example, SGT6-5000F in Figure 3, and SGT5-2000E in Figure 11 are two different GT architectures, designed and owned by Siemens. It would be desirable if there is a way to design growth into the current product so that as the technology matures and product evolves, the performance of the GT concurrently improves with minimum redesign or replacement effort required. This new concept requires some forward-thinking, since some of the capabilities to be implanted are not used to their maximum potential when initially deployed. The second research objective is to investigate this possibility, and compare it with the PIP path for GT development.

Research Objective 3:

Formulate an architecture-based growth framework that can be used to support a reliable and strategic decision-making process of future industrial GT product development path for the manufacturer.

Following the two objectives above, the third objective aims to formulate a growth-based approach once the capability of obtaining built-in growth and implanting design-in growth is fully equipped. Whenever an uprate is conducted, part of previous designed-in growth is realized and converted to performance gains. As such, there will be less built-in growth after each upgrade. The remaining built-in growth is then to be re-analyzed. Once the amount of growth potential is considered negligible for the next upgrades or there is an impending new technology class, it indicates a time for the manufacturer to embark on a new architecture so that the newly redesigned product configuration would have a brand-new designed-in growth. This new architecture will be recalibrated with respect to emerging technologies, and is additionally expected to be more competitive in terms of contemporary market performance and cost. Growth can be thought as the distributable capital a manufacturer possesses on hand for each architecture, and that each GT architecture is a checking account. At the initial development of each architecture, the manufacturer deposits the dedicated capital in its entirety to the account as it does not need this portion of cash immediately. The company is expecting this bank-backed checking account to be able to cash out through multiple installments over an extended period. Therein, the amount of capital paid back by the bank account is equivalent to the cumulative performance development the architecture achieves via multiple upgrades.

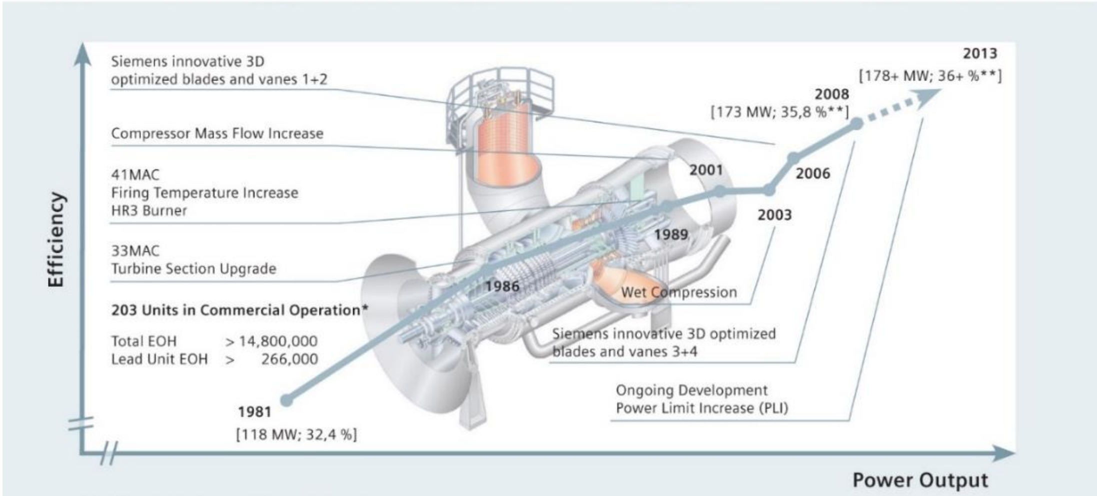


Figure 11. Product Development of Siemens SGT5-2000E [19]

2.3 *Research Questions*

These aforementioned research motivations and objectives provide directions to answer the global research question of this work:

Overarching Research Question:

Given a set of available technologies and existing industrial gas turbine architectures, how can the capability of growth-based product design framework be used to support an informed decision upon future product development path?

One common avenue to address a global research question like this is to break it into several research questions systematically and try to solve them one after another. This dissertation follows this path and research questions are presented in a logical order below.

Based on the observation that the built-in growth is tapped into by using the PIP package that is enabled by a combination of technologies, the first Research Question Set is designed to quantify the built-in growth in PIPs for the purpose of system performance evaluation and optimized resource allocation for technology development.

Research Question 1:

How to identify competitive technologies that will be integrated into future GT product development?

Research Question 2:

How to account for the built-in growth of the GT architecture included in its dedicated PIP?

The second Research Question Set is formulated to investigate the probability and the potential advantage of using a structured method of designing growth into a new architecture by leveraging forecasted technology information from the future.

Research Question 3:

How to design growth into a new GT architecture given forecasted information about emerging technologies?

Research Question 4:

What are the advantages of using designed-in growth when launching a new architecture?

To address the overarching question as well as the four research questions formulated, a literature review section is dedicated to providing an overview of the relevant topics and methodologies in the public domain. The information surveyed intends to pave the way for the establishment of architecture-based growth approach.

2.4 *Gas Turbine Product Design and Development*

The intention of thoroughly reviewing the existing literature is to summarize methods, processes, and techniques already publicly available, which touch upon previously stated research objectives. This step is critical in that it helps the author identify if and where there are gaps between the published literature and research objectives to be achieved. Based on the information summarized in the review, existing gaps will be evaluated and benchmarked to determine where new and advanced methods are needed to enable the completion of the proposed framework in its entirety.

The history of the land–based gas turbine dates back to late 1930s when the first commercial industrial gas turbine from Brown, Boveri & Cie (BBC) became operational at Neuchâtel, Switzerland. Significant progress has since been made, and nowadays, the generic process for the design of a GT is well established. Yet still, there is a continued need to interpret and understand this process, and use it to absorb newly developed concepts and techniques for improved design practices.

2.4.1 *Gas Turbine Product Design Process*

The design process of a GT varies from company to company, and hence Dieter claims, "there is no single universally acclaimed sequence of steps that lead to a workable design. [20]." Schopfer [21] presented a good summary of gas turbine product development process conducted in Honeywell Engines and Systems. It is shown in Figure 12, with boxes of phases colored in orange being related to the focus of this thesis. This process model covers the gas turbine's product life cycle from concept to product in six discrete phases:

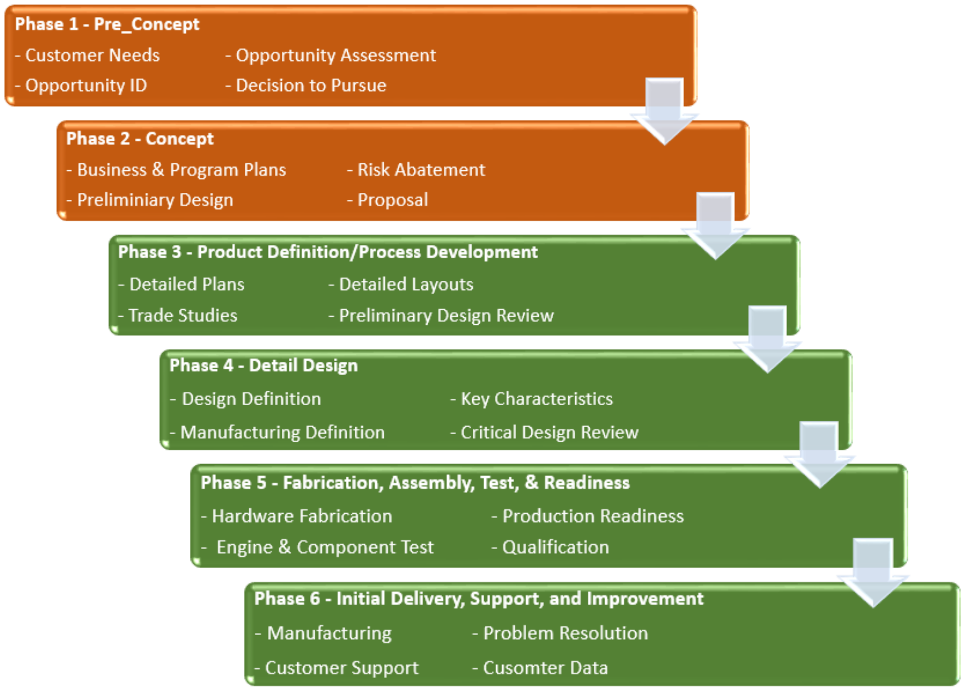


Figure 12. Integrated Product Development Process for Gas Turbine [21]

Phase 1 – Pre-Concept is the step to identify "the business opportunities for new or derivative products" [21]. This process of opportunity assessment is achieved by collecting information about customer needs/requirements, and pre-selecting potential technologies to be used on new products. An informative decision has to be made during this phase regarding whether to pursue this opportunity further.

Phase 2 – Concept devotes most of the time to developing preliminary design concepts and conducting feasibility/risk reviews. A proposal is handed to the customer after the product design and the management teams complete the review. The customer is expected to place an order once the proposed contract is negotiated, modified, and finally accepted.

Phase 3 - Product Definition/Process Development is a stage to define detailed product features and layout, develops processes such as program and test plans, and concludes with a preliminary design review (PDR) for the customer.

Phase 4 – Detail Design begins with component detailed design and reviews. At this point, a quality plan needs to be laid out at this point to prepare for subsequent manufacturing. A customer's critical design review (CDR) is scheduled prior to the final.

Phase 5 – Fabrication, Assembly, Test, and Readiness involves steps such as fabrication or acquisition of hardware, components assembly, and extensive testing for qualification and certification purposes.

Phase 6 - Initial Delivery, Support, and Improvement begins first with the completion of first purchasing order and engaging activities such as personnel training, and maintenance plan scheduling.

On the other hand, Mattingly has a visibly more detailed proposition when it comes to the GT design process. In his book, he lay out a "generalized representations of the design process [22]" for a gas turbine engine, which is illustrated in Figure 13. During the conceptual stage, after a need is established by inputs from RFP and market research, the primary task for the design team is to determine if a potential engine will be able to satisfy those requirements. Engineers may need to select the best GT architecture that meets those specifications both technically and economically. The choice is largely based on the information from the thermodynamic design point, as well as off-design performance. Once the conceptual design is completed, the proposed system is decomposed for a more sophisticated analysis by discipline, subsystem, or component. The detailed design concludes with freezing every subsystem, components for subsequent manufacturing, and system-level testing/development.

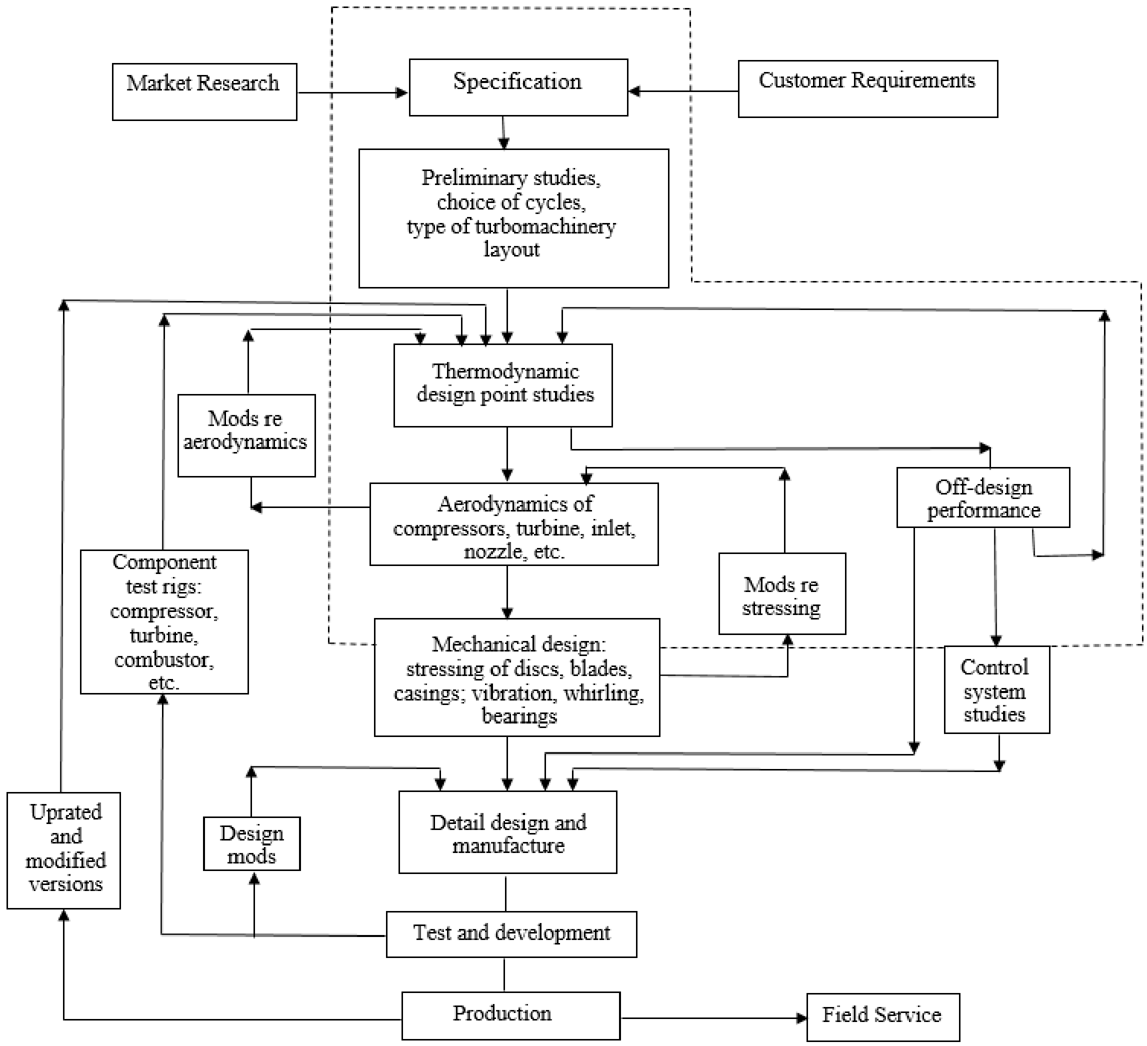


Figure 13. Gas Turbine Engine Design System [22]

2.4.2 *Gas Turbine Performance Improvement*

There is often an opportunity to improve GT's thermodynamic performance after a particular type of GT has been in production for a while. Depicted in Figure 13, there is a step called "Uprated and modified versions" directly after "Production" step, which indicates that the finalized GT product is expected to have the capability to satisfy a different set of requirements, after a component redesign and new technology infusion. It is observed that this technique has been practiced across different GT manufacturers [9-11,16, 17] to improve the performance of existing GT products so that customized needs of existing/potential clients can be fulfilled and that design and manufacturing costs can be minimized by recycling existing knowledge and resources. As such, Sands [23] states, "a successful commercial gas turbine engine program is one that offers a wide variety of competitive products."

In CHAPTER I, it is briefly mentioned that there are more than one option to conduct gas turbines' performance uprates, such as geometric scaling and technology infusion. Geometric scaling starts with a baseline GT and uses rules of scaling to get a product in a different size. This approach is believed to require minimal development effort, and additionally inherits the proven durability of the existing design.

It is assumed that the scale factor is the ratio between the diameters of the new GT to that of baseline, with rules of scaling summarized in Table 5[12, 13].

Table 5. Rules of Scaling

Scaled Quantity	**Scale Factor**		
Linear dimensions (in)	**0.5**	**1**	**2**
Volume (in^3)	0.125	1	8
Weight (lb)	0.125	1	8
Power (kW)	0.25	1	4
Flow rate (lb/sec)	0.25	1	4
Pressure Ratio	1	1	1
Efficiency	1	1	1
Stresses (psi)	1	1	1
Tip speed (in/sec)	1	1	1
RPM	2	1	0.5

When this set of rules are applied, most of the original aerodynamics and mechanical safety margins remain unchanged. This implies that the original values of Mach numbers, velocity triangles, and gas properties (temperatures and pressures) maintain the same in the new design. Similarly, the original stress margins, the percent vibration, and critical speed are all maintained. However, there are subsystems and quantities that do not follow these rules, where design modifications and re-analyses become imperative. Table 6 lists some of those subsystems/components that require extra attention.

Table 6. Some Unscalable Components [12]

Subsystem/Component	Quantity Concerned	Possible Design Changes
Turbine cooling system	Heat transfer characteristics	Cooling flow percentages & airfoil cooling passages
Combustor liner	Radial temperature profile	Amount and size of the liner dilution holes
Fuel injector	Combustor exit pattern factor	Design and the number of injectors

Ragland [13] gives an example to illustrate the impact of applying scaling rules into GT design, with the result reproduced in Table 7. The scaling factor is assumed to be 1.5. The baseline light-duty GT has an output power at 5,816 kW and cycle efficiency of 31.5%. After direct scaling, it is expected that the output power and airflow rate scale with the square of the scale factor, while cycle efficiency remains the same as shown in Table 7. The values from the last column are obtained after some minor design changes to accommodate the size effect, such as “reduced tip clearance, constant surface finish, and reduced leakages through improved tolerances.” [13] As a result, this improved version ends up with slightly better performance and more airflow.

Table 7. Approximate Gas Turbine Performance Using a 1.5 Scaling Factor [13]

Performance Metric	Baseline	1.5X Scale (Direct)	1.5X Scale (Improved)
Output power (kW)	5,816	13,087	13,348
Cycle efficiency	31.5%	31.5%	32%
Airflow (lb/sec)	50	112.5	113

The second option to augment an existing GT is to rely on cutting-edge technologies. "Advanced technology is usually introduced for new unit production and subsequently applied to customer-operated gas turbines by an uprate program" [11]. The ultimate goals of infusing those technologies include increasing output, improving cycle efficiency, enhancing reliability and availability, lowering maintenance costs, and reducing emissions. Table 8 provides a small subset of available options which can be used to uprate GTs manufactured by General Electric [9-11]. It is evident that they are fruitions thanks to recent advancement in areas such as material, coating, cooling, and sealing. Chances are that technologies previously used in aircraft engines can similarly be repurposed for ground-based GTs. It's equally important to point out that technologies listed in Table 2.6 are fully matured, which means the operational effectiveness of each technology has been proven both in the lab, and/or in the field. In this research, uprates involving only matured technologies represent short-term product solution. The technology-selection process is a deterministic decision-process since technical performances regarding those technologies have been well recognized and tested. In other scenarios, when developmental technologies are also under consideration, a long-term solution is needed to take into accounted emerging technology information and maturity schedule. As such, long-term solution is more applicable to the strategic decision for designing and manufacturing the next architecture of industrial GT products.

Table 8. A Subset of Advanced Technologies Used for GT Uprates [9-11]

No.	Subsystem	Technology	Immediate Benefit	Impact on System Performance
1	Compressor	GTD-450 high flow reduced camber Inlet guided vane (IGV)	Better aerodynamics and higher airflow	Increase in power output and cycle efficiency
2	Compressor	Increase IGV angle	Higher airflow	Increase in power output with a slight decline in cycle efficiency
3	Compressor	GTD-450 blades and stator vanes	Higher tensile strength, corrosion resistance, and crack resistance	Increase in the reliability and cycle life of the part
4	Compressor	High-pressure packing brush seal	Minimization of airflow leakage	Increase in power output with s slight decline in cycle efficiency
5	Combustion	Thermal barrier coated (TBC) combustion liner	Lower underlying base metal temperature, reduced cracking, and thermal stress	Increase in cycle life and reduce maintenance
6	Combustion	Breech loaded fuel nozzle	Reduced combustion liner cap cracking	Extended inspection interval and lower NOx levels
7	Combustion	Water injection	Reduced flame temperature	Reduced NOx level and increase in power output with a decline in cycle efficiency
8	Combustion	Dry low NOx (DLN)	Reduced flame temperature	NOx reduction
9	Hot gas path	Perimeter cooled Stage 1 buckets	More cooling air to reduce thermal gradients and cracks	Extended life of the buckets at the higher firing temperature
10	Hot gas path	TBC Stage 1 buckets and nozzle	Lower surface temperature	Extended life of the buckets at the higher firing temperature
11	Turbine	Firing temperature uprate	Higher firing temperature	Increase in power output and cycle efficiency
12	Turbine	Rotor speed increase	Higher airflow	Increase in power output

2.4.3 *Gas Turbine Product Development*

During the evolvement of industrial GT products, a choice between an uprated engine from an existing architecture, and a redesign product from a new architecture, is the challenge often confronting the design and management team of the manufacturer. Such a decision cannot be made lightly, as products like GTs often require lengthy and expensive development programs. Dix and Gissendanner [24] maintain that "although some factors which govern such a choice are necessarily subjective, there are objective factors which should be considered." Despite that their subject of interest is the aircraft engine, the rules that the ground-based industrial GTs development program follow are not expected to be much different from their air-based counterparts. These two authors highlight capability, cost, and risk as the three major dimensions of interest in an engine development program. The capability consideration includes unit performance and tradeoffs between shorter/longer term product capabilities. The cost consideration engages a list of items during a product's life cycle: estimated cost, up-front costs (Research, Development, Test, and Evaluation cost), and Return-on-investment (ROI). Risk consideration includes schedule risk, technical risk, and cost risk. Both authors state that a "new engine is always riskier than a derivative engine." and that "big technical jumps generally imply higher risk regardless of whether the engine is a derivative or new engine". In summary, there is a shortened list of items requiring rational analysis and prudent deliberation before the final decision is made [24]:

1. The impact on mid- and-term (military) capability, as well as the short-term impact.
2. The relationship between unit capability and force structure, as opposed to specific requirements for each.
3. The range of potential applications of an engine beyond that under specific consideration.
4. The impact on industrial capability, both in terms of maintaining an industrial base and avoiding overload.

5. The acquisition strategy to be employed with respect to “competition”, and the purposes, attendant economics, and alternatives to the same.
6. The ROI criterion, or discount rate, to be used, and its application to all cost elements.
7. The relatively greater importance of RDT&E costs.
8. The applicability of the proposed development/qualification approach to derivative engines, and potential differences in the resulting final product.
9. The impact on the logistical support system.
10. The relationship between risk, cost, and time, as opposed to independent assessments.

Some of the items are beyond the scope of this research as they cover almost every angle of the product life cycle.

To fulfill a new set of customer requirements, Sand [23] postulated that if time is of major concern, a simple derivative engine with rating change of an existing GT might be the best solution despite significant performance compromises. A completely new design is only warranted if the customer wants the utmost performance out of the product and is willing to cover the entire development cost, which rarely happens in today’s world. As a compromise, derivative or variant engine of an existing architecture would offer a balanced solution upon achievable performance and affordable cost of development. The new improved engine achieves an increased capability by taking in the latest aerodynamics and material technology with minor modifications. Indeed, this is a reality in gas turbine purposed for the aircraft industry. Similar philosophies and practices are exercised in the product design and development of industrial GTs. As such, the focus of this work revolves around thermodynamic capability and cost of development for industrial GT products.

2.4.4 *Product Growth in Gas Turbine Design*

In industry, the concept of product growth is no stranger to those gas turbines placed under wings – aircraft engines. A successful product development program rolls out engines that perform exceptionally well while also providing growth capability for future customers [23]. The development trajectory of the CFM56 engine since the 1970s could not serve as a more perfect example to illustrate this point.

"The CFM56 has a built-in and planned growth potential to 24,000 lb. thrust and then to 25,000 lb. with increased airflow and higher operating temperatures. Also planned is a 27,500-lb.-thrust version that will require definite modifications from the preceding member of the engine family." [25]

Clearly, the engine team did not just stop at the immediate design requirements when launching the CFM program. The foresight they had made them not only blend then state-of-the-art technology into a powerful core and advanced cycle, but also allocate ample room for later improvement products after the first-generation engine – CFM56-2. This foresight enables the constant infusions of emerging technology into the CFM56 family once it reached maturity, i.e. the growth implanted at the beginning of CFM56 program was tapped in and converted to performance gains in its later variants, which were tailored for Boeing and Airbus applications with minimal modifications. This growth-based design philosophy turned out to be a tremendous success and CFM56 engines have become the dominant engine selection for the highest-selling-commercial jetliner in history, the Boeing 737. In 2009, the 20,000th CFM 56 engine was delivered to the customer. Within the span of almost four decades, CFM engines have evolved through 6 generations, with their technology-driven evolution path summarized in Figure 14. The growth initially built-in by the designers was realized step-by-step and the story of this unbelievable family continues.

Figure 14. CFM 56 Engine Family Evolution [26]

In addition to turbofan engines, growth methodology is also used in larger turboshaft engine development by the team of Rolls-Royce [27]. Based on the consideration that the demand for larger turboshaft engines is limited, it was difficult to justify the cost to develop new engines. As such, the designers used the existing design as a starting point and made efforts to extract more power from it via well-established growth steps in-house. Initiated in 1986, Rolls-Royce AE 1107 (T406) is a product used in V-22 aircraft with 14–stage axial compressor and a 2-stage gas generator turbine. During the stage of growth development, engineers investigated multiple possible paths to meet anticipated requirements of a "future" transport rotorcraft. The then "new" flying machines were to be equipped with a pair of more powerful turboshaft engines. The possible growth options on the table included growth via temperature increase, growth via increases in air flow, and growth via throttle push. The first option works by maintaining the airflow through the entire engine and improves its specific power output. However, this change cannot be realized without an apt upgrade for parts and cooling mechanisms deployed in the hot gas path section (combustors and turbine), which is subject to the cost and capability of additional material and cooling technologies. The increases in airflow require either up-sizing the compressor or adding stage count. In case this path is taken, a trade-off study is conducted as additional weight from the compressor and its implication should be taken into account. The throttle push approach relies on RPM increase to produce more power. This would result in higher operating temperature, flow, and pressure ratio all at the same time. Nevertheless, the flip-side of this option is the potential limitation by ramping up the shaft speed above its designed value, i.e. the point of diminishing returns might be within reach and further increases in engine speed is not justifiable. By looking into all three options and their combinations, designers of AE1107 were able to roll out an AE1107 growth version with a 20% increase in airflow and 19% in temperature. The product features an overall 40% increase in power, but with only less than 5% weight increase (Figure 15). The compressor now has 12 stages but with improved pressure ratio thanks to the higher stage loading enabled by advanced technology. What's more, the growth version still fits within the same basic envelope as the baseline engine, providing an alternative for the existing clients. This success story of AE1107, once more, demonstrates the applicability of growth notion upon turbomachinery product development.

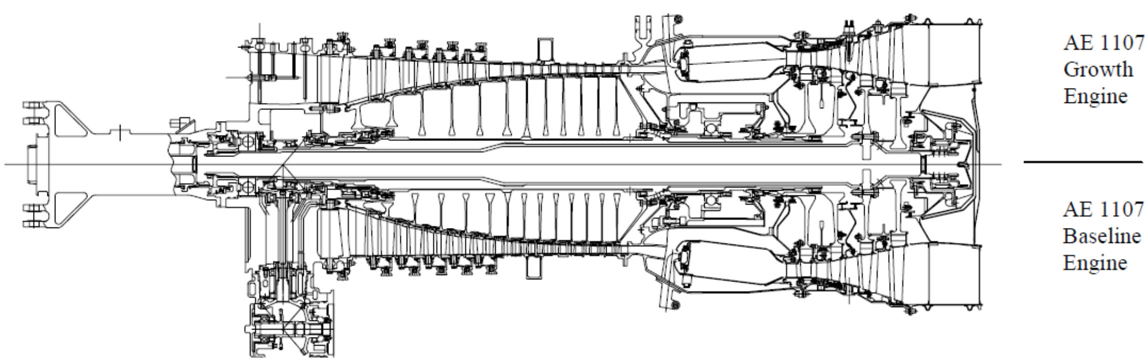


Figure 15. Rolls-Royce AE 1107 Growth and Baseline Engines [27]

It is not surprising that, General Electric echoes Rolls-Royce's growth concept in their turboshaft engine design. In his publication on maturity and growth of T-700 turboshaft engine program, Martin [28] states that "historically all successful aircraft powerplants have undergone an extensive growth program either to keep up with weight increases in their primary applications or to obtain additional applications." For the power growth of T700 family, airflow, cycle temperature, and cycle efficiency were the items under designs' consideration. The highlight of T700 product development by GE is the presentation of a 4-step growth plans scheduled for the future power growth of this family, (Figure 16). With a clear fully-grown end-goal in mind, the roadmap shows the steps and corresponding growth techniques designed to improve the performance of this engine. The formulation of growth idea in [28] represents a more structured way to grow an existing product series to its full potential via a planned roadmap. The present research will take a similar approach to manage growth for industrial GT product design and development.

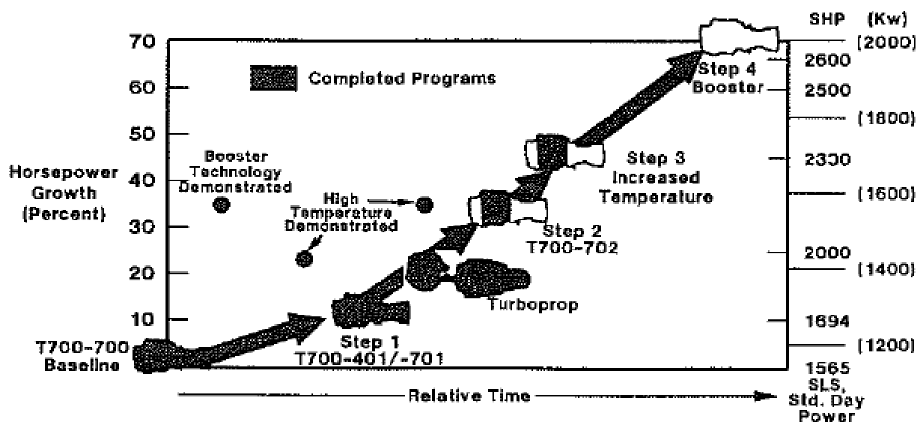


Figure 16. T700 Family Growth Engine Roadmap [28]

Meantime in academia, Mavris et al. [29-32] presented an architecture-based design space to capture impacts brought via both scaling and technology infusion in the context of aircraft engine design. A notional, two-dimensional design space is sketched in Figure 17 with thrust and engine weight as two major design requirements. The grey area indicates the feasible design space posed by the customer. Two types of growth are highlighted in this plot: physics-driven and technology-driven. Provided with fixed technology settings, physics-driven growth includes changes made wherein the resultant design maintains the same architectural integrity. In the plot, this means the new design point stays on or close to its original architecture line, A or B, with each representing a notional engine architecture. This type of growth "involves an interaction between metrics where an improvement in one causes degradation in another [30]." For example, a large engine is able to produce more thrust but carries more weight, eventually penalizing the aircraft's performance. On the other hand, technology-driven growth highlights that "improvements may be made in several metrics at once" but at the cost of more development spending. As such, the new engine may gain more thrust with a marginal weight increment, or even weight savings. In the case where more than two requirements are concerned in a design problem, this two-dimensional space can be extended to n-dimensional for multi-dimensional decision-making. In [31] and [32], Mavris and Briceno formulated a structured process for an engine development decision support system that captures uncertainties from both changing customer requirements and technology infusion.

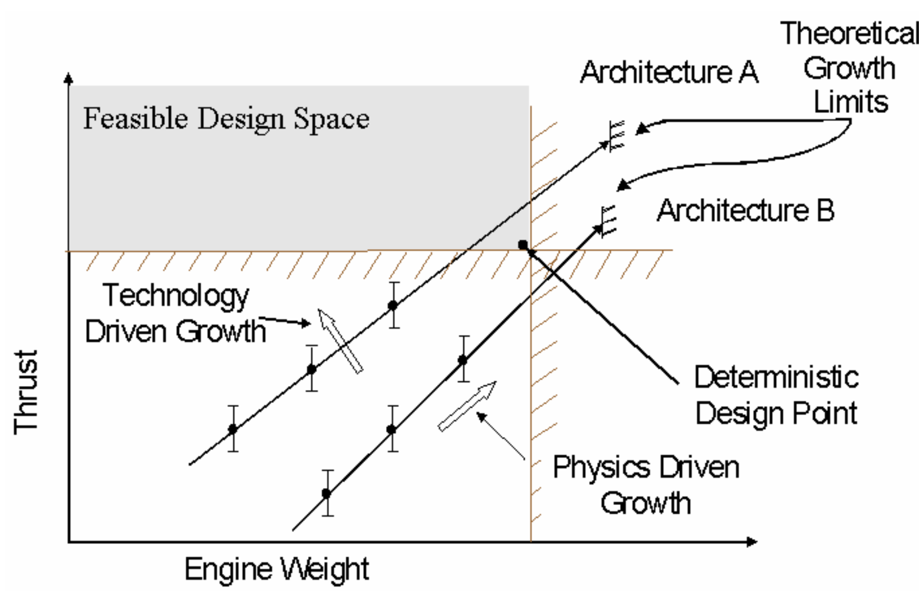
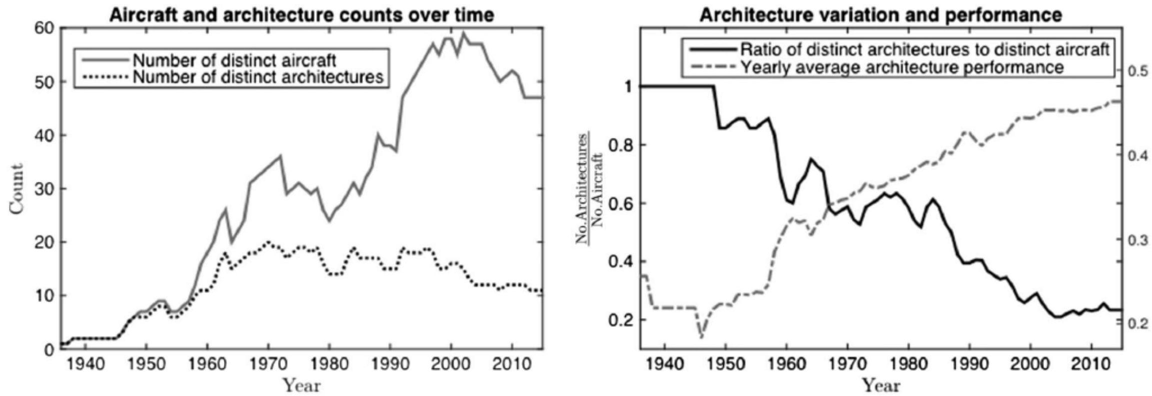


Figure 17. Aircraft Engine Architecture Growth Trends [32]

Thanks to the similarity between aircraft engines and ground-based GTs, this process can be transplanted and improved to address research questions regarding GT uprates and architecture evaluation in this work. The techniques and concepts used will be elaborated in later chapters.

Another finding on architecture is on the aircraft side, Kellari et al. [33] recently looked into architectural decisions in commercial aircraft in the past eight decades, and observed that "the variation in architectural decision options has decreased and a dominant architectural design has emerged". They carried out a functional decomposition and used architecture decisions to account for different configurations of different aircraft. On the performance side, they formulated an aircraft performance metric so that different aircraft architectures can be compared using a relatively consistent manner. They surveyed all historical aircraft architectures in the past, and concluded that while there are more and more distinct aircraft, the number of distinct aircraft architectures actually going down. Interestingly, as the ratio between distinct architectures and the distinct aircraft has gone down, the performance of aircraft has actually doubled since compared to that of 1930s (Figure 18). Those trends indicate, "Passenger aircraft have gone through a period of architectural innovation followed by incremental and modular innovation, mainly in propulsion and materials technologies." [33] This situation is similar in the field of industrial gas turbines as architecture diversity remains stable and uprated gas turbines become more prevalent in the business model of GT manufacturers. The authors finally comment, "**History would suggest that there are limits to the performance gains from every architecture and that fuel price gains, technology maturation, or new regulations could force consideration of alternative architecture to realize performance beyond the incremental growth trend seen today.**" [33]



a) Distinct architectures and distinct aircraft per year

b) Ratio of distinct architectures to distinct aircraft and architecture performance

Figure 18. Analysis of Aircraft Architecture over Time [33]

2.4.5 *Performance Limits of Turbomachinery*

The intention of PIPs is to integrate technology into the gas turbine at the component level. A closer look at Table 8 indicates most of the options listed target and enhance component-level characteristics. The table may create an impression that the more options the client selects to uprate, the more performance gain the system will benefit, which is not always the case. Indeed, a potential performance limit exists for each product, which is implicated by physics laws. No matter how many technologies are deployed, the performance limit can only be approached but not reached. This section reviews some of the existing work on GT performance limit, covering the scope of both component level and system level.

Hall assesses limits of axial compressor turbine efficiency both at stage-level and component-level in his work. By using “a bottom-up loss model”, he was able to take only unavoidable sources of inefficiency into account and estimated the limit of the efficiency. The type of losses considered includes profile losses, endwall boundary layer dissipation, and tip clearance losses. The peak stage efficiency for a compressor (first stage) turns out to be approximately 95.5%. This is a substantial improvement compared to the state-of-the-art compressors, which have polytropic efficiencies standing around 92% [34]. On the turbine side, the uncooled stage efficiency limit is approximately 97.3%. In the same work, Hall also presented the maximum thermal efficiency (η_{th}) limits for the entire simple-cycle gas turbine with respect to changes in component polytropic efficiency (η_{poly}), as well as cycle pressure ratio (π_c). These results shown in Figure 19 and Figure 20 are based on the assumption that all components have the same polytropic efficiency and that cycle temperature ratios are fixed to represent levels of turbine cooling and material technology. θ_t is the cycle stagnation temperature ratio. It is observed that the maximum thermal efficiency for the entire GT increases linearly with component polytropic efficiency. For a 95% component efficiency with $\theta_t = 5$, the efficiency limits stands at 51% for a temperature dependent constant pressure specific heat (c_p). At the same component efficiency level, as the cycle pressure ratio increases to 100, the thermal efficiency eventually reaches at about 51%.

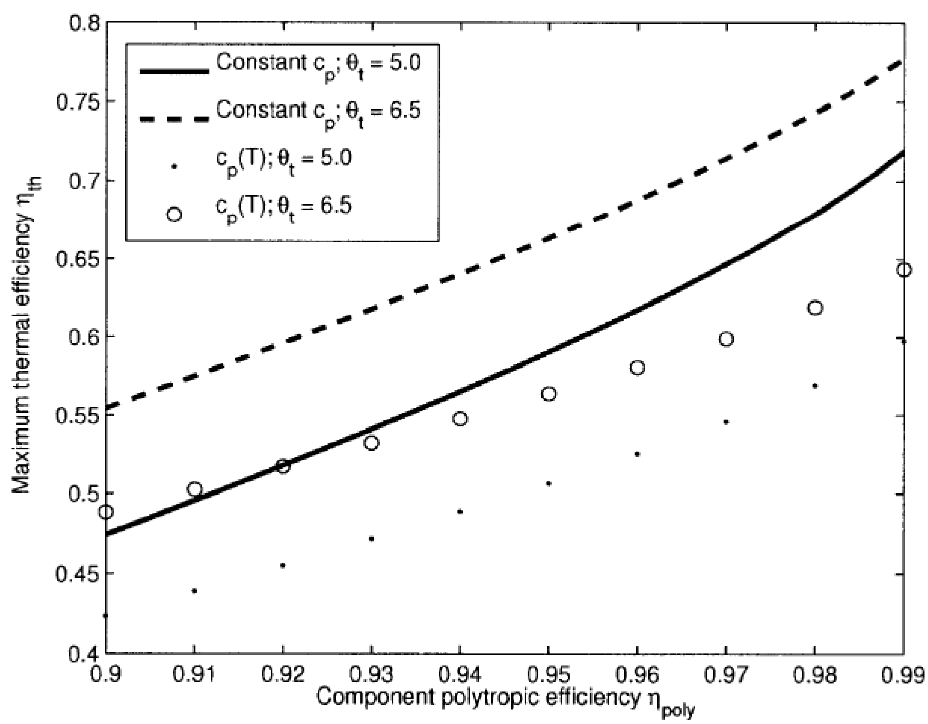


Figure 19. Maximum GT Thermal Efficiency vs. Component Polytropic Efficiency

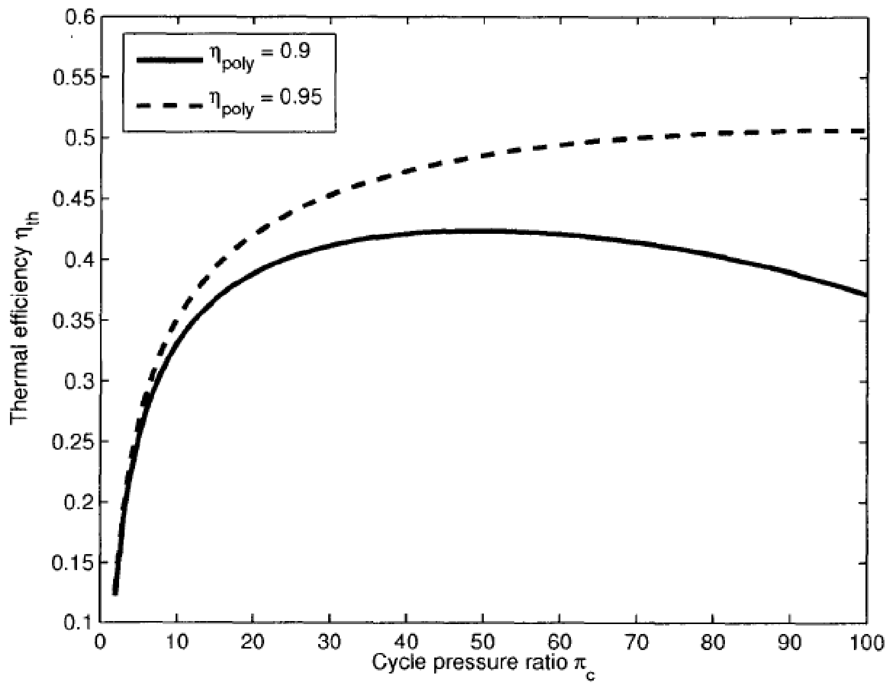


Figure 20. Maximum GT Thermal Efficiency vs. Cycle Pressure Ratio ($\theta_t = 5.0$)

At the system level, Gulen introduced the rule of 75% [35] by plotting a regression line going through data points from trade publications. Cycle efficiencies of GTs belonging to different technology classes are included in Figure 21, along with the temperature-based Carnot efficiency curve. It is observed that for a given turbine inlet temperature (TIT), the majority of the existing simple-cycle GTs fall within 75% value of the efficiency defined by Carnot cycle. Note that Carnot cycle possesses the theoretical maximum thermodynamic efficiency for any known cycle. Commenting on the status quo of GTs' cycle efficiency improvement, Gulen stated that "although TIT is still a main driver of the efficiency, advances in materials, coating, and cooling technologies make inroads without pushing the TIT further." The author explicitly expressed pessimism in terms of the room for further cycle efficiency improvement, as the prevalent avenues, such as TIT, pressure ratio, and component efficiency all have their limitations (emission, cost, etc.). However, he still believed the 75% efficiency barrier can be conquered if the game-changing development in materials is able to obviate or drastically cut the need for cooling air extraction.

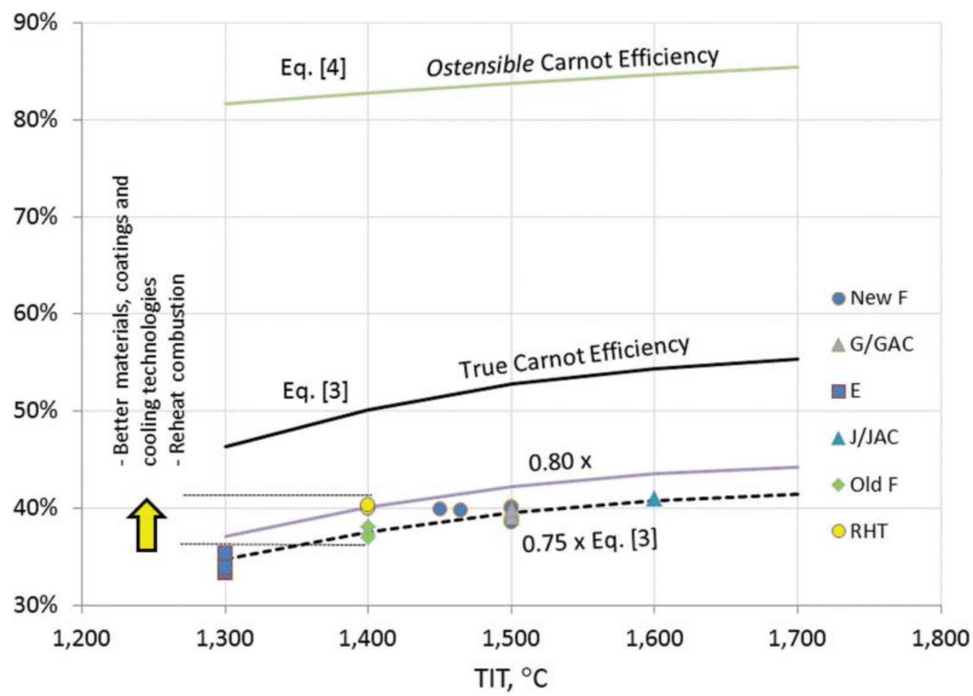


Figure 21. Gas Turbine Brayton Cycle Efficiency and Carnot Effciency [35]

2.5 *Modern System Engineering Design Methodology*

System design is the process of defining and developing systems to satisfy the specified requirements of the end-users. The enormous stride made by computational power in the last three decades has enabled engineers to use a more quantitative-based approach to design, and optimize their products. As a result, more elements within the product's life cycle have entered the vision of designers, in turn blending "the perspective of marketing, design, and manufacturing into a single approach to product development [36]". Concurrent Engineering by Kusiak [37] and Integrated Product Development are just two examples of numerous modern system engineering methods aiming to "enable the organization to define, develop, manufacture, deliver, and support products that meet all customer and internal business requirements [21].”

2.5.1 *Integrated Product and Process Development*

Integrated Product and Process Development (IPPD) is “a management technique that integrates all acquisition activities starting with requirements definition through product, fielding/deployment, and operational support in order to optimize the design, manufacturing, business, and supportability processes [38]”. This technique “has its roots in integrated design and production practices, Concurrent engineering, and Total Quality Management [39]”. To implement the IPPD strategy, Schrage and Mavris [40] proposed a version of Georgia Tech Generic IPPD Methodology based on principles from Concurrent Engineering, as shown in Figure 22. At the heart of IPPD is a “top-down decision support process”. This is a guided product design process providing “a logical, rational means for including factors that must be considered when making a decision [41]”. Note that system engineering methods are all process-design driven while quality engineering methods are product-design driven. Both of them are tightly bound into the central decision process on a computer-integrated environment, which is “needed to facilitate the process, reduce the design cycle time, and provide a transparent and seamless integration [42].” Since the inception of its proposition, Schrage’s approach has seen numerous practices in the realm of system design. The methodology presented in this research will evolve from this approach with necessary adaption to actual industrial GT product conceptual design and decision-making from a manufacturer’s perspective. The top-down design decision support process [40] shown in the center column is used to establish the architecture-based growth approach. The value in the step of “establish the value” is represented by quantifiable growth metrics introduced in this research work. Those metrics serve as key decision factors for future industrial GT products architectures.

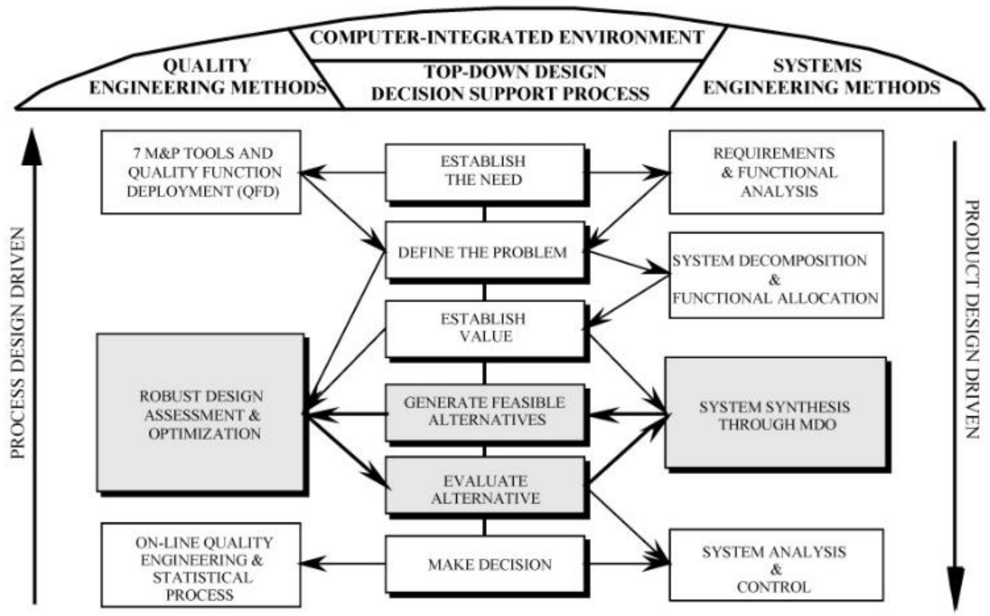


Figure 22. Georgia Tech Generic IPPD Methodology [40]

2.5.2 *Technology Modeling and Portfolio Assessment*

As observed in CHAPTER I, the constant evolvement of technology and infusions are behind these PIP uprating options that drive the continuous performance improvement of GT products. Successful selection of those technologies for development and incorporating them into newer product design requires a thorough assessment of their impact on design objectives. Additionally, the need for smart resources allocation necessitates the capability to identify technologies that demonstrate the potential to fulfill design requirements. In the past, the research field of technology portfolio selection and assessment has been plowed since the beginning of this century [43-51].

Technology identification [43] is conducted by a thorough search among an existing in-house technology database, which includes technologies either ready to deploy or still under development. Technology level (TL), or technology readiness level, is a time-sensitive metric to measure the estimated spread of technology impact on the performance of baseline.

There are two pieces of the information required to accurately model a technology. The first is whether this technology can be used alongside other technology, i.e., technology compatibility. Multiple technologies are used in combination to jointly improve the system's performance. The technology compatibility matrix (TCM) [43] is used to address this relation on whether two technologies can be deployed together as a pair. An example of TCM is presented in Table 9, depicting six dummy technologies, where "0" represents an incompatible technology pair and "1" represents a compatible technology pair. By taking account for compatibility, feasible technology combinations are formed as potential candidates for later evaluation.

Table 9. Technology Compatibility Matrix Example [33]

#	T1	T2	T3	T4	T5	T6
T1	1	1	1	1	1	1
T2	1	1	0	0	0	1
T3	1	0	1	1	1	1
T4	1	0	1	1	0	1
T5	1	0	1	0	1	1
T6	1	1	1	1	1	1

For full matured technology or technology close to maturity, the impact is already known, without any additional changes in time. As such, a technology impact matrix (TIM) [43] is created at component-level based on the following assumption:

1. Technology impact is deterministic and independent of each other;
2. The joint impact of technology combination formed by compatible technologies can be modeled as the lump sum of each individual technology's impact at component-level. In short, the technologies' impact is stackable.

A notional TIM is shown in Table 10, with six dummy technologies mapping out nine component-level model parameters (also called "k-factors"). Note that the value showing the impact of each technology is the relative amount, with respect to a given baseline. As such, its value could be positive, negative, or zero (no change).

Table 10. Technology Impact Matrix Example [33]

Model Parameters	T1 CPR	T2 CMC	T3 SX	T4 TBC	T5 Cool	T6 BShape	Unit
Comp_delta_effPoly	0.03						NA
Comp_delta_FSPRmax	0.6						NA
Turb_delta_desVaneTemp		300		150			R
Turb_delta_Stator_rho		-0.09	0.024				lb/in3
Turb_delta_desBladeTemp			300	150			R
Turb_delta_filmc_eff					0.1		NA
Turb_delta_internalc_eff					0.05		NA
Turb_delta_effPoly						0.02	NA
Cost_delta_RDT	20	10	20	5	20	15	M$

Technology identification, evaluation, and selection (TIES) is a structured process first developed in 1999 [43] by Kirby et al. at Aerospace Systems Design Laboratory at Georgia Institute of Technology. The approach focusses on quantifying and forecasting the impact of emerging technologies to be integrated into advanced system concept design. The 8-step iterative procedure (Figure 23) uses statistical and probabilistic methods to account for design uncertainty and allows for the infusion and subsequent affordability assessment of immature technologies. The introduction of TIES sparked a series of subsequent research topics on effective evaluating technology portfolio screening for decision making in advanced system conceptual designing. Roth et al. came up with a technology-impact forecasting environment used in conjunction with a genetic algorithm to efficiently explore the technology combinatorial space [46-48]. They also formulated a bi-level approach for tackling the technology selection problem to assist the designer in obtaining quick estimates of the minimum level of expectation from the combination of genetic algorithm-TIES approach [49]. Raczynski et al. conducted technology space trade-off by utilizing a multi-objective genetic algorithm along with TIES. They postulated that this algorithm allows for a better understanding of the areas of the minimum for each response compared to the traditional single-objective genetic algorithm [50]. McClure created a methodology to deal with technology assessment in the context of evolving requirements as both technology and design requirements are dynamic, subject to technology readiness, and rapidly changing market preferences [51].

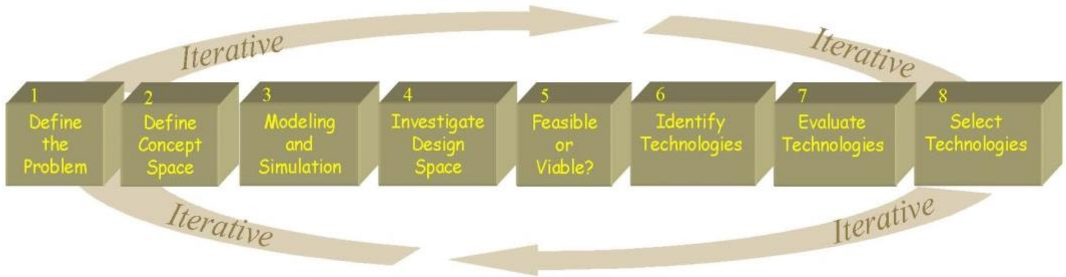


Figure 23. Technology Identification, Evaluation, and Selection [43]

In this work, the technology portfolio assessment capability is considered as an important avenue to enable the built-in growth quantification of GT products. The techniques and their applicability reviewed above present a good starting point to develop technology assessment techniques in the context of GT product growth management.

2.5.3 *Optimization Algorithms for Combinatorial Problems*

Optimization is a critical technique used in design practice to achieve better product performance. In the context of design, it is a process of selecting the best element from a set of available alternatives subject to some given criterion and constraints. A typical problem statement for a constrained optimization problem can be formulated as follows [52]:

Objective function: Minimize: $F(\boldsymbol{X})$ **(Eq. 1)**

Subject to:

Inequality constraints: $g_j(\boldsymbol{X}) \leq 0 \quad j = 1, 2, \cdots, m$ **(Eq. 2)**

Equality constraints: $h_k(\boldsymbol{X}) = 0 \quad k = 1, 2, \cdots, l$ **(Eq. 3)**

$$\textbf{Side constraints}: X_i^l \le X_i \le X_i^u \qquad i = 1, 2, \cdots, n \qquad \textbf{(Eq. 4)}$$

$$\textbf{Design variables}: \boldsymbol{X} = \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_n \end{Bmatrix}$$

The objective function $F(\boldsymbol{X})$ and the constraints functions defined by **(Eq. 3)** and **(Eq. 4)** can be a linear or nonlinear function of the design variable $\boldsymbol{X}$.

In a combinatorial optimization problem, where the candidate set can be discrete, exhaustive research is not tractable. This is due to the number of feasible solutions that usually grow exponentially with the size of the instance to be solved [53]. The combinatorial optimization is interested in this work as it has been repeatedly deployed in the technology assessment process for design performance optimization [47-50]. In this section, a review of the existing approaches to conducting combinatorial optimization are provided as a potential toolbox for the growth-based approach formulated later in this document.

Combinatorial optimization problems have a practical impact, given their applicability to real-work scenarios [54]. In fact, they arise in several heterogeneous domains, along with many others called routing, scheduling, production planning, decision making process, location problems, transportation (air, rail, trucking, shipping), energy (electrical power, petroleum, natural gas), and telecommunications (design, location) [55]. There are different types of algorithms designed to address combinatorial optimization problem, i.e., exact, approximation, and heuristic. An exact algorithm always solves an optimization problem to optimality, such as Branch & Bound [56] and Dynamic Programming [57]. These types of algorithms use divide-and-conquer methods, which takes the approach of breaking the problem into multiple sub-problems, solving them individually, and then combining solutions together. Approximation strategies find a suboptimal solution by providing an approximation guarantee on the quality of the solution found [55]. It applies to the scenario when the exact algorithm cannot solve the problem in polynomial time. Heuristic algorithms can be good candidates in an instance where the traditional exact approaches are too slow, or the approximation algorithms fail to find an exact solution. This type of algorithm is typically considered a shortcut, as it trades optimality, completeness, accuracy, and/or precision for speed. Examples of such algorithms include simulated annealing [58], tabu search [59-61], and genetic algorithm [62]. Table 11 provides a short summary of optimization algorithms that can be used toward combinatorial optimization.

Table 11. Algorithms Used for Combinatorial Optimization

Category	**Positive**	**Negative**
Exact	Guaranteed optimality	Speed
Approximate	Guaranteed quality	No guarantee on optimality
Heuristic	Speed	No guarantee on optimality or quality

2.6 *Summary*

In this chapter, the research objectives and questions are formulated. The concept of architecture-based product growth was presented in the context of aircraft engine conceptual design. The notion is deployed for industrial GT development with a further extension in this work. A substantial literature review on topics regarding turbomachinery product design and system-engineering approaches are additionally included. The purpose of surveying those areas is to better understand the status quo of industrial GT design and to explore those published design methodologies and optimization algorithms that can be leveraged in this work. The intelligence collected in this chapter will serve as a sturdy basis upon which the architecture-based growth approach is formulated and deployed.

CHAPTER III

TECHNICAL APPROACH AND EXPERIMENTATION

The approach to be presented in this chapter addresses the overarching research question that given a set of technologies (matured and emerging) and an existing GT architecture, how the framework built out of growth could be useful in the product design and development for future GT products. The product growth metric is formulated in this chapter and used as a key enabler in a structured and yet transparent process applicable to the conceptual design stage of industrial GTs. This provides a way to understand the past GT product performance evolvement history and helps the industrial GT Research and Development (R&D) team layout the product roadmap for the next decade or even beyond. As a summary of the research purview, the research formulations presented are tabulated in Table 12 and each of them will be tackled in this chapter. Multiple existing design techniques introduced in the literature review section of CHAPTER II are to be leveraged and improved if necessary to be deployable in this research work.

Table 12. Research Formulations Revisited

Research Objective 1	Extend the capability of existing conceptual-level technology integration and selection procedure applicable to GT product design and development so that the new framework is anticipated to quantify the built-in growth exists in the current architecture.
Research Objective 2	Propose a structured way of using design-in growth concept for GT New Architecture Introduction path by leveraging both GT traditional design techniques and product growth consideration, and prove its technical

	feasibility as well as potential added-value to current design practice.
Research Objective 3	Formulate an architecture-based growth approach that can be used to support a reliable and strategic decision-making process of future industrial GT product development path for the manufacturer.
Global Research Question	***Given a set of available technologies (matured and emerging) and existing industrial gas turbine architectures, how can the capability of product growth management in a GT architecture be used to enable an informative decision upon its future product development path?***
Research Question Set 1	a. How to identify competitive technologies that will be integrated into future GT product development? b. How to account for the built-in growth of the GT architecture included in its dedicated PIP?
Research Question Set 2	a. How to design growth into a new GT architecture given forecasted information about emerging technologies? b. What are advantages of using designed-in growth when launching a new architecture?

The context of the proposed GT product growth approach is presented in Figure 24, which includes the proposed notion of built-in growth for existing architecture and designed-in growth for a new architecture. The approach starts with quantifying the built-in growth in the current products and architectures. This is done by evaluating the currently available technologies compatible with the existing architecture. Based on the result, the design team can proceed with the option of either pursuing the existing architecture further or launching a new GT architecture. In case the first path is to be taken, the process evolves into a requirements-driven technology assessment problem. The improved product is expected to be an upgraded version of its previous generation with incremental performance uptick. On the other hand, if it turns out that the current products are getting close to maxing out their extant growth potential or there is a looming new technology class in the horizon, then it's considered a good time to start preparation for launching a different product architecture. In other words, a redesigned architecture infused with a breaking-through technology class would reset or further extend this growth. To better plan and manage its future evolution path, the engineering team is advised to start thinking to design growth into the very first product of this newly created architecture. This portion of designed-in growth is to be fulfilled gradually in its later uprating versions, i.e. via PIP until the built-in growth is realized completely. In this approach, the NAI and PIP are the two programs paving the product development path ahead for newer industrial GTs. Whenever a decision is to be made about the architecture of the next GT product, this "follow or switch" bifurcate type decision requires a thorough performance and economic valuation of the two programs of interest. The purpose of this entire approach is to assist the product development team to formulate and deploy a rational product growth strategy tailored to industrial GTs.

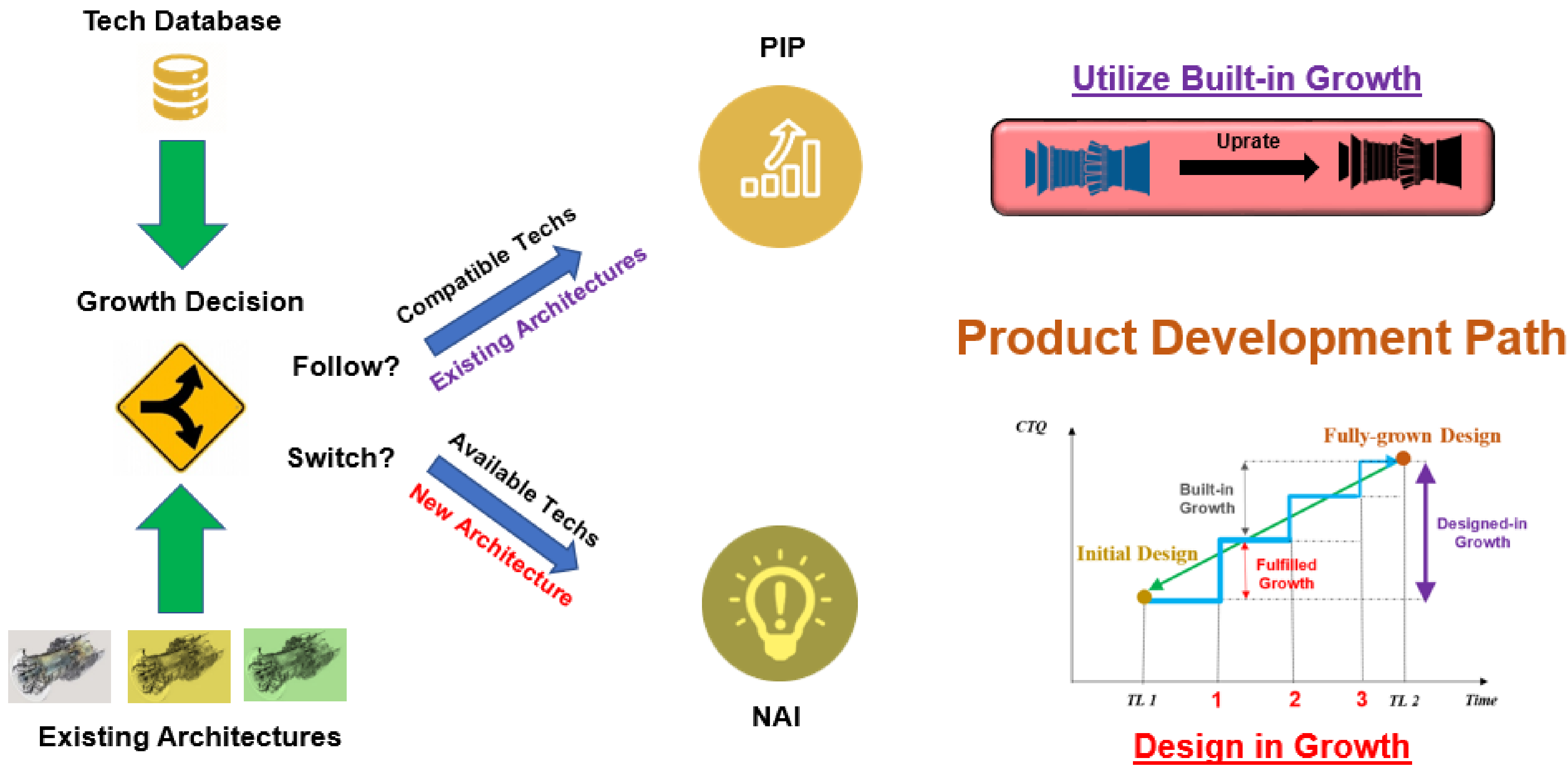


Figure 24. A Structured Manifestation to Understand GT Product Development

3.1 *Overview of Approach*

The design flow depicted in Figure 24 manifests a way to understand and conduct a GT product design and development process. For the sake of implementation, this entire product growth framework is converted to a block diagram in Figure 25.

Growth is a metric to effectively quantify the amount of built-in growth in the current GT architecture. As the amount of growth is dependent on available technologies and their maturity level, so is the maximum growth. Once all compatible technologies are under consideration, the maximum growth can be obtained for a given architecture. When an architecture of interest has enough built-in growth, i.e. the current GT performance metric is nowhere close to its maximum growth, it would be reasonable to design the next generation of product with an incremental performance improvement compared to the existing one. In the meantime, a list of uprating options is provided for an existing clients to create their customized versions of GTs. If it turns out that the amount of built-in growth is marginal for the existing architecture or a new technology class is on the horizon, the need for a new architecture should be seriously considered. A new architecture is expected to be engineered with both existing and emerging technologies in mind. Note that the inclusion of recent technological progress does not convert into GT's performance gain upfront or at once, i.e. the expected growth is not fully reflected in the first product of the new architecture. As such, it is called "designed-in" growth. This portion of growth would be realized as fulfilled growth with the procession of a series of PIP programs. The remaining "designed-in growth" is considered as "built-in growth" of this architecture.

Whether it's a PIP path or NAI path, once a newer product is hammer out, a complete re-calibration of built-in growth is conducted. The purpose is to make sure the decision is always made using the most updated product architecture and technology information applicable. The detailed content of each individual block is to be elucidated in the sections to follow.

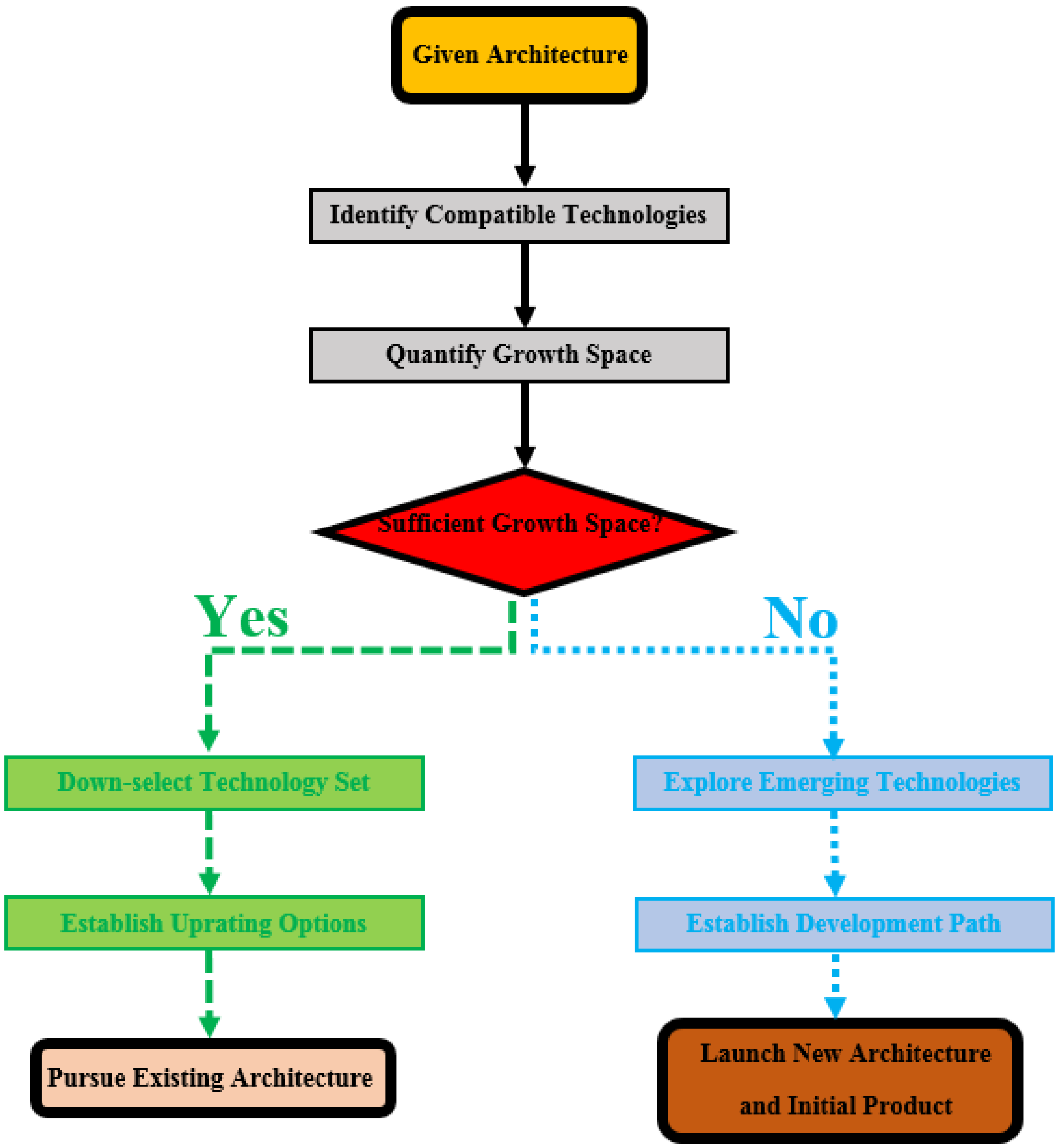


Figure 25. Architecture-based Growth Approach for Industrial GT Design

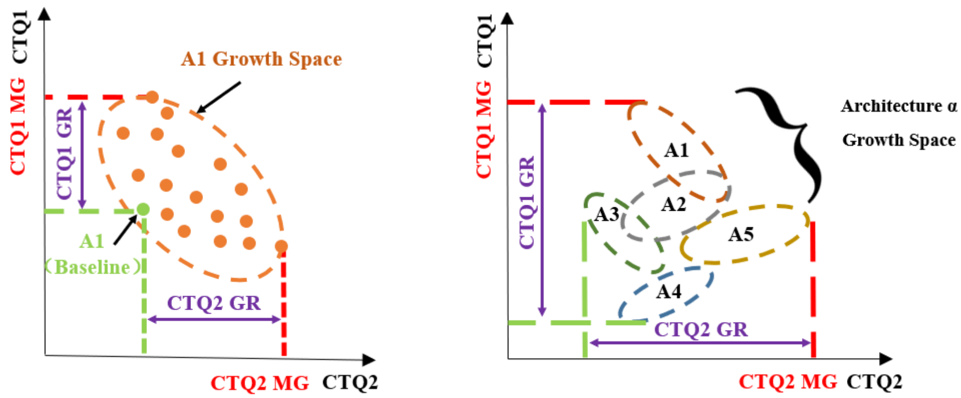
3.2 *Industrial Gas Turbine Maximum Growth Quantification*

It has been defined in this work and repeated here that growth of a GT product is the quantifiable potential improvement in performance for a given set of technologies at a certain technology level. The growth of a GT architecture is the maximum room of performance improvement for those products under that architecture is expected to achieve with all compatible and available technologies. This section is dedicated to formulating a solution to quantify both product-level and architecture-level of growth used for GT development. The implication of growth quantification capability is two-fold:

1. This obtained growth space defines the potential performance envelope of each product or architecture. This piece of information is highly valued as it equips the design team to have the capability to have a quick response to whether the current GT products or their uprated versions would be able to meet the upcoming customer demands, which is accessible from a new power plant project or a predicted market trend.
2. The technology selection process enabled by this capability renders an efficient way to identify technologies that belong to the category of "common beneficiary" type. Those technologies are considered "common denominators" in product development as they would have a far-reaching impact on existing or even future products. If resources are not sufficient to finally mature all of them, a prioritized list of technology is generated to give preference to those technologies that are expected to have larger "footprint" over products.

3.2.1 *Product Level Growth*

For companies designing and manufacturing industrial GT products, the research and development unit within those entities bear a paramount role in incubating cutting-edge technologies that can further advance the operational performance and economic competitiveness of their products. For a given GT product, the contribution of its growth relies on the seamless integration of those technologies with the product in hand. It is presumed that each technology's impact can be reasonably captured and that multiple compatible technologies would place a joint influence on the product of interest. A product-dependent growth space is generated by evaluating the corresponding Critical-To-Qualities (CTQs) with regard to different feasible combinations of technologies. A CTQ is the key measurable characteristics of a product. The requirement of a CTQ has to be met so as to satisfy the customer. In the context of industrial GT, it could be either one of several key system-level metrics of GTs (power output, heat rate, the unit cost of electricity, etc.) or a composite function of them.



(a) (b)

Figure 26. Growth Space for (a) a GT Product; (b) a GT Architecture

In Figure 26(a), GT product A1 has two CTQs of interest, with characteristics of being larger the better. The point corresponding to its current performance (baseline point in green) is shown in the plot as well. With each feasible combination of technologies being simulated and integrated to the baseline, there are changes expected in both CTQs. As such, a new design point is created after evaluating each feasible technology combination. After all possible combinations have been covered, a cloud of design points on a scatter plot is generated, which is referred to as **growth space** of A1. It is evident that the size of this 2-dimensional growth space visually represents how much growth potential this product owns with respect to the 2 CTQs shown, i.e. the remaining built-in growth. In the event of a multi-CTQs, a multi-dimensional growth space is created. However, it is not practical to visualize this hyper growth space directly for the designers. As such, there are needs to introduce requisite metrics to depict the size of this growth space in the context of multi-CTQ situation. To address this problem, a **Maximum Growth** (MG) is obtained with respect to each CTQ in question. In this case, MG of a specified CTQ is the maximum value that all those improved versions of baseline can reach given the compatible technology combinations. The **Growth Range** (GR) is the difference between the MG established and the baseline value for each CTQ. Therefore, to quantify the design space of a given product, each CTQ has one MG, which caps the limit and one GR, which renders a simplified way to approximately quantify the potential improvement each baseline can achieve. Note that in most cases, the design point corresponding one CTQ MG does not necessarily generate MG of another CTQ, which implies those values typically come from different design points. It is also important to point out that the MG values and GR values across all CTQs help approximately depict the growth space the product can tap into for each individual CTQ. Due to the correlation among different CTQs, it's possible that parts of this hyperspace (e.g. area next to a boundary or a vertex) is not accessible for all the improved designs created by the given technology set. For example, in Figure 26, the design point with coordinate (CTQ2 MG, CTQ1 MG) is not accessible by the baseline design and applicable technologies. The design space does include CTQ2 MG value and CTQ1 MG value, but those values are achieved in two different design cases.

To sum up, for a given technology setting, every GT product has a dedicated growth space. Since the growth space may be multi-dimensional and complex, a proposed way to approximately describe a growth space is to use a set of CTQ dependent MGs and GRs to quantify this space in each CTQ dimension. Despite the fact that using these quantities does not provide the complete details of the growth space, there are still advantages of doing this. One argument is that using MGs and GRs is not susceptible to the adverse characteristics of the growth space, i.e. tractability from dimensions, complexity due to non-linearity, etc. Another point worth mentioning is that the MG and GR information gleaned for each CTQ in this process is an indispensable puzzle of the whole architecture approach formulated in this work since those quantified values would be treated as decision factors for further GT product growth.

3.2.2 *Architecture Level Growth*

A GT architecture is a group of GT products sharing (almost) the same flow-path design and technology class. To define the growth space for a particular GT architecture, the individual growth space of each product within that architecture must be accounted for. In order to get an estimate, product-level MG and GR information must be established first for those qualified products belonging to architecture α, as shown in Figure 26(b). As an extension from product-level growth, **the growth space of an architecture** is the combined growth space of all GT products within architecture α. In the case of larger CTQ, the better, **the maximum growth of an architecture** is defined at each CTQ dimension by taking the maximum MG across all GT products. **The growth range of an architecture** is computed by taking the difference between the maximum growth and the minimum baseline line value for that particular CTQ dimension.

Note that the growth space of the architecture is expected to be much more complex and irregular in shape than that of a product due to the fact it's obtained by superimposing multiple product growth spaces. The MGs and GRs corresponding to different CTQs help sketch a hyper-box in the space that encloses the architecture-level growth space. The box essentially provides an approximate boundary that the performance of products of that architecture can achieve under the current technology settings in case the exact growth space is impractical to generate because of the intractability of design variables or incompetence of existing computational resources.

3.2.3 *Growth Quantification for Selected GE GT Architectures*

Take a second look at those series of products GE manufactured during a period of half a century (Figure 27), it is not hard to notice how different GTs in each product series evolve with time. GE MS5001, which is a product series spanning three decades, became fully developed in 1987 as the power output started to gradually show signs of loss of upward momentum as early as the 1970s. The total built-in growth realized for this architecture can be computed by simply taking the difference between the performance metric of the first product and the latest one. In this case, the power output went up from 10.750 MW in 1957 to 26.820 MW in 1987, achieving an increase of almost 150%. During the same period, the heat rate dropped from 15,821 BTU/kW-hr down to 11,860 BTU/kW-hr, making it almost 25% more efficient.

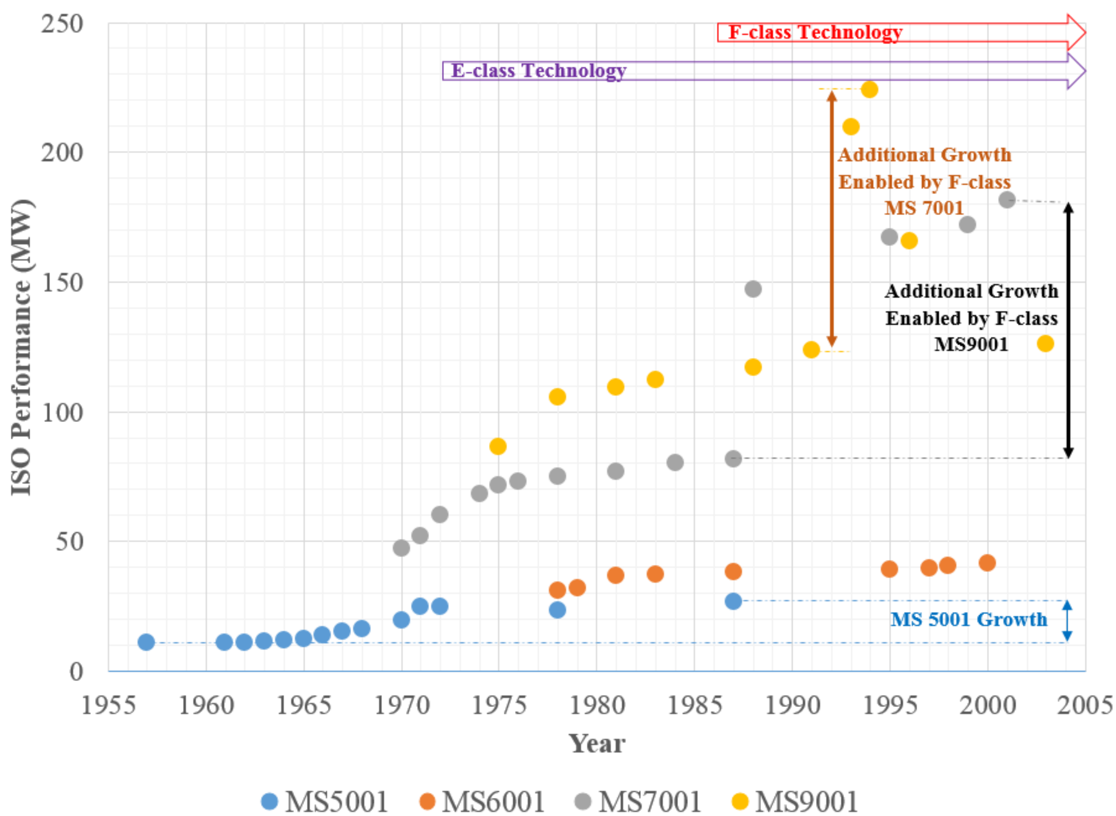


Figure 27. Growth Observed for Various GT Architectures by GE

For architectures still in development, the built-in growth is gradually fulfilled in a stream of products until it finally gets close to depletion in a future time. However, there are cases when the introduction of a break-through class of technology tapping into the previously unrealized potential by the original designers, which is also noted in Figure 27. The F-class technology was initially incubated in the 1980s and deployed first to the MS7001 series in 1988 and later to MS9001 and MS6001 series in 1993. This class of technology "represented a quantum leap in the operating, temperatures, cooling technology and aerothermal performance of heavy-duty gas turbines" [63]. One common feature of F-class products is that the firing temperature has been raised to 2,300 °F and above, which is enabled mainly by utilizing better cooling design and parts made with superior heat-resistant material in the hot gas section. As such, the performance leap is truly amazing as it can be told by the later development trajectory of both MS7001 and MS9001. The comparison can be conducted between the last E-class GT product manufactured as well as the latest F-class in production which are tabulated in Table 13 per technical specifications in [10, 11].

Table 13. Additional Growth Enabled by F-class Technology for GE Products

Product Model	**PG7121EA**	**PG7251FB**	**PG9231EC**	**PG9311FA**
Product Series	MS7001		MS9001	
Architecture	7E	7F	9E	9F
Year of Introduction	1996	2001	1996	1994
Firing Temperature (°F)	2,035	2,555	2,200	2,350
Power (MW)	86.58	181.4	165.7	223.76
Percentage Change in Power	Baseline	110%	Baseline	35%

Within the same type of architecture, the built-in growth to be realized is incremental. Take a look at another architecture of GT products designed and manufactured by GE. MS6001 series gas turbines were first introduced back in 1978 for both 50 Hz and 60 Hz markets. Over the time span of four decades, incremental performance gains have been pursued and realized thanks to continuous advances in areas such as materials, coating, cooling, sealing, and design. Those improvements help "enhance performance, extend life, and provide economic benefits through increased reliability and maintainability of operating MS6001 turbines" [9]. APPENDIX A – A SUMMARY OF GE MS6001 UPRATING OPTIONS AND TECHNOLOGIES provides a summary of the background of this evolving architecture, including the existing models, technical specification, and a brief summary of selectable technical options for product upgrades. Detailed coverage of individual uprating option and package for this product series are presented in [9]. For the sake of the present example, Table 51 summarizes the system-level CTQ improvement values with respect to each uprating choice provided. Two CTQs of interest shown in the table is power output and heat rate for a GT product. Note that there is a total of 4 models within a single architecture ("Architecture 6B") under consideration and each of them has its own compatible options.

In this simple case, maximum growth and growth ranges for each model are to be derived. Take a closer look at the contribution of improvement from each available choice, it is observed that the package to increase firing temperature (Tfire) to 2084°F has the most percentage increment in terms of power output as it is a collection of multiple individual uprating options. Previously, all 4 models have the same firing temperature at 2020°F per Table 49. Since this is a package, the additional temperature of 64°F is realized by a synergy of material replacement, better cooling treatment, and advanced sealing. According to theory of thermodynamics, the thermal efficiency of an ideal Brayton cycle relies on the pressure change before and after the compressor, which is limited by the turbine inlet temperature (TIT). The higher TIT the hot gas path can tolerate, the greater pressure ratio and efficiency the system can reach. As such, the contents making up this package jointly enable the hot gas path to stay hotter and to produce more power given the same airflow passing the GT.

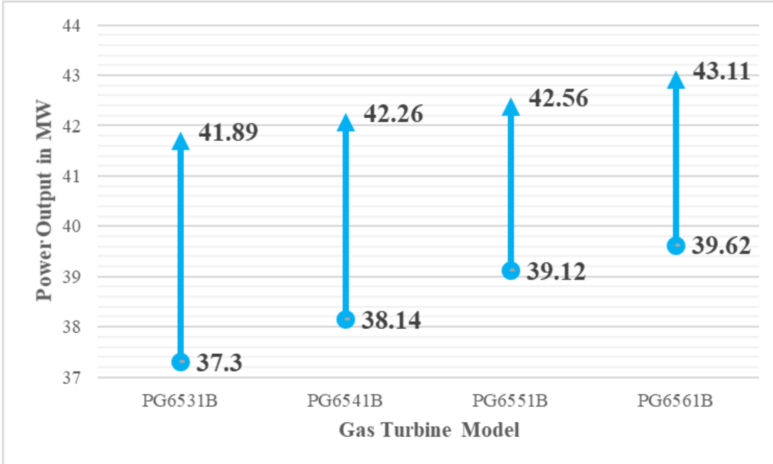


Figure 28. Maximum Growth for 4 GE Products under 6B Architecture (Power)

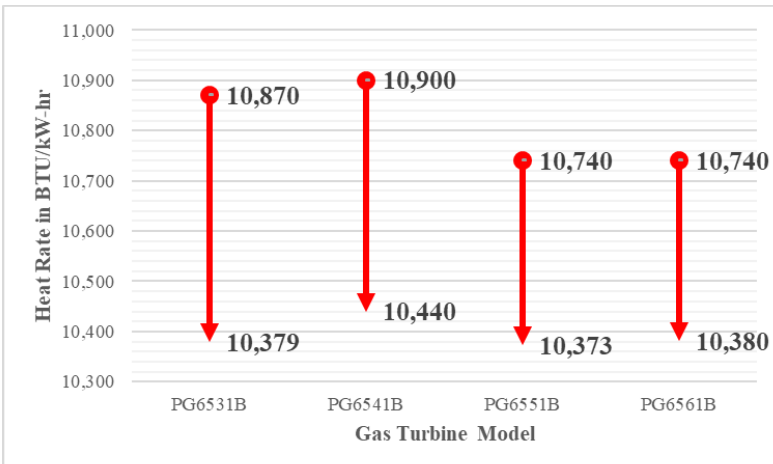


Figure 29. Maximum Growth for 4 GE Products under 6B Architecture (Heat Rate)

Note that those options are considered stackable by assumptions in the manual and each option is applied to a different component of GT, which means the greatest system-level impact on each model would be accomplished by a simple superimposition of all available options. In addition, the baseline specifications for all four industrial GT products can be looked up in Table 49. With the information given, the total percentage change is tracked along with the maximum growth of each CTQ for each individual product. The maximum growth results are presented in both Figure 28 and Figure 29, with colored dots representing baseline values and colored arrowhead pointing to the maximum growth for each model of interest. The length of each arrow indicates the growth range. It is observed that the oldest model (first ship date of 1983), i.e. PG6531B would benefit the most if all those options have been applied to the platform since it has the maximum amount of growth range in both power and heat rate. This is not surprising as it uses the greatest number of uprating options during this process and all those options will contribute to the overall performance improvement based on the stackable assumptions introduced earlier. It's also interesting to notice that the later version of the products benefits less compared to the earlier version in terms of the potential growth space brought by the combining all the applicable options. This is because some of the options may have already been upgraded or deployed in those newer versions before they come off the production line. One instance is that, for uprating option 9 (GTD-222 Stage 2 Nozzle) in GE's manual, the option is not available to PG6551B and PG6561B as this type of parts later became part of the standard system configuration in production when manufacturing these two products. The complete results are tabulated in Table 14.

Table 14. MG and GR Results for 4 GE under Architecture 6A

MS6001 Model	PG6531B	PG6541B	PG6551B	PG6561B
Ship Date	1983	1987	1995	1997
Baseline Power (MW)	37.3	38.14	39.12	39.62
Power MG (MW)	41.89	42.29	42.56	43.11
Power GR (MW)	4.59	4.15	3.44	3.49
Percent Change	12.00%	11.00%	8.79%	8.81%
Baseline HR (BTU/kW-hr)	10,870	10,900	10,740	10,740
HR MG (BTU/kW-hr)	10,379	10,440	10,373	10,380
HR GR (BTU/kW-hr)	(491)	(460)	(367)	(360)
Percent Change	-4.52%	-4.22%	-3.42%	-3.35%

3.3 *Growth-based Technology Development*

Technologies are the key drivers to push the products' continuous performance upgrade. In the case of PIP, the built-in growth is gradually fulfilled during multiple rounds of product uprating along the path. This section is dedicated to addressing the first two research questions pertaining to GT-related technology.

As indicated in the uprating manual for GE MS6001[9], each GT upgrade option for this product series is enabled by one or more improvement in various technology fields and reflected in its impacting parts of the system. Each type of technology pertained in uprating can be grouped into one of the five areas listed below:

1. Materials: The introduction of new materials such as alloys renders substantial improvement in material properties. In the hot gas path section, the new material to be deployed could either enables operations at higher TIT or simply last longer in adverse working condition compared to the part made from the existing material.
2. Coatings: Similar to material change, the advanced coating put on the surface of the part also make a higher TIT possible and prolong the life span of turbine parts operating in a hostile environment.
3. Cooling: Better cooling effectiveness reduces the amount of bleeding flow extracted from the compressor so that more useful work is accomplished by the GT system given the same total air intake flow.
4. Sealing: The enhancement in sealing design effectively minimizes impacts from clearances that would cause partial loss of useful work done to the flow. The deployment of cutting-edge sealing technique contributes to the uptick of operational efficiency in the individual stage located in either compressor or turbine.
5. Aircraft Engine Technology: various aircraft technologies have found their places in the industrial GT to either reduce emissions from combustion or increase system-level availability and reliability.

It's stunning to see that technologies from areas above have shaped more than 50 different uprating options for MS6001 architecture alone [9]. It is presumed that each option is supported and enabled by at least one technology. It's not unreasonable to conjecture that the total number of technologies dealt by GE "think-tank" can easily add up to a hundred and even more, considering technologies applicable to other product series or those still under development. Hence it would be ideal if there is a systematic way to model those technologies' impact both individually and jointly, and then use these inputs to quantify the growth space as shown in Figure 26. On the other hand, from the perspective of technology development, it is desired to have a structured evaluation and prioritized scheme for a manufacturer like GE to lean towards the development of common technologies that can be utilized for growth among different products.

3.3.1 *Requirements in Technology Evaluation*

Technologies portfolio assessment for conceptual system design has been explored since the turn of the 20th century. A structured process called TIES was proposed by Kirby [30] in her Ph.D. dissertation to address this topic. The methodology is an 8-step iterative process (Figure 23) used during the conceptual design stage to quantify and forecast the impact of emerging technologies on an existing engineered system's ability to meet requirements. For matured technologies, the approach uses a technology modeling technique to systematically capture the potential improvement/degradation of feasible technology combinations upon the existing base system. On the other hand, it uses statistical and probabilistic methods to account for design and technology development uncertainty, which enables infusion and subsequent affordability assessment for immature technologies. This platform has served as a springboard to its enriched extensions [44-51], derivatives such as Technology Impact Forecasting [64, 65], and Unified Trade Environment [66, 67]. Traditionally, technologies are evaluated and selected to maximize a single product's performance with reasonable add-on cost. For the challenge faced by GT manufacturers, they would expect more, i.e. the technologies to be invested should factor in a broader scope of existing designs. To be more specific, products in operation/production and under development should be all under the consideration if possible. As a key enabler of growth quantification, technology assessment capability plays an important role in both technology development as well as GT product evolvement. As such, a method of technology assessment is in need to address both challenges.

Technology impact modeling is considered as an important contribution to technology selection process. In this context, examples of technology impact include component-level efficiency improvements and part material property change. A baseline GT model definition is established upfront since the impact of technology is an evaluation of relative change with respect to a datum. All the evolutionary GT models are obtained by applying component-level technology advancement upon the baseline model.

In this work, in order to use technology information to help quantify the growth space of a GT product or an entire GT architecture, the technology evaluation and selection process is anticipated to have capabilities to address requirements listed below:

A large number of technologies either already deployed or under development: For a typical GT manufacturer, technologies handled by the development team covers a wide scope of fields. For instance, Global Research Center of GE has 12 different technology domains, which could be all pertaining to GT development, i.e. electric power, thermal science, material, mechanics and design, software & analytics, control and optimization, digital technologies, etc. [68]. In this case, it is reasonable to deduce that the total number of technologies in their database is enormous. As such, the process formulated in this work should be expected to handle and evaluate this intractable number of technologies in an efficient manner.

Compatibility between the two individual technologies: When applying multiple uprating technologies to an existing GT at component-level, it's likely that more than one technology can be applicable to the exact same part. Thermal coating and improved aerodynamics are both available options for turbine blades. Since the use of one does not exclude deployment of the other, they are a compatible pair. In other cases, the two technologies are competing. Film cooling and transpiration cooling are two different cooling blade cooling techniques. However, these two cannot be applied to the same part located in the hot-section of the gas path as each cooling design comes with a different internal blade structure.

Compatibility between the technology and a given GT platform: This is one level up from technology compatibility. Considering the configuration of each GT product, not all uprating technology is able to fulfill its designated benefit. This is because some of the GT products may already have the technology included in its production.

Technology impact quantification for a given GT platform. Each individual technology's impact is evaluated at the component level with respect to the baseline. The impact value may change from one baseline to the other due to differences in datum value and GT configuration.

Once the list of requirements enabled by the approach is complete, the

3.3.2 *Technology Selection Approach*

Fortunately, technology down-selection capabilities have already been established by TIES [43]. Following the approach in TIES, a product-technology compatibility matrix is created for each GT product to address the technology-product relation (Figure 30. In the plot, red (or '0') indicates incompatible and green (or '1') means compatible. An individual technology impact matrix (Figure 31) is also prepared for each GT product to capture the unique impact of the technology upon a given baseline product. For both types of matrices, the information required can be either collected from subject-matter experts from an R&D team or if available, from a well-established technology knowledge database of a company or organization. The gleaned information is then converted into corresponding matrix forms for subsequent usage.

Figure 30. Product-tech Compatibility Matrix

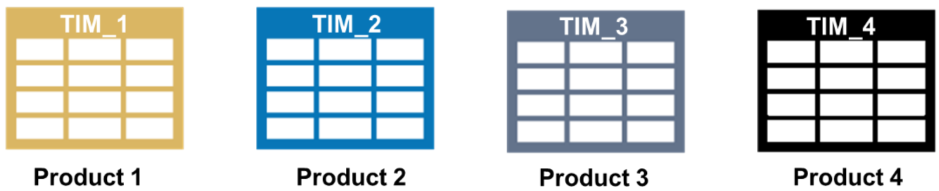


Figure 31. Product-dependent Technology Impact Matrix

It's worthwhile to reiterate at this point that the purpose of conducting a technology-driven growth evaluation is two-folded: one is to quantify the growth space metrics of a current product or architecture by identifying and evaluating compatible technologies; the other is to identify the top technologies that maximize the utilization of built-in growth of a product or an architecture. The complete procedure of evaluation is presented in Figure 32 and will be elaborated subsequently. The process is articulated with the two enabling elements below:

1. A technology candidate database from which all GT technology-related information can be queried. Compared to an expert, a database is a great tool for data sharing with an organization. A well-established technology database established is expected to provide useful information that supports the design process, including elements to create technology-technology matrix, technology-product matrix, and technology impact matrix. In this case, as all technologies in uprating options are fully matured, technology is modeled in a deterministic way. For emerging technologies, the technology level, expected maturity year, and expected impact should be included for future GT design development and technology evaluation.

2. For each existing GT product, there is a corresponding thermodynamic model to model on-design and off-design performances. This thermodynamic model is able to ingest technical inputs from technology matrices and translate the technology impact to CTQs as system-level outputs.

To quantify the growth space metrics of a product, it is considered essential to obtain maximum growth and growth ranges along each CTQ dimension. The design problem is then converted into a set of discrete optimization problems (Table 15). The objective can be selected to either maximize or minimize each system-level CTQ (e.g. maximize power output, minimize heat rate, etc.). All technologies involved in updating options are fair play. Each technology is either included or not included in the technology packages for CTQ improvement analysis based on their compatibility with other deployed technologies and the product given. Hence the design variables are supposed to be a binary vector with each item representing the corresponding technology included ('1') or not ('0'). The length of the constructed vector is anticipated to have the same dimension as the total number of technologies in consideration.

Table 15. Converting a Design Problem to an Optimization Problem

Design Elements	Optimization Elements
Maximum Growth of a CTQ	Objective Function
Technology Combination	Candidate Solution
Possible Uprated Design	Functional Evaluation
Design Constraint	Penalty Function

For a tractable number of technologies, enumeration of each feasible technology combination is possible. Note that each technology combination would correspond to an improved design point on the CTQ plot, as shown in Figure 26(a). The growth space can be constructed exactly. The maximum growth and growth range are obtained via their respective definition for each CTQ. For an intractable number of technologies, it's impractical to explore all their feasible technology combinations one by one. Therefore, an appropriate optimization scheme is requisite to find those growth space-related metrics.

Typically, for binary design variables, genetic algorithm (GA) is often top on the list as it "naturally handles discrete variables" [69] in optimization. It is a heuristic algorithm that is inspired by the process of natural selection to solve both constrained and unconstrained problem. The beauty of this population-based algorithm is that it mimics the production of genes in its basic operations such as reproduction, crossover, and mutation, which it relies on to produce the children for the next generation. Over successive generations, the entire population is expected to evolve toward the global optimal solution. Nevertheless, there are downsides of using this algorithm. As it may require a very large number of function calls, the computational costs could be prohibitive if the function evaluation time is overwhelming. However, a situation like this can be mitigated by using a transfer function or a surrogate to replace the original model. Another word of caution is that despite GA is used to find the global optimum, due to its stochastic nature, the global optimum is not 100% guaranteed. As such, it is considered a common practice to conduct multiple GA runs and then analyze their respective optimization results to maximize the likelihood of finding the true global optimum. Once the final design solution is acquired in each CTQ dimension, maximum growth and growth range can be calibrated. To conduct technology selection, a list of top technology combination(s) is analyzed for each CTQ dimension. The individual technology included in those top technology combination(s) is the contributing candidate that maximize the built-in growth of the given product.

The growth space of a given architecture is procured by repeating the product-level practice above for those GT products belongs to the same architecture. As shown in Figure 26(b), each cloud of points represents the growth space of a product. As defined before, the architecture-level maximum growth is then gained by locating the best performance CTQ that is achievable for all products under consideration. The growth range of a particular CTQ is the difference between the lowest CTQ value and the maximum growth. In this way, the growth metrics are computed for all CTQ of interest. The technology selection process at architecture-level starts with the top technology combination(s) for each product. A pattern study is conducted to pick the top individual technology based on its frequency. Technologies with top frequency counts are considered “common beneficiary” and they are able to bring in the built-in growth to the greatest extent. In the case of emerging technologies, this evaluation serves a good argument for the company to devote more resources into the final development of those technology candidates.

In summary, the GT performance improvement is highly driven by continuous technology advancement. It is observed that the built-in growth of an existing architecture can be quantified by the Product Improvement Program. This part of growth is tapped into by using the PIP package that is supported by a combination of matured technologies.

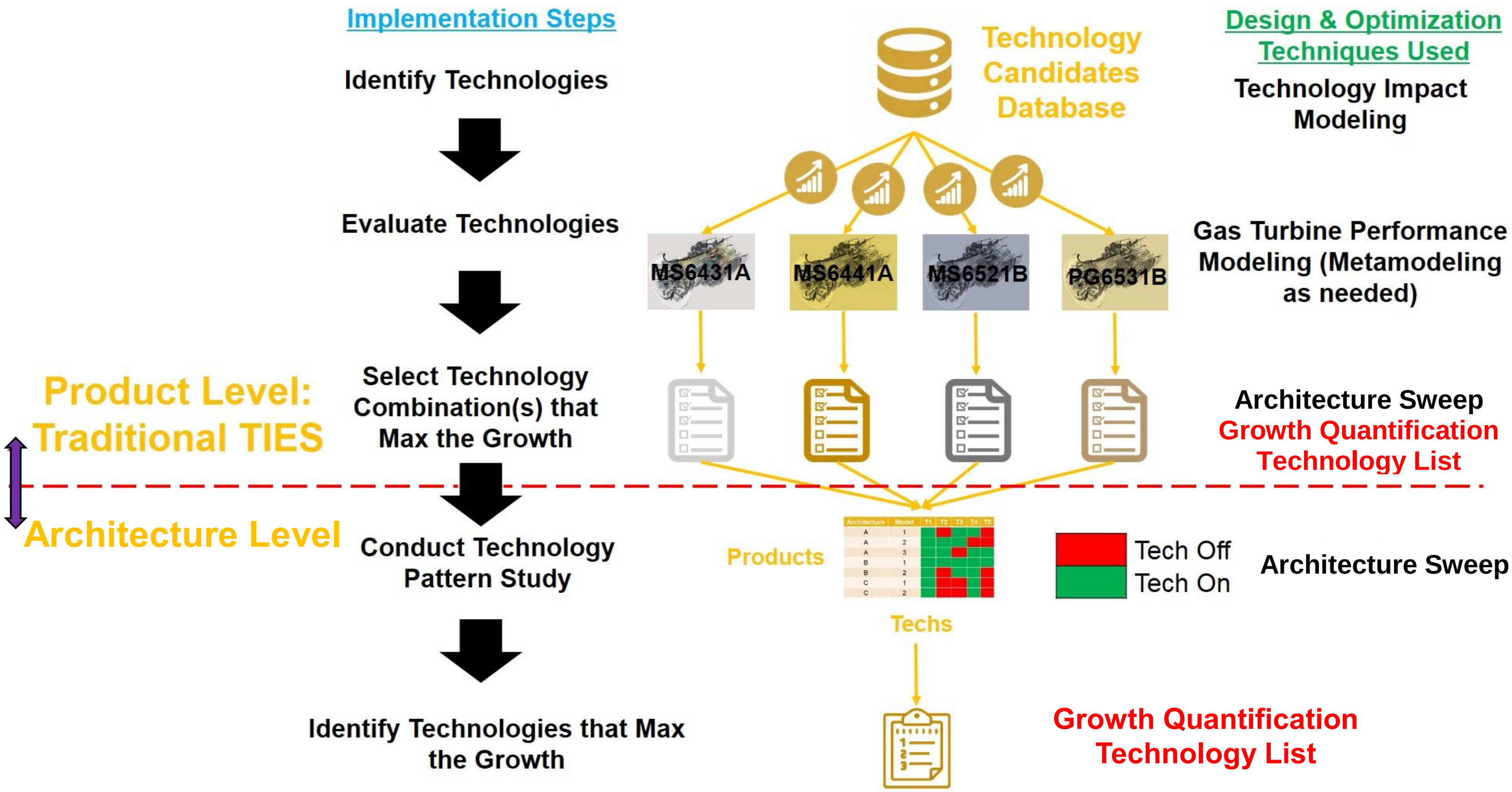


Figure 32. Proposed Growth-based Technology Selection Approach

3.3.3 *Technology Candidate Database Prototyping*

As a key initiative of the technology selection approach, an efficient way of organizing and managing existing and emerging technology information and their ties to GT products is presented in this section. A database created for technology management is a common and effective practice in the industry to accomplish this goal. This section is dedicated to the database structure tailored to product growth management. In general, this database prototype is expected to serve as an information repository which can supply up-to-date information to address almost all technology-level design challenges. To establish such a database, a list of requirements from Section 3.3.1 and 3.3.2 is repeated below:

1. Product-technology compatibility relation
2. Technology-technology compatibility relation
3. Product-dependent technology impact relation

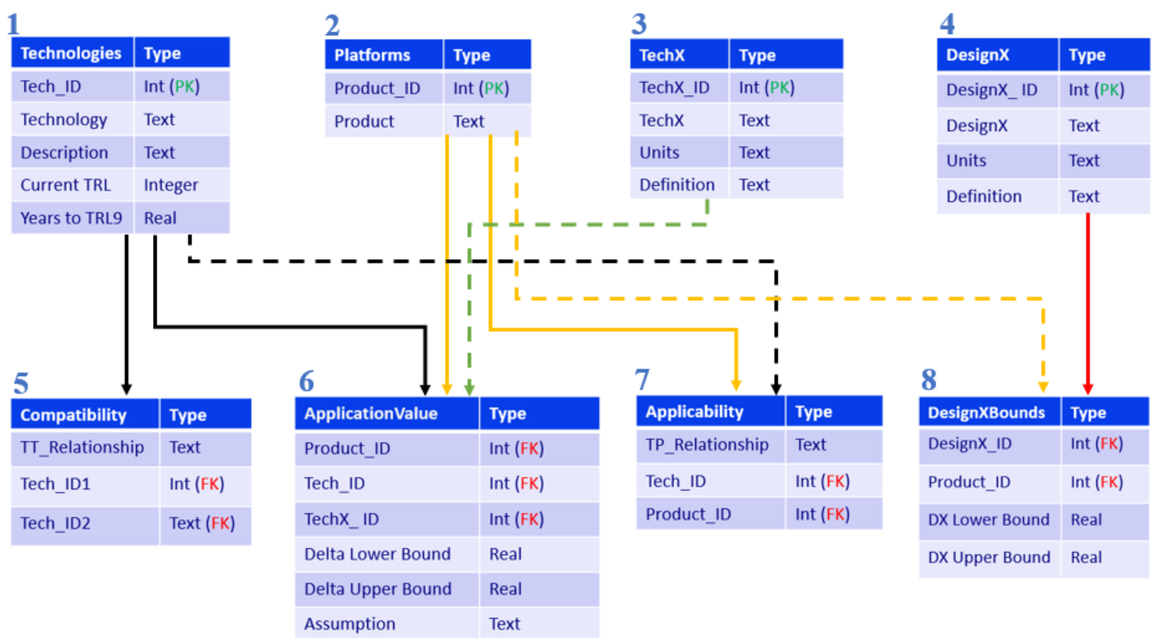


Figure 33. Entity Relation Diagram for Technology Candidate Database

From the perspective of database structure, an entity relation diagram (ERD) is created in Figure 33 to show the relationships of entity sets stored in a database. **An entity** in this context is an object, i.e. a component of data. There are eight such entities shown in this diagram.

The first four entities (1-4) are used to specify basic information about technologies, GT products, technology k-factors, and design variables respectively. Entity 1 assigns a technology ID to each technology in the database, along with technology name, description, current TRL, and the number of years to reach a technology level of 9. Entity 2 assigns a product ID to each GT product in the database, along with the product description. Entity 3 is used to enumerate and identify those technology k-factors that are affected by the technology, with both its unit and definition specified. Entity 4 lists all design variables that are applicable to industrial GT products, such as mass flow rate, pressure ratio, and fuel flow rate.

The last 4 entities are detailed information source necessary to generate information of interest for conceptual product design and technology evaluation. Entity 5 contains technology-technology compatibility information. Entity 6 contains the technology k-factor information (estimated lower and upper limits in terms of relative change amount) for a given product and technology pair. Entity 7 specifies the compatibility information between a given product and a given technology. Entity 8 includes information about the design variable range (both lower and upper limits) for a given product.

Items shared by different entities are linked by established "keys" so that when a query is executed, the relevant information can be retrieved from different entities and put together in an efficient manner. Using the ERD in Figure 33, a list of critical spreadsheets can be generated by executing corresponding queries for subsequent technology evaluation and assessment: Technology-technology compatibility matrix for a set of given technologies can be created by utilizing Entity 1 and 5. Product-technology compatibility matrix for a given set of products and technologies is generated by combining information from Entity 1, 2 and 7. Product-dependent technology impact matrix is created by querying Entity 1, 2, 3, and 6. Lastly, Entity 1 and 4 combined produces a matrix of applicable design variables and ranges for a given GT product. For demonstration purpose, a GT technology database prototype using the ERD shown in Figure 33 is created in APPENDIX C – TECHNOLOGY CANDIDATE DATABASE along with queries used to obtaining necessary technology information.

From an organizational point of view, the impact of using a well-established database is profound in many aspects. Technology information for industrial GT products comes in substantial volume and dimension, the use of database provides an organized and efficient solution to store and retrieve those data, usually coming with complex structure. The routine database management offers benefits such as flexible technology information update and modification, prevention of data redundancy, and maintaining data consistency within the entire product development team. The additional access control feature coming with a database differentiates user privileges and allow targeted users to have access to only resources they are entitled to. The multi-user access feature creates a collaborative and secure environment that help shortens the product design cycle time and facilitates real-time technology information sharing.

3.3.4 *Experiment 1: Growth-based Technology Selection*

The purpose of this section is to demonstrate the process of using technology-level information to acquire the growth metrics about two existing GT products and their GT architecture. In addition, technology selection based on growth maximization is demonstrated by taking the approach of technology identification and evaluation presented in Section 3.3.3. The demonstration process of this experiment is designed and used to introduce and test the two hypotheses formulated to address the first two research questions. They are stated below:

Research Question 1:

How to identify competitive technologies that will be integrated into future GT product development?

Hypothesis 1:

For a given set of technologies, the application of TIES is able to identify competitive technologies that bring performance benefits to products within the same GT architecture.

Research Question 2:

How to account for the built-in growth of the GT architecture included in its dedicated PIP?

Hypothesis 2:

For a given industrial GT architecture, its built-in growth can be quantified by evaluating feasible technology combinations provided in the PIP with respect to system-level metrics of interest.

This experiment is dedicated to investigating two industrial GT products from GE MS7001 series. This line of products was first rolled out in 1966. "At that time there was enormous demand in the U.S. for gas turbines with the capability for peak load power generations" [10]. The GT features a 17-stage compressor coupled with a 3-stage turbine, each operating at 3,600 rpm axial rotation speed. The product is designed to target for a market with 60Hz utility frequency. MS7001 fleet has evolved through different models and stages (A, B, C, E, F, and H) during a time span of almost half a century. The most recent version of this product series, i.e. 7HA.02 model, relies on H-class technology and achieves a simple cycle power output of 384 MW [70].

Product-level Evaluation Process

PG7241FA is one product from MS7001 series with 18 compressor stages and 3 turbine stages. The year of the first production dates back to 1999. This product evolves from its predecessor PG7231FA from the same architecture, with design improvements including robust compressor rotor, flexible combustor seals, and hot gas path improved sealing [71]. The technical specification of PG7241FA is included in Table 16 [72-75]. A

GT aerothermodynamics cycle performance model has been built using the Numerical Propulsion System Simulation (NPSS) platform. This software was developed by engineers working for National Aeronautical and Space Administration (NASA) at Glenn Research Center in 1995 [76]. It is object oriented, multi-physics, engineering design and simulation environment which enables development, collaboration and seamless integration of system models. Primary applications areas for NPSS include aerospace systems, thermodynamic system analysis such as Rankine and Brayton cycles, various rocket propulsion cycles [77].

Table 16. Information for PG7241FA and NPSS Model [72-75]

	Variable Type	Baseline	NPSS Model	Percentage Error
Pressure Ratio	Input	15.5	15.5	N/A
Shaft Speed (rpm)	Input	3,600	3,600	N/A
Mass Flow (lbm/s)	Input	987.67	987.67	N/A
Turbine Inlet Temperature (°F)	Input	2,420	2,420	N/A
Turbine Exit Temperature (°F)	Output	1,110	1,175	5.8%
Power Output (MW)	Output	174	180.4	10.3%
Efficiency	Output	36.7%	38.44%	4.7%

A structure of the NPSS thermodynamic model used in this example is displayed in Figure 34 and it is assembled and calibrated based on the following assumptions:

1. Fuel flow into the combustor of GT is varied so that the TIT matches the data from in Table 16;
2. Air flow into the inlet of the compressor is changed to match known exhaust gas flow shown in Table 16;
3. Horsepower extraction from the main shaft is tuned to match the exhaust gas pressure, which is set to be standard atmospheric pressure.

In addition to the thermodynamic side of modeling, there are two parts in secondary modeling included to compute various metrics of interest, as shown in Figure 34 below.

The first part is a cooling model named "coolit". This module is used to perform a low-fidelity heat transfer analysis to compute the amount of bleeding flow needed to extract from rear stages of the compressor. This part of air intends to go into downstream combustor and turbine to provide sufficient cooling for the hot gas path section, which is required to maintain a specified metal temperature [78]. Modifiers within "coolit" are available for tuning in cooling effectiveness, combustor pattern factor, and material capability, which are all potential subjects of impact once better technologies are included. In this GT model, "coolit" works by relying on the NPSS solver to match the required cooling flow from the hot gas path section with the extracted cooling flow from the compressor.

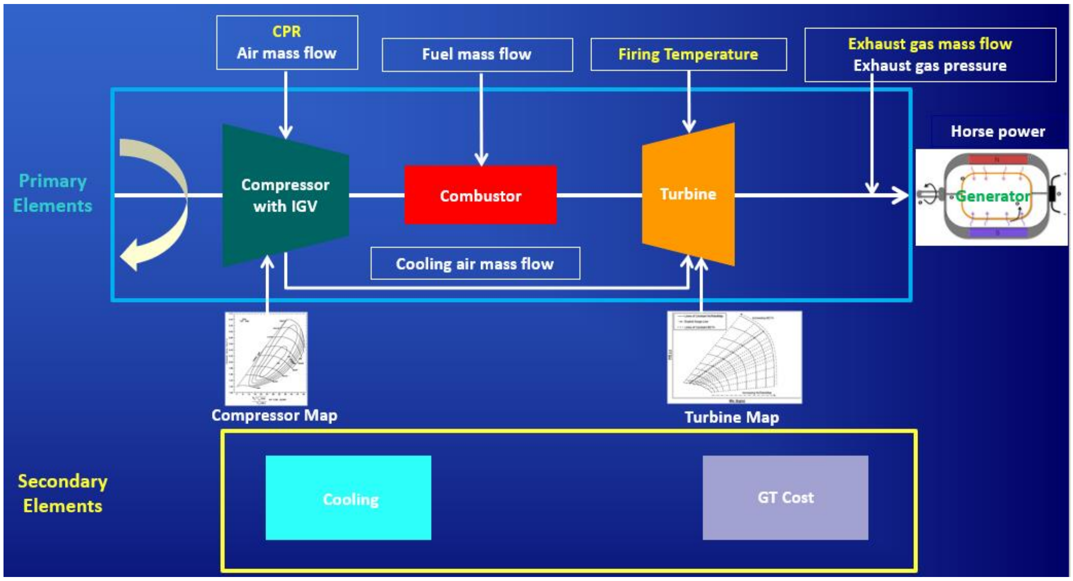


Figure 34. Structure of NPSS-based GT Model

The second part is composed of two cost models, accounting for the acquisition cost and operation/maintenance cost of the GT respectively. The acquisition cost uses a regression model based on numerous historical GT cost data points [79]. Those gas turbines in consideration cover a wide range of manufacturers and power settings (1 MW to 334

MW). There are two trained models presented in [79], one is for the heavy-duty industrial GT and the other is for the aero-derivative type of GT. The regression statistics from the plot shows heavy-duty regression model has a better curve fit indicator R^2 over aero. As PG7241FA falls into the category of industrial heavy-duty GT, the former model is used to estimate the acquisition cost. The resultant cost prediction formula is an exponential function displayed as follows:

$$y = 763.6x^{-0.223}. \qquad \text{(Eq. 5)}$$

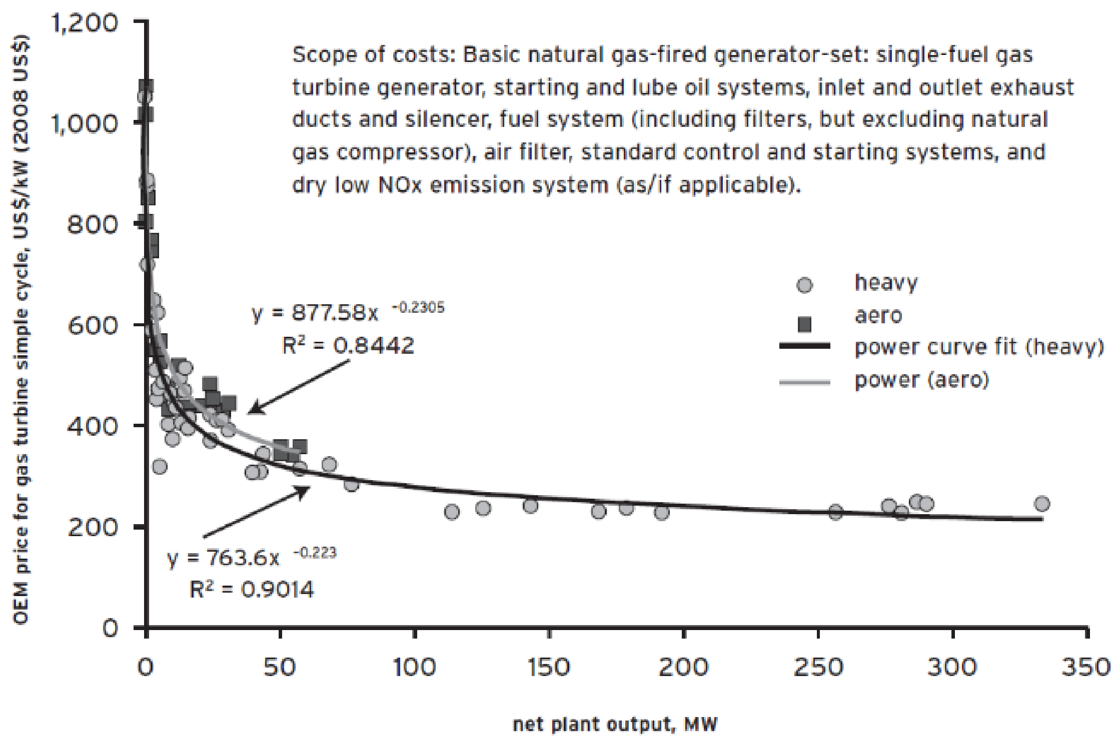


Figure 35. Impact of Size on Acquisition Cost for Simple Cycle Gas Turbines [79]

x above is the net plant output in MW. The operation/maintenance cost model takes care of those costs incurred during the daily operation of a simple-cycle power plant, i.e. fuel and the operation/maintenance. Per Walsh [80], the latter is estimated to be around 15% of the total fuel cost.

Once the model is built in the simulation environment, it is subject to calibration. Table 16 carries the design point information of the NPSS model built, i.e. model variable name, type, and percentage error with respect to the actual performance at base load. It is observed that the maximum error occurs for power output with 10.3% percentage error. This magnitude of maximum error is considered acceptable as the current NPSS model is a 0-dimension low-fidelity thermodynamic model only dedicated to conceptual design study. In addition to design point performance validation, an analysis of trend on efficiency, specific work, firing temperature, and pressure ratios is performed. This is considered as a trend modeling validation as it gives designers a good representation of what the gas turbine operational performance would look like when (1). the firing temperature is increased; (2). the pressure ratio is allowed to vary. A typical carpet plot showing the expected trend is included in Figure 36 with gas turbine inlet temperature (firing temperature) increasing from 1,000 °C to 1,250 °C and pressure ratio increasing from 10 to 28.

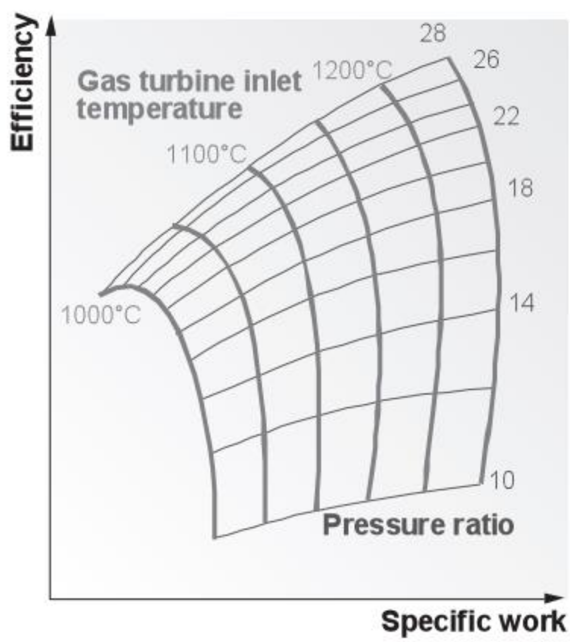


Figure 36. A Carpet Plot Showing Simple Cycle Efficiency-Specific Work [81]

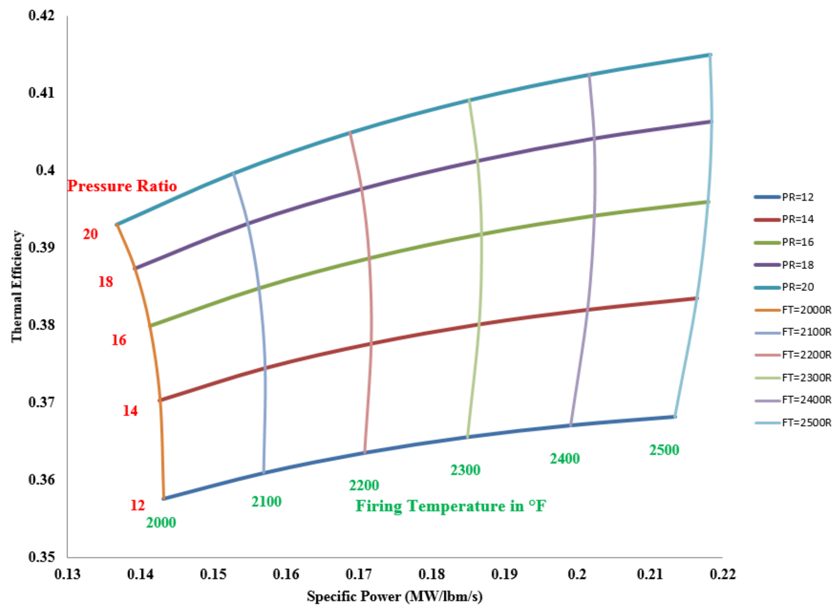


Figure 37. Performance Plot for GT PG7241FA (Firing Temperature in °F)

To better understand how the carpet plot works here, it's helpful to leverage some thermodynamic and algebraic knowledge from an engineering textbook on the shelf. For an ideal Brayton cycle, the cycle efficiency and specific work can be obtained using the two equations below:

$$\eta_{cycle} = 1 - \frac{T_1}{T_2} = 1 - \pi^{\frac{\gamma}{1-\gamma}}. \qquad \textbf{(Eq. 6)}$$

$$w = \frac{T_3}{T_1}\left(1 - \pi^{\frac{\gamma}{1-\gamma}}\right) - (\pi^{\frac{\gamma-1}{\gamma}} - 1). \qquad \textbf{(Eq. 7)}$$

In (Eq. **6**) and (Eq. **7**), π is the air pressure ratio between the inlet (P_2) and the outlet (P_1) of the compressor (Figure 1). γ is the ratio of the specific heats, and for air, γ = 1.4. From (Eq. **6**), the cycle efficiency η_{cycle} depends on the ratio between ambient temperature T_1 and compressor exit temperature T_2 or alternatively, only on the pressure ratio π. **Specific work** is a measure of power density and it is the amount of work done on per unit mass of air flow. The temperature ratio between firing temperature T_3 and ambient temperature T_1, combined with and the cycle pressure ratio π jointly determine the amount of specific work produced by the GT. A couple of interesting observations from Figure 36 can be understood with the help of (Eq. **6**) and (Eq. **7**):

1. Higher cycle efficiency is achieved if pressure ratio is raised, with firing temperature held at a constant. This can be understood by looking at (Eq. **6**). It is easy to see that cycle efficiency $\boldsymbol{\eta_{cycle}}$ goes up as the pressure ratio $\boldsymbol{\pi}$ increases as its exponent takes a negative sign.
2. A higher firing temperature produces more specific work under constant pressure ratio. As ambient temperature $\boldsymbol{T_1}$ is treated constant and pressure ratio is also fixed, the specific work $\boldsymbol{w}$ only depends on the firing temperature $\boldsymbol{T_3}$. In (Eq. **7)**, specific work $\boldsymbol{w}$ is an increasing function with respect to firing temperature $\boldsymbol{T_3}$. This clearly explains the trend of firing temperature $\boldsymbol{T_3}$ vs. specific work $\boldsymbol{w}$ in the plot.
3. Higher cycle efficiency is achieved if the firing temperature is raised, with pressure ratio held at a constant. As ambient temperature $\boldsymbol{T_1}$ is usually treated constant, a higher compressor exit temperature $\boldsymbol{T_2}$ would yield a higher cycle efficiency $\boldsymbol{\eta_{cycle}}$. As from the theory of turbomachinery, the compressor exit temperature $\boldsymbol{T_2}$ is limited by firing temperature $\boldsymbol{T_3}$, which is an indicator of technology level. As such, a higher firing temperature $\boldsymbol{T_3}$ would enable a higher compressor exit temperature $\boldsymbol{T_2}$, which leads to a higher cycle efficiency $\boldsymbol{\eta_{cycle}}$.

To generate carpet plot for GT PG7241FA, the pressure ratio is varied from 12 to 20 with an increment of 2 and the firing temperature is changed from 2,000 °F to 2,500 °F with an increment of 100 °F. These lower and upper bounds are selected to reflect a range encompassing design point of the product at its base load. The corresponding trend result is presented in Figure 37. The observation that the carpet plot displays a similar trend as in Figure 36 indicates that the NPSS model built in this case is thermodynamically consistent with empirical trend published in the literature. In other words, the trend is validated.

12 dummy technologies are being evaluated in this product-level process. It is presumed that 3 of them have an impact on compressor's performance and the remaining 7 help improve the operation of the turbine. The maximum number of technology combinations formed by those technologies are 2^{12} = 4,096, which is no small number for

enumeration. Once the technology compatibility matrix (Table 52) is taken into account, the number is expected to be slightly lower. The technology impact matrix (Table 54) matches the 12 technologies to 9 technology k-factors, which can be treated as component-level impact bearers for different feasible technology combinations. A detailed explanation about the meaning of each k-factor is tabulated in Table 53. Those k-factors are expected to translate the technologies deployed into either system-level performance change (gain or degradation). Among all the k-factors, there is only one used to account for relative R&D cost, i.e. "Cost_delta_RDT". The detailed accounting of R&D cost is usually treated as a commercial secret and is not readily available in the public domain. As such, one remedy used in this example is to track the relative R&D cost increment incurred by deploying individual technology. The R&D baseline cost for a technology is hence taken out of the equation and only relative cost change is under evaluation. In this way, the net cumulative amount increase represents the actual R&D cost increase for the applicable technology combination. Note that the relative amount of R&D cost for each individual technology in this example is only estimated by using fictitious but reasonable numbers based on engineering judgment. However, this part of the model could be easily improved once the actual information is available.

Table 17. Implementation Procedure for Growth Quantification

Step	**Specification**	**Platform**
1	Create a DoE Spreadsheet	MATLAB
2	Run a GT Model	NPSS
3	Create a NN Surrogate Model	BRAINN
4	Run GA Optimization	MATLAB
5	Data Analysis and Visualization	EXCEL

For product-level example, the growth quantification and technology selection procedure are itemized in Table 17 along with the modeling and simulation platforms engaged. The goal of the first three steps is to create a surrogate model dedicated to GT thermodynamic evaluation for faster function calls. Considering the fact that genetic algorithm may require a large number of function calls during the optimization process, a surrogate model is deemed inevitable to expedite the solution-searching process. In the first step, commercial software MATLAB is used to create a Latin-hyper-cube type of DoE spreadsheet with 20,000 cases to efficiently sample the entire design space. This design space includes the three design inputs to the model, i.e. cycle pressure ratio, firing temperature, and exhaust mass flow rate, as well as all technology k-factors, which parameters are altered by applying different technology options. The NPSS model then runs through all 20,000 cases and generate corresponding outputs.

Considering the NPSS model created is nonlinear in nature, artificial neural networks (ANN) is selected to be its surrogate due to its superiority in dealing with a highly nonlinear problem if an appropriate "architecture" is selected. Note this "architecture" is not supposed to be confused with the architecture of gas turbines. The "architecture" of an ANN includes those elements that contribute to the actual configuration of connected NN network, such as the number of hidden layers, the number of hidden nodes on each layer, and signal transmitting direction (Figure 38). Another advantage of using ANN is that it requires the minimum amount of knowledge about the original physics-based model as it relies on training weights of each node to learn and predict trends and performance.

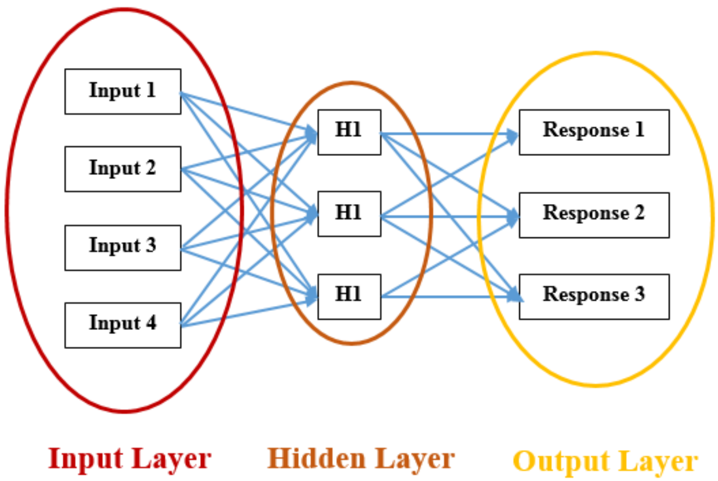


Figure 38. An ANN Conceptual Architecture

The spreadsheet of DoE is then loaded into BRAINN, which is a MATLAB-based ANN training environment developed in-house at ASDL. To generate a model with adequate quality, different ANN model "architectures" are explored in BRAINN 2.3. Each architecture has to go through a tuning process, which includes varying a set of hyper parameters. They are the number of hidden layers, the number of neurons in each hidden layer, and the number of epochs. The training algorithm is the optimization method used to determine the coefficients for the network that minimize the training error. A large variety of training algorithms are available in BRAINN. The output of BRAINN contains the surrogate model generated as well as four model-fit statistics plots. Those metrics are key indicators of how well the trained surrogate model is able to represent the original physics-based model using the hyper parameters specified. The four modeling metrics are summarized below:

1. Model Fit Error (MFE): the distribution of error obtained by comparing the predicted performance of the surrogate model with respect to the actual performance of the original model using the training set. The MFE of an ideal surrogate model is expected to resemble a normal distribution with a mean close to zero and standard deviation less than one.

2. Model Representation Error (MRE): the distribution of error obtained by comparing the predicted performance of the surrogate model with respect to the actual performance of the original model using the validation set. The MRE of an ideal surrogate model is expected to resemble a normal distribution with a mean close to zero and standard deviation less than one.
3. Actual by Predicted: The point with coordinate pair containing both actual data point and its corresponding predicted one is plotted along the perfect fit line, which is a $y = x$ straight line if drawn in the Cartesian coordinate. The fewer number of plotted points deviate from the perfect line, the better of the surrogate model fit is.
4. Residual by Predicted: This plot is obtained by plotting each point with coordinates made up of both residual error and the actual predicted value. The residual error is defined as the difference between the actual and predicted value. If this error is at least 2 orders of magnitude less than the actual response level, the surrogate model is considered as acceptable.

In addition to the four plots above, the coefficient of determination or $\boldsymbol{R}$ squared is another numerical metric to describe the fit performance of the ANN. $\boldsymbol{R^2}$ is a statistical measure of how much the output variance is accounted for by the regression model. It is determined by:

$$\boldsymbol{R^2 = 1 - \frac{SS_{residual}}{SS_{total}}}, \qquad \textbf{(Eq. 8)}$$

where

$$\boldsymbol{SS_{residual} = \sum_{i}^{n}(y_i - f_i)}, \qquad \textbf{(Eq. 9)}$$

and

$$\boldsymbol{SS_{total} = \sum_{i}^{n}(y_i - \overline{y})}. \qquad \textbf{(Eq. 10)}$$

$SS_{residual}$ is called the residual sum of squares and SS_{total} is called the total sum of squares. n is the number of data points evaluated and f_i is the corresponding predicted value for y_i. In general, a higher R^2 value is desired as it indicates a model with a better fitting of the given data. The maximum R^2 value is one. A qualified surrogate model is expected to have desirable performance in all five fit statistics. In this case, the model fit result for the NPSS model is displayed in Figure 62 through Figure 65. Once an ANN is trained for each system-level metric, individual technology combination can be evaluated for built-in growth quantification and performance improvement.

At this point, it is interesting to see that an industrial GT design problem has been successfully converted into a discrete optimization problem. Given a set of technologies, the quantification of maximum growth turns out to be a process of pursuing better objective function values. Different technology combinations used for performance enhancement are treated as candidate solutions to be evaluated. Design constraints can be integrated into the optimization process as a penalty function. Each function evaluation of a certain technology combination is a representation of a potential uprated design.

The quantifications process is applied to power (CTQ1) and efficiency (CTQ2) as well as one composite CTQ. The composite CTQ uses a non-dimensional overall evaluation criterion (OEC) that is composed of all 4 system-level metrics. It is derived by using the equation below:

$$CTQ3 = \frac{\frac{eta}{eta_{BL}} + \frac{Power}{Power_{BL}}}{\frac{AC}{AC_{BL}} + \frac{OMC}{OMC_{BL}}}, \qquad \textbf{(Eq. 11)}$$

in which the subscript "***BL***" refers to the corresponding baseline value. All three CTQs are in the category of larger the better, which is translated to a maximization problem for each objective function. To minimize the occurrence of local optimum, multiple GA runs are dedicated to each CTQ for better optimization results. The parameters pertaining to the GA implementation is summarized in Table 18. In most cases, the optimization converges within 50 steps, indicating a reasonably fast convergence rate. The parameters are subject to change if the convergence to optimization process is lengthy or optimization results are drastically different from different runs.

Table 18. Genetic Algorithm Parameters Used

	Specification
Population per generation	36
String Length	12
Cross over rate	0.7
Mutation rate	0.06

The result of the GA optimization is tabulated in Table 19. It is not suspiring that there is substantial potential growth space in each of these CQTs with the given set of technologies. Efficiency has the most room for improvement, followed by OEC. Power has the least space to grow compared to the other two, partially due to the fact that mass flow is fixed. As such, the only way to gain more power is to improve individual components' efficiency.

Table 19. Maximum Growth and Ranges for PG7241FA

	NPSS Baseline	Max Growth	Growth Percentage	Growth Range
CTQ1: Power in MW	180.4	206.3	14.3%	25.9
CTQ2: Efficiency	0.3844	0.575	49.6%	0.191
CTQ3: OEC	1	1.34	34%	0.34

The technology set used to attain the maximum growth is also obtained for each CTQ optimized, they are tabulated in Table 20. Note that it requires larger number of technologies to get to the power maximum growth compared to the other two, which makes the improvement of power relatively more expensive. As more technologically affordable options, efficiency and OEC improvement actually share the same set of technology at their maximum growth. They only require half the number of technologies used by power, however, the improvements are significant.

Table 20. Technologies Used in Optimized Cases

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	Total
CTQ1: Power in MW	0	0	1	1	1	1	1	1	0	1	0	1	8
CTQ2: Efficiency	0	0	1	0	1	1	0	0	0	0	0	1	4
CTQ3: OEC	0	0	1	0	1	1	0	0	0	0	0	1	4

In this case, T3 T5, T6, and T12 are “common beneficiary” type of technologies across these 3 CTQs selected and they should be considered more competitive compared to the rest of technologies in this study for PG7241FA.

Architecture-level Evaluation Process

Designed and manufactured just a couple of years earlier than PG7241FA, PG7231FA was initially introduced in 1997. A thorough design comparison between PG7231FA and PG7241FA is illustrated in Figure 8. Note that only incremental improvement took place between these two versions and that the flow-path design of PG7241FA remains the same as that of PG7231FA. Per the definition of architecture articulated in this work, both GT products belong to the same architecture, named using “7FA”. The specifications for both products are tabulated in Table 21. As expected, the system-level performances difference is between these two products are marginal. It looks like the power output uptick of PG7241FA is made possible thanks to the slight increase in the mass flow rate and operating at a higher pressure-ratio. All other system level metrics have less than 1% and are hence considered insignificant.

Table 21. Specification for PG7231FA and PG7241FA [71-74, 76]

	PG7231FA	PG7241FA	Percentage Change
Pressure Ratio	14.9	15.5	6.04%
Shaft Speed (rpm)	3,600	3,600	0
Mass Flow (lbm/s)	921	987.67	7.24%
Turbine Inlet Temperature (°F)	2400	2,420	0.83%
Turbine Exit Temperature (°F)	1,105	1,110	0.45%
Power Output (MW)	167.8	174	3.6%
Efficiency	36.4%	36.7%	0.82%

In this part, the growth space of PG7231FA is quantified using the same three CTQs as for PG7241FA. Moreover, technologies are selected to best utilize the built-in growth of this product. As a step further, growth and technologies are evaluated at architecture-level with information obtained from both PG7231FA and PG7241FA. The implementation procedure to find built-in growth still follows the same flow chart present in Figure 32. In this case, it is assumed that the same set of technologies is given and that their compatibility relation remains the same. In other words, the compatibility matrix for PG7131FA still looks the same as shown in Table 52. The technology impact matrix (TIM) for PG7131FA (Table 55) is slightly different. The differences in TIM between these two products are used to account for the minor design, material, and part changes made to PG7231FA. These would result in the corresponding component performance variation in PG7241FA.

A similar procedure is taken for GA optimization for PG7231FA case. The maximum growth and growth ranges from the optimized cases are present in Table 22, with corresponding technology combination tabulated in Table 23.

Table 22. Maximum Growth and Ranges for PG7231FA

	NPSS Baseline	Maxium Growth	Growth Percentage	Growth Range
CTQ1: Power in MW	167.38	203.52	21.6%	36.14
CTQ2: Efficiency	0.42	0.584	39%	0.164
CTQ3: OEC	1	1.39	39%	0.39

Table 23. Technologies Used in Optimized Cases

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	Total
CTQ1: Power in MW	0	0	1	0	1	1	1	1	0	0	1	1	7
CTQ2: Efficiency	0	0	1	0	1	1	0	0	0	0	1	1	5
CTQ3: OEC	1	0	1	0	1	1	0	0	0	0	1	0	5

It is observed that using the same technology set with slightly different component-level impact, PG7231FA enjoys a wider growth range than PG7241FA in terms of power and OEC. This can be attributed to the lower performance starting point of this product as it was introduced two years earlier when there was a lower technology level. The newer technologies used for uprating PG7231FA help bring the product performance up-to-speed and thus create a growth space larger than PG7241FA. On the technology side, those optimized cases show a mixed choice of technologies. To drive the power up to optimality, a total number of 7 technologies are used, which is one fewer compared to PG7241FA case. On the other hand, the remaining two CTQs requires larger number of technologies.

For the sake of this example, it is presumed that architecture 7FA has exactly two products, PG7231FA and PG7241FA. At architecture-level, the information gleaned about those two products on performance and technologies is sufficient to paint the bigger picture. For the purpose of better visualization, the growth space metrics of both products and architecture FA are displayed in Figure 39-Figure 41, with colored dots representing baseline values and colored arrowhead pointing to the maximum growth for each subject of interest. The length of each arrow indicates the growth range for each CTQ dimension.

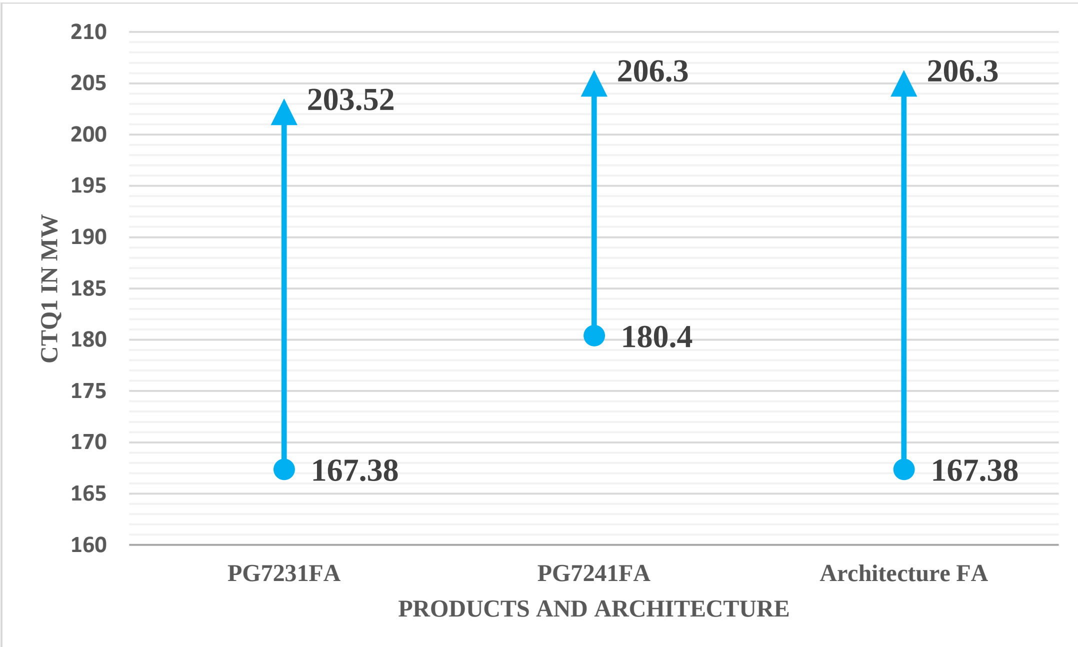


Figure 39. Product and Architecture Growth Specifications for Power

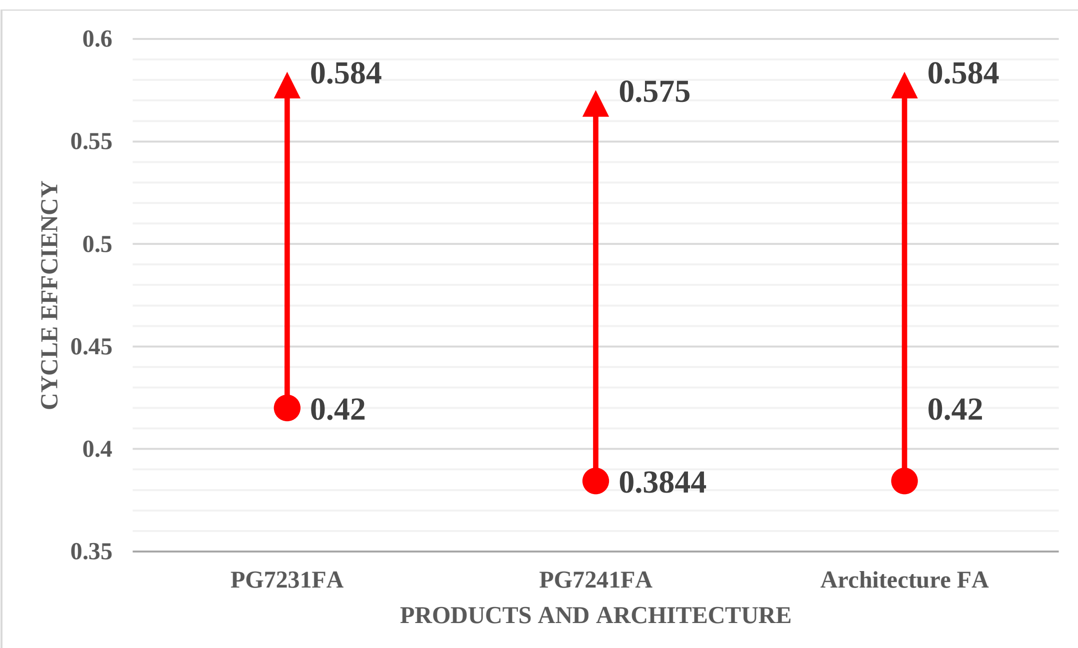


Figure 40. Product and Architecture Growth Specifications for Cycle Efficiency

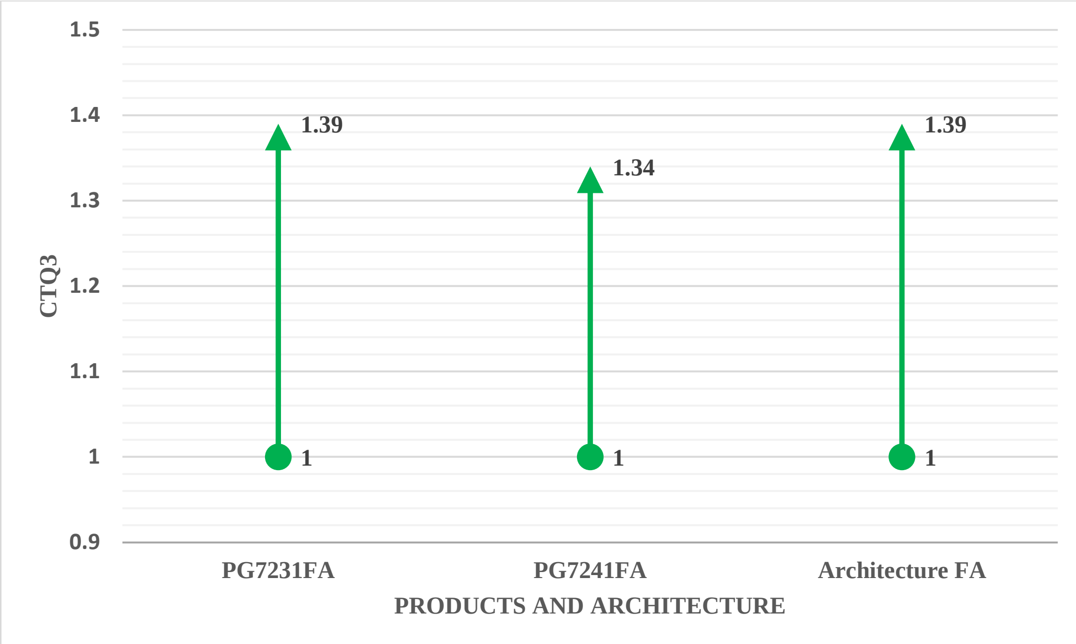


Figure 41. Product and Architecture Growth Specifications for CTQ3

The top technology solutions from each individual optimization problem are presented in Table 24 ("-3" for PG7231FA and "-4" for PG 7241FA). At architecture-level, the deployment of each technology is compared and contrasted across different products. In this case, all 3 CTQs under consideration, which means the entire table is under scrutiny for 7FA architecture. It is not difficult to find out that T3, T5, and T6 show up in all 6 different scenarios (a scenario is a combination of one product and one CTQ). Note that T12 is turned on in 5 out of 6 scenarios. It is reasonable to believe that those 3 or 4 technologies impact the maximum growth of this architecture and that they bear the property of "common-beneficiary" of Architecture 7A. The implication of using this growth-based approach to identify those architecture-level technologies are profound. In the case those technologies are fully matured, the finding here renders justification to include them or their corresponding uprating options for other existing GT products since they stand out in the context of both thermodynamic performance and plant operation. In case those technologies are still under development, the same evaluation can be used to provide justifiable foresight on which technologies should be given priority on the list of further development. On the contrary, for those technologies that are less preferable per the optimized product performance improvement (T2 and T9), their development program should be put on hold until further deliberation.

Table 24. Top Technology Combination for CTQ Selected

	CTQ1-3	CTQ1-4	CTQ2-3	CTQ2-4	CTQ3-3	CTQ3-4
T1	0	0	0	0	1	0
T2	0	0	0	0	0	0
T3	1	1	1	1	1	1
T4	0	1	0	0	0	0
T5	1	1	1	1	1	1
T6	1	1	1	1	1	1
T7	1	1	0	0	0	0
T8	1	1	0	0	0	0
T9	0	0	0	0	0	0
T10	0	1	0	0	0	0
T11	1	0	1	0	1	0
T12	1	1	1	1	0	1

As a summary of this experiment, the built-in growth quantification approach (Figure 32) has shown the capability to identify maximum growth and growth range for an existing architecture. It also renders a way to smartly identify preferred technologies based on individual product-based performance evaluation. Finally, this approach is so designed that it can be easily scaled to a larger number of products and technologies, the level a typical GT design company would encounter. With the help of this practice, it is expected to help the management to make informed decisions on both product performance uprating and technology investment.

The growth quantification and technology selection technique presented in this study confirm the two hypotheses formulated at the beginning of the study and repeated below:

Research Question 1:

How to identify competitive technologies that will be integrated into future GT product development?

Hypothesis 1:

For a given set of technologies, the application of TIES is able to identify competitive technologies that bring performance benefits to products within the same GT architecture.

Research Question 2:

How to account for the built-in growth of the GT architecture included in its dedicated PIP?

Hypothesis 2:

For a given industrial GT architecture, its built-in growth can be quantified by evaluating feasible technology combinations provided in the PIP with respect to system-level metrics of interest.

3.4 *Growth-based Architecture Development*

Product growth framework is to use the concept of quantifiable growth to pave GT product development path ahead for a GT architecture of interest. The two options discussed in this work are: 1. PIP: staying on the existing course; 2. NAI: blazing a trail for a new one. Using the notion of maximum growth, the built-in growth of the architecture is quantifiable, and this serves as a key factor in deciding which direction to pursue in terms of product development path. This section presents an innovative process to design growth into the new architecture and then conducts an experiment to compare the performance gain from NAI and PIP.

3.4.1 *Modeling Growth in Product Improvement Program*

Product growth by PIP is ubiquitous in GT industry, i.e. the majority of new GT designs are derivatives of previous generations. There are obvious reasons why GT manufacturers have been practicing this for decades:

1. From a designer perspective, one would like to avoid reinventing the wheel by recycling available design resources and experimental data inherited from previous products.
2. In terms of manufacturing, the fact that the same production line can be used to fabricate parts for a different generation drives down the production cost.
3. Operationally, introducing newer generations without significant cycle or design changes helps maintain the high reliability and operational availability possessed by previous products.

As formulated in previous work, the growth cannot be achieved without a synergy of improvement/change in design coupled with advancement in turbomachinery technologies. The design of a GT in this context encompasses its thermodynamic cycle, architecture, and overall dimension. From a thermodynamic point of view, compressor pressure ratio and turbine inlet temperature are the two critical cycle design parameters that impact the overall thermal efficiency of the GT, with higher values the better. However, these design parameters are constrained by factors such as stage loading of the compressor and material properties of the turbine. The flow-path design elaborates how the designated cycle is realized by tracking the properties of mass flow throughout the gas turbine engine. The size of the GT is highly dependent on the mass flow required to generate a specified power output. The diameter is determined by how much airflow is designed to pass through the engine and the length is dependent on how many stages are required in the compressor and turbine. Implementing state-of-the-art technologies in GT design, on the other hand, helps components or subsystems achieve better performance. For example, turbines with improved cooling techniques can prolong the lives of those hot gas path parts with the minimal thermodynamic penalty. Components utilizing better seals or tighter clearances will prevent unnecessary pressure-related performance losses.

In this context, it is reasonably assumed that an uprated product is designed to be a retrofit for a gas turbine from a previous generation. This assumption means that the newer GT must operate in approximately the same environment as the old one does, and it is expected to be compatible with current plant accessories (e.g. exhaust gas stack and generator), existing layout (e.g. footprint), and contemporary regulations (e.g. emissions and noise). A notional representation of an uprating process is shown in Figure 42. For this particular CTQ, it is considered as the larger the better. Design A is the existing product using the technology level of the time it was designed (TL1). Later at some point, the manufacturer may consider it necessary to conduct an uprating on Design A due to a change in the client's requirements. The uprated product B is then equipped with the technology level available at that time (TL2). The uprating helps the new product to achieve a better CTQ. It is worth mentioning here that A and B belong to the same architecture and that the eventual size of B is no larger than that of A per the uprating requirement.

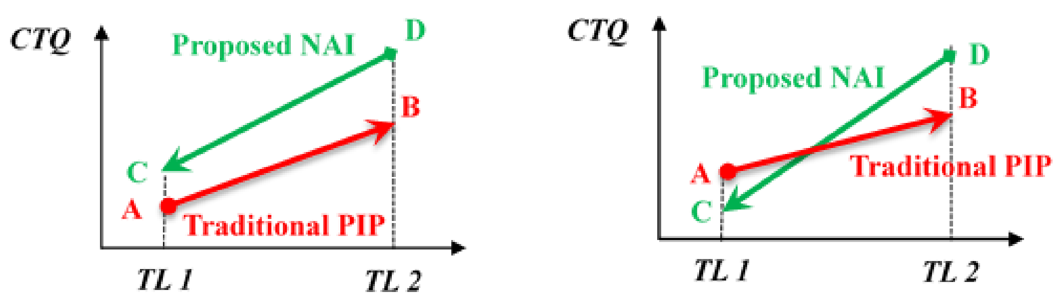


Figure 42. Traditional PIP and Proposed NAI

3.4.2 *Modeling Growth in New Architecture Introduction*

Contrary to the traditional uprating path, this growth option starts with a design tailored to the higher technology level (TL2) conceptually and then ends up with an "adjusted design" (Figure 42). In this approach, Design D has exactly the same core design space as Design B with the exception that no dimensional constraints are active. Of course, aero-mechanical constraints are always present in both uprating and "downgrading design" settings to ensure an operational GT product. In this case, with fewer constraints active, the performance of Design D is expected to be at least the same if not better than that of Design B. It is conjectured here and will be later shown that Design D would become a new architecture, which comes with a different flow-path geometry.

In additional to sharing the same technology level (TL1) and core design space of A, Design C is obtained by "downgrading" D using the dimensional constraints "inherited" from D. The size constraint imposed this way ensures a smooth "growth" from C to D and a built-in growth capability is implanted in C intentionally for later exploitation. It is noted here that the order shown (D→C) is only used for conceptual design purpose and actual production is supposed to follow the direction of TL1→ TL2.

For a given CTQ, there are two possible scenarios for the position of Design C can end up with at TL1: (1) above or (2) below Point A, as shown in Figure 42. If Scenario 1 is the case, i.e. Design C achieves better performance than Design A, it would be concluded that the new architecture by implementing this proposed approach is more competitive in performance at both current and improved technology levels. This would serve as a strong argument to justify the decision to launch an NAI instead of keeping the current PIP going further. If Scenario 2 indeed occurs, it would make the introduction of a new architecture less compelling: Design C is outperformed by Design A at TL1 and there is a possibility that Design C is not able to fulfill the CTQ required by the client at the time of TL1.

3.4.3 *Experiment 2: Growth-based PIP and NAI* [82]

The demonstration process of this experiment is designed and used to introduce and confirm the two hypotheses formulated to address the second set of research questions. They are stated below:

Research Question 3:

How to design growth into a new GT architecture given forecasted information about emerging technologies?

Hypothesis 3:

The product growth can be designed into the new industrial GT architecture by sizing the design for technologies at a future technology level and then adjust its performance to its current technology level.

Research Question 4:

What are advantages using designed-in growth when launching a new architecture compared a traditional Product Improvement Program path?

Hypothesis 4:

If a new architecture is developed using a designed-in growth path, the architecture benefits from more performance gain throughout its planned horizon when compared to the path of a PIP.

In this study, a side-by-side comparison of the proposed NAI approach with traditional PIP path on current and future product performance to prove the designed-in growth's feasibility and to demonstrate the possible value of following this path. And the proposed steps are as follows:

1. Formulating and modeling both GT product development approaches: traditional PIP and proposed NAI;
2. Estimating the on-design performance parameter(s) using the model and processes established;
3. Making observation via a side-by-side comparison from a conceptual experiment.

For this study, a thermodynamic model of a notional E-class GT is to be modeled in NPSS at its current technology level (*TL1*) as in Figure 42. The major technical specification for this baseline (Design A) is summarized in Table 25. Design inputs are a group of variables that are related to either the thermodynamic cycle or flow-path. The values of technology inputs are dependent on the specified technology level, which is set at *TL1* for the baseline.

“Heat rate” is a term to measure the efficiency of a power plant. The heat rate is inversely proportional to the plant thermal efficiency, which implies a lower heat rate is better. It is computed using the following equation:

$$\boldsymbol{Heat\ Rate = \frac{Thermal\ Energy\ In}{Electricity\ Energy\ Out}} \qquad \textbf{(Eq. 12)}$$

The denominator is the total energy provided to the plant and the nominator indicates the energy produced by the plant. Most power plants have a target or design heat rate they would like to operate under. In the power industry, another term “spark spread” is a common metric to estimate the profitability of natural gas-fired electric generation [83]. It has a unit of $/MW-hr and can be computed using the following equation:

Spark spread = power price – (natural gas price × heat rate) **(Eq. 13)**

Both power price ($/MW-hr) and natural gas price ($/MMBtu) are readily available from U.S. Energy Information Administration. For the sake of this study, the price of electricity is taken at $30.5/MW-hr and the price of natural gas price is taken at $2.87/MMBtu, which are both based on the trade data dated on May 23rd, 2017 [84]. The CTQ of interest in this paper is the product of spark spread and power output. This quantity carries the unit of $/hr and is defined as revenue in this study. The composite CTQ is selected to compound two critical system metrics - Power Output (MW) and Heat Rate (MMBtu/MW-hr) into one single quantity, making the design problem into a single-objective optimization problem. It should be noted that the firing temperature (T41) used throughout this paper is based on ISO (sea level and 59°F/15°C) conditions.

Table 25. Design Inputs and Outputs for Baseline Gas Turbine (Design A)

Design Input	Description	Value	Baseline Output	Value
OPR	Overall Pressure Ratio	12.637	**Revenue ($/hr)**	**2392.8**
T41 (°F)	Firing Temperature	2029.71	Power Output (MW)	78.53
COMP.HTR	Compressor Stage 1 Hub-Tip-Ratio	0.595	Heat Rate (Btu/kW-hr)	10611.82
COMP.Reaction	Compressor Stage 1 Degree of Reaction	0.85	Air Flow (lbm/sec)	665.29
COMP.M1	Compressor Stage 1 Mach Number	0.498	# of Compressor Stages	13
TURB.HTR	Turbine Last Stage Hub-Tip-Ratio	0.65	Compressor Inlet Diameter (in)	71.13
TURB.Reaction	Turbine Last Stage Degree of Reaction	0.6	Compressor Total Length (in)	91.59
TURB.M3	Turbine Last Stage Mach Number	0.4324	# of Turbine Stages	3
Technology Input	**Description**	**Value**	Turbine Outlet Diameter (in)	110.76
OPL	Overall Pressure Loss	0.16	Turbine Length (in)	28.66
SHAFT.L	Loss Factor due to Shaft Transmission	0.05		
COMP.Eff	Compressor Polytropic Efficiency	0.9082		
TURB.Eff	Turbine Polytropic Efficiency	0.9033		
TURB.xFactor1	Cooling Flow Weighting Factor 1	1.984		
TURB.xFactor2	Cooling Flow Weighting Factor 2	1.234		

The optimization study to be conducted in this experiment includes three cases: Design B, C, and D, all represented notionally in Figure 42. The design space for each point is created for subsequent optimization (Table 26). Note that the design space is technology-level dependent. There are two types of constraint involved in the study: aeromechanical constraints and dimensional constraints. The former are constraints such as maximum AN2 and maximum blade loading, which ensure that the on-design operation of the gas turbine does not violate any law of physics or material strength limits. It is requisite to point out here that this type of constraint is TL dependent and may change when the corresponding TL of interest goes up or down (Table 27). Dimensional constraints are applicable when conducting a product uprating or “downgrading”. Since the focus of this research is on the compressor and turbine, it is reasonable to assume that the footprint contribution from the inlet (before compressor), combustor, and duct (after turbine) remain approximately constant and the change of these dimensions after product growth is negligible. In this paper, the concept of “effective footprint” is used and it is defined by the cumulative length of compressor and turbine (CL+TL) and the maximum value taken from compressor diameter and turbine diameter (Max(CD, TD)) (Figure 43). It is easy to prove that the effective footprint of a new GT does not get larger if the cumulative length and maximum diameter respectively are no larger than those from the current one.

Table 26. Engine Design Space and Technology for *TL1* and *TL2*

		Design B and D (*TL2*)		Design C (*TL1*)	
Design Input	**Description**	**Min**	**Max**	**Min**	**Max**
OPR	Overall Pressure Ratio	12.64	20	12.637 (Const.)	12.637 (Const.)
T41 (°F)	Firing Temperature	2000	2600	2029.71 (Const.)	2029.71 (Const.)
COMP.HTR	Compressor Stage 1 Hub-Tip-Ratio	0.3	0.94	0.54	0.65
COMP.Reaction	Compressor Stage 1 Degree of Reaction	0.6	0.9	0.77	0.94
COMP.M1	Compressor Stage 1 Mach Number	0.498	0.6	0.498 (Const.)	0.498 (Const.)
TURB.HTR	Turbine Last Stage Hub-Tip-Ratio	0.3	0.94	0.59	0.72
TURB.Reaction	Turbine Last Stage Degree of Reaction	0.6	0.9	0.54	0.66
TURB.M3	Turbine Last Stage Mach Number	0.35	0.5	0.432 (Const.)	0.432 (Const.)
Technology Input	**Description**	**Value**		**Value**	
OPL	Overall Pressure Loss	0.07		0.14	
SHAFT.L	Loss Factor due to Shaft Transmission	0.02		0.05	
COMP.Eff	Compressor Polytropic Efficiency	0.92		0.9082	
TURB.Eff	Turbine Polytropic Efficiency	0.92		0.9033	
TURB.xFactor1	Cooling Flow Weighting Factor 1	1		1.984	
TURB.xFactor2	Cooling Flow Weighting Factor 2	1		1.234	

Table 27. Aeromechanical Constraints for *TL1* and *TL2*

Constraint Name	Description	*TL1* Specification	*TL2* Specification
COMP.EHTR	Compressor Exit Stage Hub to Tip Ratio	< 0.97	< 0.97
COMP.AN2*	Compressor Stage 1 AN Square Limit	< **4**	< **7**
COMP.HL	Compressor Stage 1 Hub Loading	< **1.2**	< **1.5**
COMP.HR	Compressor Stage 1 Blade Hub Degree of Reaction	> 0.2	> 0.2
COMP.TMach	Compressor Stage 1 Blade Tip Mach Number	<**1.2**	<**1.4**
TURB.IHTR	Turbine Inlet Hub Tip Ratio	< 0.97	< 0.97
TURB.AN2*	Turbine Last Stage AN Square Limit	< **6.01**	< **8**
TURB.HL	Turbine Last Stage Blade Hub Loading	< **2**	< **3**
TURB.HR	Turbine Last Stage Blade Hub Degree of Reaction	> 0.2	> 0.2
TURB.TMach	Turbine Last Stage Blade Tip Mach Number	< 1.2	< 1.2

Table 28. Optimization Formulations for Three Design Points

Design	Optimization Formulation
B	$Max\ Revenue$ $s.t.\ \mathbf{Dimesion\ 1}: Max(CD,TD)\ of\ Design\ B \leq Max\ (CD,TD) of\ Design\ A,$ $\mathbf{Dimension\ 2}: (CL+TL) of\ Design\ B \leq (CL+TL) of\ Design\ A,$ $All\ of\ the\ applicable\ \mathbf{aeromechanical}\ constraints\ applied\ at\ TL2.$
D	$Max\ Revenue$ $s.t. All\ of\ the\ applicable\ \mathbf{aeromechanical}\ constraints\ applied\ at\ TL2.$
C	$Max\ Revenue$ $s.t.\ \mathbf{Dimension\ 1}: Max(CD,TD)\ of\ Design\ C \leq Max\ (CD,TD)\ of\ Design\ D,$ $\mathbf{Dimension\ 2}: (CL+TL)\ of\ Design\ C \leq (CL+TL) of\ Design\ D,$ $All\ of\ the\ applicable\ \mathbf{aeromechanical}\ constraints\ applied\ at\ TL1.$

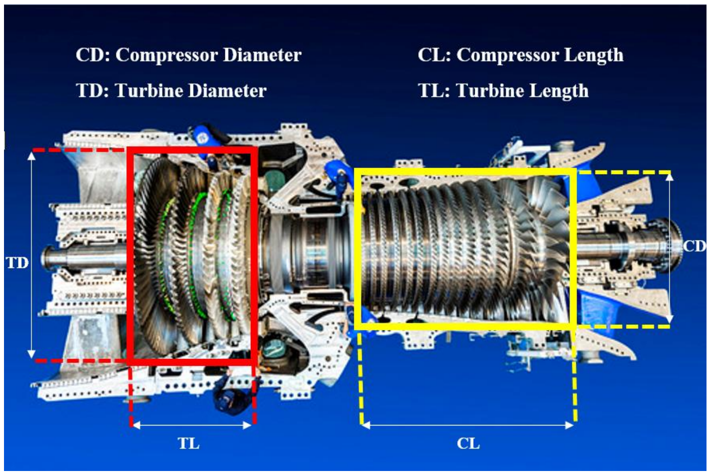


Figure 43. Effective Footprint (Gas Turbine Photo Courtesy of GE Power)

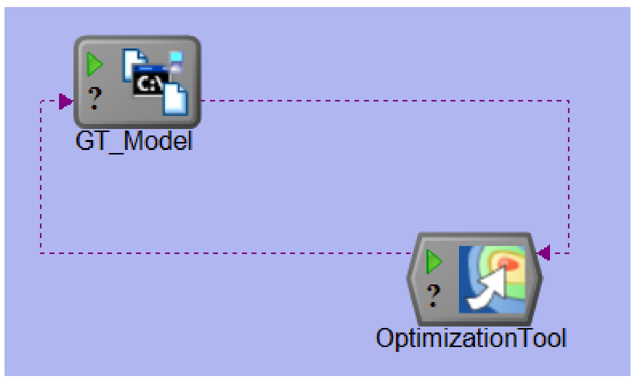


Figure 44. ModelCenter® Simulation Environment for Optimization Study

The thermodynamic model is devised to compare the alternatives of starting a new GT architecture today, and growing it as TL improves, versus continuously growing an existing architecture by infusing advanced technologies. This entails quantifying the “technology reach” potential of an existing architecture as well as the effects of “downgrading” a future design to current-day technology capabilities. The thermodynamic modeling of the gas turbine for this study is carried out using the NPSS framework, extended with supplementary calculations for the turbomachinery flow-path as needed to apply the technology and dimensional constraints. For this study, the engine dimensional limits of concern are the compressor inlet diameter, the turbine exit diameter, and the flange-to-flange engine length. In reality, these parameters are determined by a complex iterative multi-disciplinary design process. For the purposes of this study, it is desired to simulate the actual turbomachinery design process by a relatively simple process which can be automated and applied consistently to each combination of engine cycle and technology level under consideration while producing reasonably realistic results. The compressor inlet and turbine exit diameters are primarily determined by the designer's choice of stage flow coefficient and hub-to-tip radius ratio at each location. The engine length is primarily determined by the number of compressor and turbine stages, which are in turn primarily determined by the designer's choice of stage work coefficient. Thus the major design characteristics to be determined for the compressor and turbine are the three non-dimensional parameters flow coefficient, work coefficient, and hub-tip ratio. These three parameters may not be specified independently of one another.

In this study, the turbomachinery design process is simulated by the use of "Smith chart" representations of the compressor and turbine stage performance. A representative Smith chart for a turbine is shown in Figure 45. While Smith charts are well known to turbine designers, the concept is easily extended to compressors, as shown by Lewis [85]. The Smith chart plots work coefficient (ϕ) vs. flow coefficient (ψ) and superposes contours of constant stage efficiency. An optimal ϕ-ψ curve may be drawn through the peak efficiencies, as indicated in the figure. Presumably, a viable design will fall on or near this line. For the purposes of this study, the compressor and turbine designs are constrained to fall along pre-specified near-optimal design curves.

For the simulated turbomachinery design process, a design flow coefficient is selected, and the corresponding design work coefficient is read from the near-optimal ϕ-ψ design curve. Both compressor and turbine design curves have been developed based on the analysis of Lewis [85]. A suitable design flow coefficient is found by iteration such that the stage efficiency is maximized within certain specified design constraints. Additional design parameters, such as the stage reaction, are assumed as necessary to enable complete stage velocity diagrams to be computed at the mean-line, hub, and tip locations, allowing the various design constraints to be evaluated.

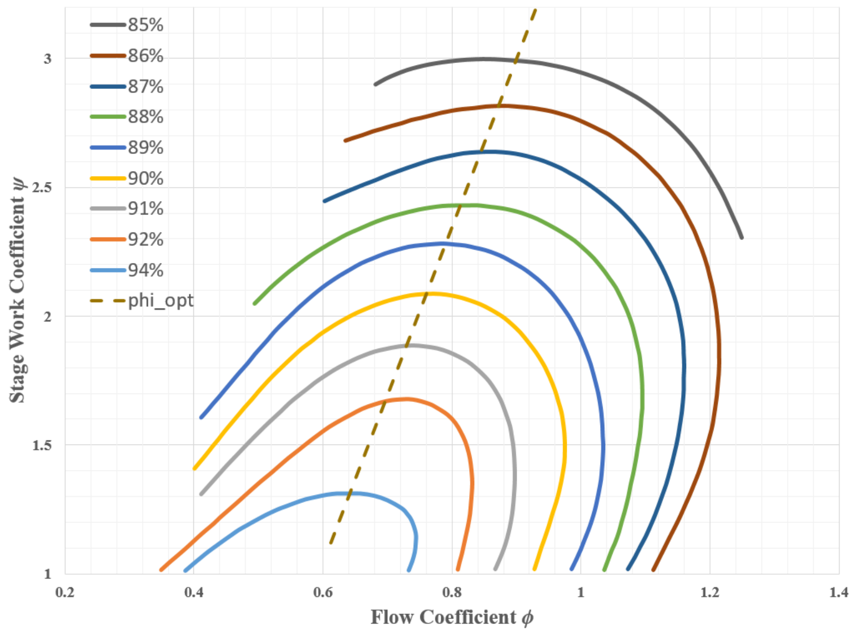


Figure 45. A Notional Smith Chart for Turbine

The three design cases were simulated and optimized in ModelCenter®. For each case, SEQOP scheme was able to locate the most optimized solution under various constraints specified previously. SEQOP works by intelligently utilizing surrogate models to accelerate the optimization process. The surrogate models are selectively updated and refined as the optimization process progresses. Global search mechanisms are implemented to avoid local minima. A final pattern search guarantees that the best design found is at least a local minimum. The optimization results are summarized in Table 29.

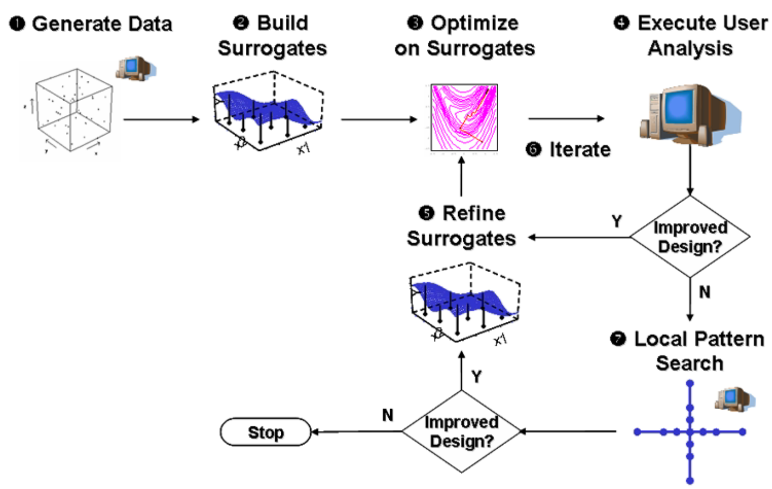


Figure 46. Procedure for SEQOP Algorithm [86]

It is observed that with a higher technology level, Design B more than doubles in both revenue and power compared to the baseline. The configuration slightly changes after the uprating. The turbine has the same number of stages as Design A while the compressor now has 14 stages instead of 13. The cumulative length of those two components is still less than those of Design A, making this design with a smaller effective footprint. It is worth mentioning here that the firing temperature hits 2600°F in this case, which is in the realm of an F-class GT. Notice that Design B is an improved version of Design A. Therefore, the performance of B sets an upper bound of the space Design A can grow by uprating to TL2. This implies that in the situation when a manufacturer is looking for a GT with even better performance than B, they can either turn to other architecture (existing or new) or wait until higher technology level is available.

Design D was obtained by removing the effective footprint constraint and yet it has the same TL as Design B. With a 13-stage compressor and a 2-stage turbine, this design achieves about 59% more in both revenue and power compared to Design B. Design D is also an F-class GT and its configuration features a long compressor and a large turbine exit diameter. As a brand-new architecture, the performance of D sets the upper bound of the growth space an F-class engine can achieve at TL2.

As a downgraded version of Design D, the optimized configuration of C has a 14-stage compressor and a 3-stage turbine. It is interesting to observe that Design C achieves 2.8% more in both revenue and power output compared to Design A despite the fact that they operate at the same compressor pressure ratio and turbine firing temperature. Design A is a more efficient engine since it has a slightly better heat rate. However, this does not necessarily guarantee more profit due to the fact that the saving incurred in Design A is outweighed by the extra revenue created by more power in Design C. Indeed, the cost of natural gas is currently at such a low level (2.87 $/MMBtu) that the saving from an efficient engine is less attractive compared to extra power. And this is in agreement with the trend observed by Langston - "the average output of each individual gas turbine unit is also increasing, and at a rate that's faster than that of electricity demand." [87]. Therefore, the inexpensive price of natural gas can be regarded as one contributing factor to the trend of more powerful GTs in the electric generation industry.

Table 29. Optimization Results for All Designs

Optimized Design Input	**A (*TL*1)**	**B (*TL* 2)**	**C (*TL* 1)**	**D (*TL* 2)**
Overall Pressure Ratio	12.637	20	12.637	20
Firing Temperature	2030	2600	2030	2600
Compressor Stage 1 Hub-Tip-Ratio	0.595	0.505	0.54	0.416
Compressor Stage 1 Degree of Reaction	0.85	0.72	0.86	0.80
Compressor Stage 1 Mach Number	0.498	0.7	0.498	0.599
Turbine Last Stage Hub-Tip-Ratio	0.650	0.686	0.72	0.835
Turbine Last Stage Degree of Reaction	0.600	0.642	0.540	0.600
Turbine Last Stage Mach Number	0.432	0.654	0.432	0.7
Optimized Design Output				
Revenue ($/hr)	**2392.8**	**5129.6**	**2459.7**	**8134.9**
Power Output (MW)	78.53	168.31	80.73	266.93
Heat Rate (Btu/kW-hr)	10611.82	8108.10	10675.28	8602.04
Air Flow (lbm/sec)	665.29	825.23	688.03	1391.38
# of Compressor Stages	13	14	14	13
Compressor Inlet Diameter (in)	71.13	66.35	69.1	85.26
Compressor Length (in)	91.59	94.70	106.05	131.06
# of Turbine Stages	3	3	3	2
Turbine Outlet Diameter (in)	110.75	110.64	118.26	160.52
Turbine Length (in)	28.66	22.60	26.85	14.27

The four simulated points are plotted in Figure 47 for the sake of better observation. Within the same architecture (Architecture 1), a PIP using uprating approach has been conducted to raise the performance level of Design A to that of Design B, which is the optimal design with newer technologies (TL2) and yet less or equal effective footprint. With the same TL as Design B, Design D is the best design without that effective footprint constraint, which makes it a completely new architecture (Architecture 2). The NAI continues as Design D is downgraded to Design C, with Design C and Design A operating at the same compressor pressure ratio and turbine firing temperature.

As an interesting extension, a second scenario is considered for peak prices happened in the wake of 2005 Hurricane Katrina. At that time, the power wholesale price skyrocketed to at $91.24/MW-hr (compared to $30.5/MW-hr in the first case) [84]. Meanwhile, the natural gas price mounted to $13.42/MMBtu (compared to $2.87/MMBtu in the first case) [84]. The impact of the dramatic price difference is simulated using the same approach and the results from both cases are plotted in Figure 48. Again, it is observed the new architecture exhibits its superiority at *TL1* and *TL2*. Note that the revenue difference between the two different architectures gets inflated at both technology levels. This peak price scenario further proves in the extreme market condition, the benefits persist if the GT manufacturer decides to pursue using the growth approach to develop future products.

From *TL1* to *TL2*, PIP and NAI can be considered as two different paths GT products can follow in their own growth space. In this case, the PIP scenario obviously has less growth space compared to its counterpart. It is highly likely that the architecture is not able to fulfill future requirements if the CTQ required by the client increases with time. However, this type of program is often believed to be conservative and hence incurs lower risk. This belief may explain why most manufacturers typically follow this path. On the contrary, the NAI path is more aggressive and bears a higher risk. Programs of this kind will incur more design and manufacturing cost since a new production line will be added to the existing portfolio. These considerations must be weighed against the extra growth space available which enables this option to be more competitive despite changes in the market trend.

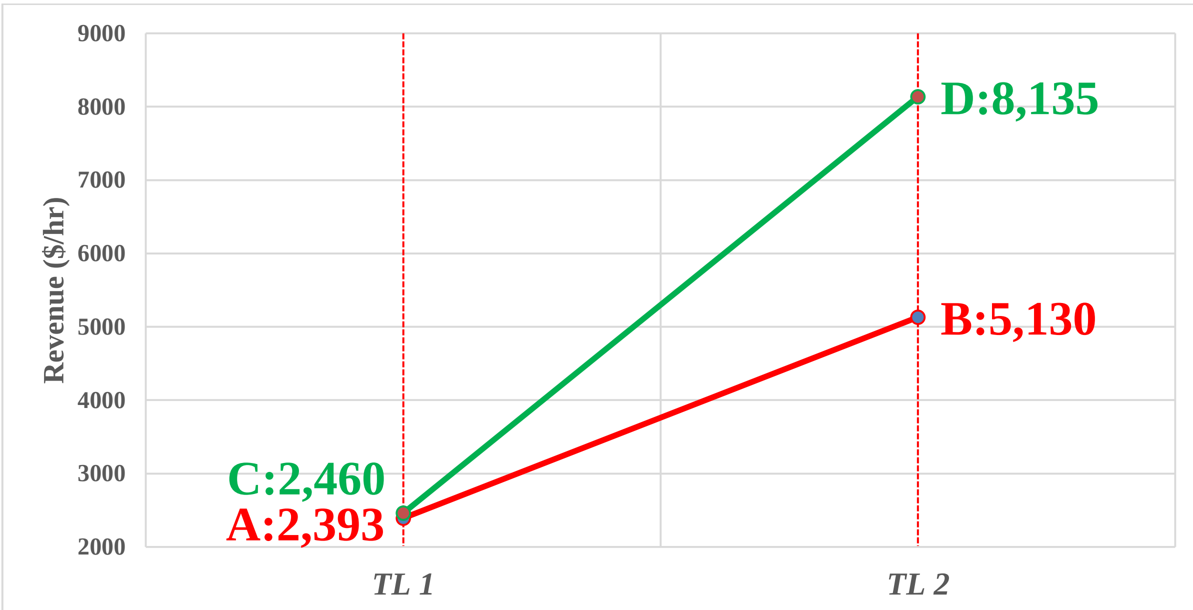


Figure 47. Revenues for All 4 Designs (Scenario 1)

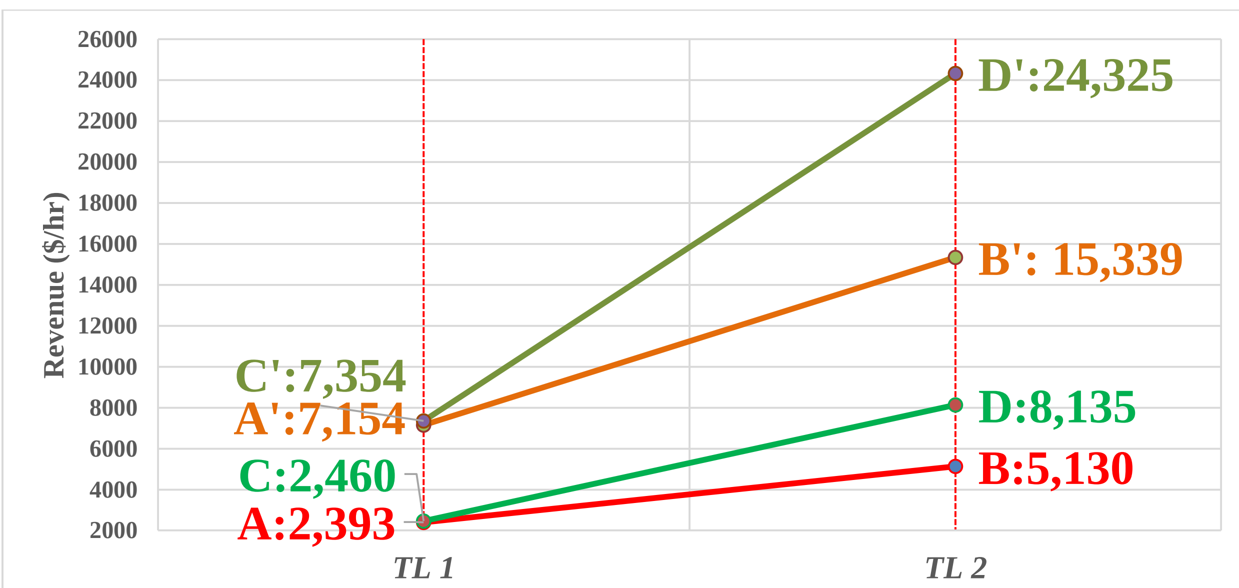


Figure 48. Revenues for All 4 Designs (Scenario 1 and 2)

As a summary of this experiment, a new architecture-based product-growth approach is presented for gas turbine product development. This approach directly sizes the GT for technologies at the future level. The new product obtained is then downgraded by design to tailor for individual operational needs at the current technology level. In order to prove the value of this approach, the performances of the new designs are compared side-by-side to that of the designs obtained using common product uprating approach. It has been shown in this study that a product designed by following this new approach can have better operational performance and more available growth space, which implies that the new architecture has more flexibility to fulfill the requirements changing with the dynamic global gas turbine market. However, the competitiveness of this architecture does come with more risk and additional cost required for a new product line.

The design-in growth technique and growth comparison between PIP and NAI presented in this study confirm the two hypotheses formulated at the beginning of the study and are repeated below:

Research Question 3:

How to design growth into a new industrial gas turbine architecture given information about emerging technologies?

Hypothesis 3:

The product growth can be designed into the new industrial GT architecture by sizing the design for technologies at a future technology level and then adjust its performance to its current technology level.

Research Question 4:

What are advantages of using designed-in growth when launching a new architecture?

Hypothesis 4:

If a new architecture is developed using a designed-in growth path, the architecture benefits from more performance gain throughout its planned horizon when compared to the path of a PIP.

3.4.4 *Design Growth into New Architecture*

In this experiment, the design-in growth has been proved to be a feasible concept to plan product development for a new architecture. It is preferred over traditional PIP as long as the emerging technology impact can be reasonably predicted and modeled. The goal of this part is to lay out a step-by-step NAI procedure to implement the approach given the context of gas turbine product design and pertaining technology development.

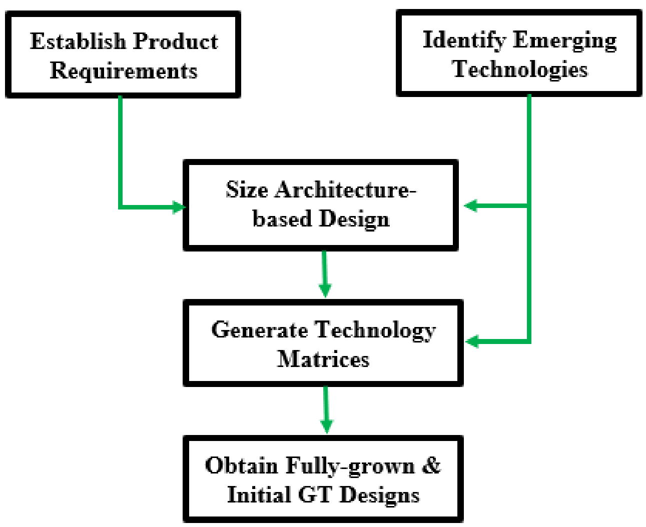


Figure 49. Procedure for Designing Growth into New Architecture

The flowchart shown in Figure 49 starts with product requirement. There are multiple contributing factors the manufacturer often considers before a new architecture is launched. Among them, future market needs undoubtedly come to the top of the list. It has been observed (Figure 5 and Table 2) that each major GT manufacturer has a similar structure of market segmentation. On top of the segmentation, incremental product performance uprating and introduction of new architecture jointly expand performance of

GT products to power levels that are not previously covered (Figure 7). Once potential requirements are identified, the next task on the agenda is to identify emerging technologies that can be fed into the new architectures. As emerging technologies in consideration are not fully matured, their impact estimates can be quantified using the best existing knowledge from either technology specialists or an exisiting database. Each technology needs to be modeled in a way that its technical improvement can be reasonably captured by the GT model. Prevalent GT design techniques such as scaling and zero-staging, are utilized to pin down the cycle and dimension for those products in the new architecture. Once the cycle and size are fixed, the conceptual GT model can be built. Using the existing and forecasted information at the time of fully-grown design, the CTQs for both designs can be obtained using the established GT model and estimated technology inputs. In the event that a scheduled technology development timetable for emerging technologies is available, the product growth plan for the new architecture can be created. This plan, conceptually shown in Figure 50 is meant to pave and later track the step-by-step performance growth for the new architecture from the initial design and fully-grown design, in which each step change is realized by a scheduled product uprate program driven by matured technologies. The procedure in Figure 49 is to be implemented in the next chapter.

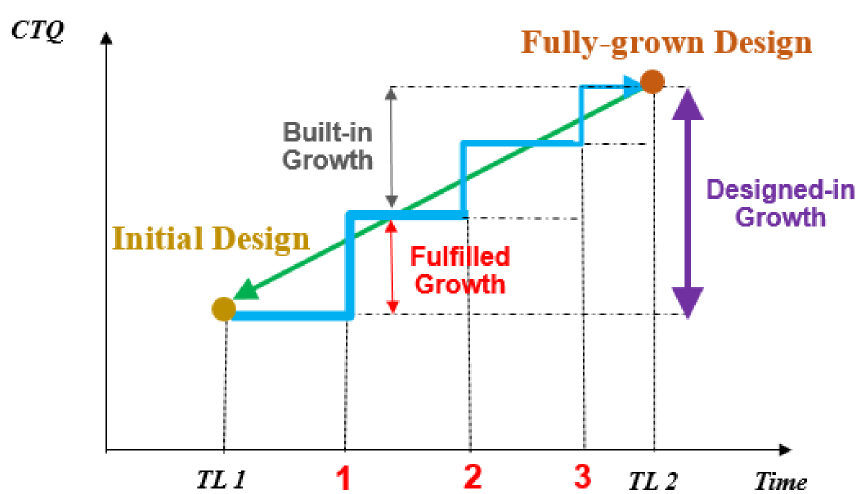


Figure 50. Design Growth into New Architecture

3.5 *Technology and Product Development Coordination*

Across industrial GT industry, each entity has an organizational unit that supports technology development. Two examples are presented here. General Electric has its Global Research Centers located around the globe, equipped with more than 1,000 talented experts and 350 ongoing research projects in 2019. Their research engine "is fueled by technology and capability", "leveraging its multidisciplinary core capabilities to design and develop advanced solutions to complex, challenging problem" [88]. Siemens' brain, which is called Siemens Corporate Technology, also has a worldwide presence. With more than 1,600 researchers, this organization is "pioneering technologies" that "will have a broad impact on Siemens businesses" [89]. Whether it's GE or Siemens, those R&D branches' existence is to brew state-of-the-art technologies that lead to product evolution and service upgrade.

In the context of GT, the advancement of technology helps enhance the product operational performance to make it more powerful, and at the same time lower the product life cycle cost to drive it more affordable. As such, any innovation in this field is perceived as a booster in competitive advantage. In regard to technology development and product development, Brilhuis-Meijer et al. [90] formulates two scenario that could happen:

1. Technology development takes place before product development, after which the developed technology is applied in product development.
2. Product development is initiated, only to discover that the concept is not feasible with existing technology. In this case, the development of the product can continue alongside the development of the technology or the product development has to be put on hold until the technology challenge has been resolved.

For a well-managed GT product development program, Scenario 1 would be highly desired as this would cause the minimum delay in the development of the next generation of GT.

The introduction of product growth management would be useful in supporting both technology and product development as they are considered two supporting pillars of a successful GT program (Figure 51. On the technology side, the concept of growth is to be used to identify "common beneficiary" type of technologies as well as to prioritize individual emerging technology development. The goal of this practice is to enable efficient product capability evaluation and preferable resource allocation leaned toward those technologies shared among a wider spectrum of products. At the product development level, this growth-based design capability would be instrumental to both short-term and long-term product development (Figure 25):

1. In the context of PIP, the growth approach would be used to come up with a list of uprating packages that are selectable by clients who may pursue different technical requirements and economic needs.
2. For NAI, the same rationale can be used to create a product development roadmap and technology development timetable that guide industrial GT product family design and decision-making for the next decade or beyond.

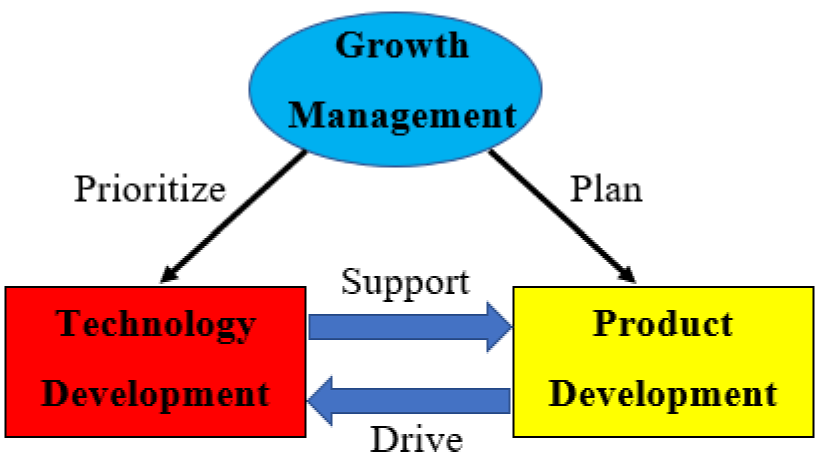


Figure 51. Interactions between Growth, Technology, and Product

As industrial gas turbines continue to grow, so are those technologies. Technologies S-curve is a good way to describe the life cycle of a technology (Figure 52). From the stage of ferment to its final maturity, technology level goes up along with technology performance. For those technologies that are included in the uprating packages of industrial GT, they have already reached full maturity and are rated at level 9, the highest technology level. As time passes by, one technology may gradually give way to a replacement technology, which brings even enticing performance improvement to the component or the whole system.

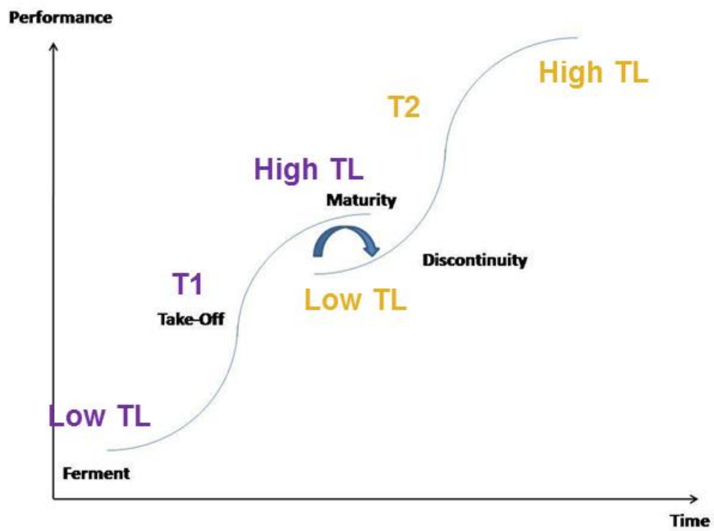


Figure 52. Two Sequential Technology S-Curves

In the context of industrial GT, the NAI approach presented in this work is highly dependent on the knowledge about emerging technologies and their development. Knowing the potential impact of each individual technology upon the component or the system enables the designer to have a better estimate on the performance of the future design (e.g. design point "D" in Figure 42). In addition, this information is also useful to identify those technologies that would bring the most goods to future product development, creating a more bang of the buck. In parallel, technology planning is also critical. A well-prepared timeline would make a smooth path from initial design "C" to full-grown design "D". Note that as this process does not happen overnight, the entire path may take a decade or even longer to complete. During that growth window, multiple uprated versions of the initial design are expected to roll out one after another. These products serve the purpose of intermediate steps to convert the designed-in growth to fulfilled growth. This type of arrangement takes the development status quo of different technology into account as one technology may take more time to reach its final maturity than the other. By grouping those technologies in batches chronically, each uprated product will use the corresponding matured batch at its introduction and unleash its impact in incremental performance enhancement. This planned product evolution path would require each technology in the batch to be ready by a certain deadline (Figure 53) or the consequence would be substantial. As such, it is up to GT designers to seek appropriate technology scheduling and planning approaches to minimize project delays due to those emerging technologies. Indeed, a successful NAI program relies heavily on the seamless integration between product development and its corresponding technology development.

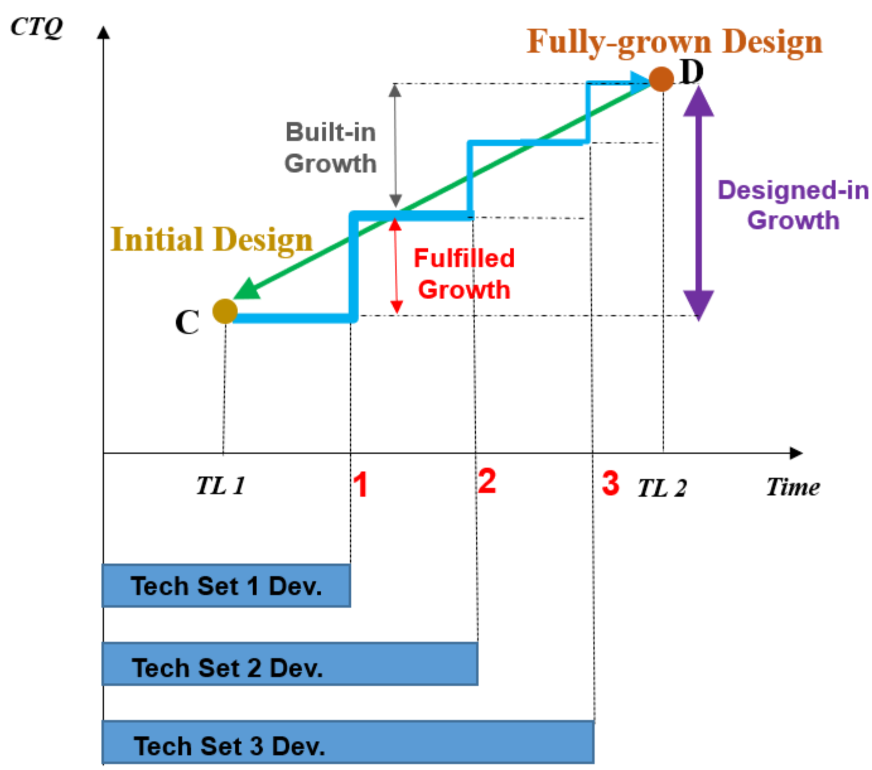


Figure 53. New Architecture and Technology Development Side-by-side

3.6 *Summary of Architecture-based Growth Approach*

In this chapter, an architecture-based growth approach is unfolded to assist industrial GT designers developing the next generation of products. The concept of growth management is used in PIP and NAI as a key product development metric. The quantification of built-in growth aims to quickly draw the maximum growth of an existing architecture so that the performance boundary of that architecture can be effectively determined. This is achieved by using a technology evaluation method, known as "TIES", which is also used to identify and select those powerful technologies that push the product-level or architecture-level performance to its full growth potential. A notional design technique is proposed and demonstrated to conduct NAI assuming the technology information at a future time can be reasonably forecasted. This advantage is then translated into designed-in growth for the newly developed architecture. A designed growth path for the architecture is paved from the initial design to its full-grown design, subject to the effective planning and completion of its supporting technology development programs.

CHAPTER IV

A CASE STUDY AND RESULTS

The four hypotheses formulated in previous chapters each provides a feasible solution to a corresponding research question. In this chapter, the overarching research question is revisited, and a case study is designed and executed to formulate the thesis statement for this research, which is the answer to this question. In order to implement the conceptual product growth framework and to demonstrate the capability of using growth for product decision-making, there are a couple of ingredients required before the whole procedure can be launched, including a well-calibrated GT thermodynamic model based on reliable data. These elements will be elaborated in this chapter and they are prerequisites for conducting systematic testing and obtaining reasonable hypothesis testing results for later analysis and discussion.

The overarching research question of this thesis is repeated below along with the primary hypothesis formulated:

Overarching Research Question: Given a set of available technologies and existing industrial gas turbine architectures, how can the capability of product growth management in a GT architecture be used to enable an informed decision upon its future product development path?

Thesis Statement: The architecture-based product growth approach uses the concept of growth as a key development metric for future product decision-making. Once this practice is implemented, it would enable a more structured, transparent, and objective decision-making process to conduct smart product improvement and develop future industrial GTs with competitive performance.

4.1 *Establishment of a Gas Turbine Model*

To build a prototype model for the subsequent case study, the determination of its required fidelity-level often poses a challenge to the designers. A low-fidelity model is quick and easy to build. It is a useful tool during the conceptual stage when there are needs to transfer high-level design information into the product concept for evaluation. However, the model error may be substantial due to the simplicity of the prototype as well as its limited capability to interpret and process input information. On the other hand, a high-fidelity model is created when a much better understanding of the system is attained or there are needs to further capture design information for a more accurate evaluation. Nevertheless, the flip side of this type of model is that it's almost always considered labor-intensive to build and computationally prohibitive to run. As such, depending on the individual application, it is imperative to tune a prototype model's fidelity based on research goals and requirements. Models with inappropriate fidelity would potentially raise questions on those simulation results and hence conclusions.

4.1.1 *Component-level vs. Stage-level Fidelity*

In this research, the thermodynamic model for industrial GT starts with the model structure as shown in Figure 34. Compressor and turbine are treated as two single and intact components in the system. As technologies in question are presumed to affect the performance of each component, it is reasonable to treat it as an individual subsystem for impact capturing. In practice, it has been observed that most of the technologies used for uprating improve the turbomachinery at the level of individual stage [9-11]. For example, Option 6-11 tabulated in Table 51 each has a designated stage number, i.e. the technology input information has a higher fidelity than that of the prototype model built using Figure 34. This would apparently cause incompatibility as the k-factor in the model is only designed to capture subsystem-level impact, not stage-level. As such, it is considered a pressing need to be able to have an improved model so that stage-level technology inputs to compressor and turbine can be completely captured.

A stage-level thermodynamic model of industrial GT is justified in this case. Instead of treating the compressor and turbine as a single and intact component, each stage characteristic of the compressor or turbine is emulated individually. This uptick in model fidelity allows the baseline to capture those technologies directly impacting stages within turbomachinery.

4.1.2 *Modeling Multi-stage Axial Compressor*

The decomposition of the axial compressor into multiple stages requires a thermodynamic analysis process. In this work, the stage-by-stage modeling is an approximation as it depends on a list of assumptions:

1. Repeating stage: velocity triangles (i.e. velocity components and flow angles) remain the same across all compressor stages.
2. Equal work per stage: The same amount of work is done upon the airflow across all compressor stages.
3. Equal polytropic efficiency per stage: Every stage of compressor shares the same polytropic efficiency within the entire compressor.
4. Constant axial velocity: The axial component of air velocity does not change across the entire compressor.
5. Compressible flow and ideal gas. Considering the velocity of the airflow in the compressor, the air flow is treated as compressible and it follows the ideal gas law.

Using the five assumptions above, pressure ratio and adiabatic efficiency for each stage of the compressor can be evaluated using the procedure summarized below:

1. Annulus area of the first stage $\boldsymbol{A_1}$. A wide spectrum of existing industrial GTs' overall technical data is available and summarized in [91]. Using the dimension data provided, the annulus area of the first stage, tip ($\boldsymbol{r_{t1}}$) and hub ($\boldsymbol{r_{h1}}$) radius of the first stage rotor can be looked up.

2. Inlet Mach number at the first stage ($\boldsymbol{M}$). Given the inlet condition just upstream of the first stage rotor, the inlet Mach number can be computed using the isentropic flow relation below:

$$\frac{\dot{m}\sqrt{T_t}}{P_t A_1} = M\sqrt{\frac{\gamma g_c}{JR}}\frac{1}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \qquad \textbf{(Eq. 14)}$$

where $\dot{m}$ is the mass flow rate, T_t and P_t is the total temperature and pressure just upstream of the first stage rotor. On the right-hand side, γ is the specific heat ratio, which has a value of 1.4 for air. g_c is the gravitational constant. R is the gas constant for air. J is the unit conversion factor.

3. Amount of work per stage (w_1). This amount can be computed by tracking the flow specific enthalpy change (Δh_t) across the stage;

$$w_1 = -\Delta h_t = \frac{c_p T_{t1}}{\eta_{ad}}\left[(PR_c)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad \textbf{(Eq. 15)}$$

where c_p is the constant pressure specific heat. η_{ad} and PR_c are the adiabatic efficiency and pressure ratio of the corresponding compressor stage respectively. This work is calculated from the first stage. Based on equal work assumption, the same amount of work is performed on every stage of the compressor.

4. Polytropic efficiency for the compressor e_c. This efficiency can be computed by using the known overall pressure ratio:

$$e_c = \frac{\gamma-1}{\gamma}\frac{ln(PR_c)}{ln\left\{1+\frac{1}{\eta_{ad}}\left[(PR_c)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}} \qquad \textbf{(Eq. 16)}$$

Per Assumption 3 above, this is also the polytropic efficiency for each stage within that compressor.

5. Stage outlet temperature T_{t2}. At the stage outlet, the total temperature by using a simple equation derived from energy continuity:

$$T_{t2} = T_{t1} - \frac{\Delta h_t}{c_p} \quad \textbf{(Eq. 17)}$$

6. Stage pressure ratio PR_1. Stage pressure ratio can be computed by using total temperature at both inlet and outlet of the stage plus the stage polytropic efficiency:

$$PR_1 = \frac{P_{t2}}{P_{t1}} = \left(\frac{T_{t2}}{T_{t1}}\right)^{\frac{\gamma e_c}{\gamma - 1}} \quad \textbf{(Eq. 18)}$$

7. Stage outlet pressure P_{t2}. Using the definition of pressure ratio, the stage outlet pressure can be calculated using the equation below:

$$P_{t2} = P_{t1} \cdot PR_1 \quad \textbf{(Eq. 19)}$$

8. Stage adiabatic efficiency e_1. Using the stage pressure ratio derived in Step 7 and the compressor overall adiabatic efficiency, the adiabatic efficiency for the stage can be computed using the equation below:

$$e_1 = \frac{(PR_1)^{\frac{\gamma-1}{\gamma}} - 1}{(PR_1)^{\frac{\gamma-1}{\gamma e_c}} - 1} \quad \textbf{(Eq. 20)}$$

9. Stage characteristics. Once the first stage characteristics have been determined, the remaining stages' characters of the compressor can be attained easily. Note that for the ***Nth*** stage, the upstream total pressure and temperature are the same as the downstream total pressure and temperature of ***(N-1)th*** stage. As such, using **(Eq. 17) - (Eq. 21)**, along with equal work and equal polytropic efficiency assumptions across stages, those stage characteristics can be obtained accordingly. This process continues until all stage characteristics are populated.

With all stages' characteristic information collected, the stage-level approximation of an axial compressor model can be created in NPSS by linking those elements together one-by-one. Those linked elements are a replacement of a single compressor element. This treatment enables the model to capture the stage-level uprating technology with corresponding stage-level k-factors.

4.1.3 *Modeling Multi-stage Axial Turbine*

Following a similar procedure as the axial compressor, the decomposition of the axial turbine into multiple stages requires the following assumptions:

1. Repeating stage: velocity triangles (i.e. velocity components and flow angles) remain the same across all turbine stages.
2. Equal work per stage: The same amount of work is done by the airflow across all turbine stages.
3. Equal polytropic efficiency per stage: Every stage of turbine shares the same polytropic efficiency within the turbine.
4. Constant axial velocity: The axial component of air velocity does not change across the entire turbine.
5. Compressible flow and ideal gas. Considering the velocity of the airflow in the turbine, the air flow is treated as compressible and it follows the ideal gas law.

Using the five assumptions above, pressure ratio and adiabatic efficiency for each stage of the turbine can be evaluated using the procedure summarized below:

1. Amount of work per stage ($\boldsymbol{w_1}$). This amount can be computed by tracking the flow specific enthalpy change ($\Delta \boldsymbol{h_t}$) across the stage;

   $$\boldsymbol{w_1} = \Delta \boldsymbol{h_t} = \boldsymbol{\eta_{ad} c_p T_{t1}} \left[\mathbf{1} - (\boldsymbol{PR_t})^{\frac{\gamma-1}{\gamma}} \right] \qquad \textbf{(Eq. 21)}$$

   where $\boldsymbol{c_p}$ is the constant pressure specific heat. $\boldsymbol{\eta_{ad}}$ and $\boldsymbol{PR_t}$ are the adiabatic efficiency and pressure ratio of the corresponding turbine stage respectively. This work is calculated from the first stage. Based on equal work assumption, the same amount of work is performed on every stage of the turbine.
2. Polytropic efficiency for the turbine $\boldsymbol{e_t}$. This efficiency can be computed by using the known overall pressure ratio:

$$e_t = \frac{\gamma}{\gamma - 1} \frac{ln\left\{1 - \eta_{ad}\left[1 - (PR_t)^{\frac{\gamma-1}{\gamma}}\right]\right\}}{ln(PR_t)} \qquad \text{(Eq. 22)}$$

Per Assumption 3 above, this is also the polytropic efficiency for each stage within that turbine.

3. Stage outlet temperature T_{t2}. At the stage outlet, the total temperature by using a simple equation derived from energy continuity:

$$T_{t2} = T_{t1} + \frac{\Delta h_t}{c_p} \qquad \text{(Eq. 23)}$$

4. Stage pressure ratio PR_1. Stage pressure ratio can be computed by using total temperature at both inlet and outlet of the stage plus the stage polytropic efficiency:

$$PR_1 = \frac{P_{t2}}{P_{t1}} = \left(\frac{T_{t2}}{T_{t1}}\right)^{\frac{\gamma}{(\gamma-1)e_t}} \qquad \text{(Eq. 24)}$$

5. Stage adiabatic efficiency e_1. Using the stage pressure ratio derived in Step 4 and turbine overall adiabatic efficiency, the adiabatic efficiency can be computed using the equation below:

$$e_1 = \frac{1 - (PR_1)^{\frac{(\gamma-1)e_t}{\gamma}}}{1 - (PR_1)^{\frac{\gamma-1}{\gamma}}} \qquad \text{(Eq. 25)}$$

6. Stage characteristics. Once the first stage characteristics have been determined, the remaining stages' characters of the turbine can be attained easily. Note that for the ***Nth*** stage, the upstream total pressure and temperature are the same as the downstream total pressure and temperature of ***(N-1)th*** stage. As such, using **(Eq. 22)-(Eq. 25)**, along with equal work and equal polytropic efficiency assumptions across stages, those stage characteristics can be obtained accordingly. This process continues until all stage characteristics are populated.

With all stages' information collected, the stage-level approximation of an axial turbine model can be created in NPSS. This stage-by-stage treatment enables the model to capture the stage-level uprating technology with corresponding stage-level k-factors for the turbine.

4.1.4 *Modeling Cooling in a Multi-stage Turbine*

The hot gas path located in a GT is a critical part of the entire thermodynamic cycle as it performs the function of converting chemical energy "stored" in the fuel into usable shaft work, which is then used to drive both the compressor and the generator on the same axle. After reaction in the burner, gas mixtures enter the turbine at such a high temperature that no existing bare metal or alloy is able to be in contact with them without any cooling treatment. For an air-cooled turbine, the first few stages of nozzles and buckets are chilled by cooling air transported from several different stages of the compressor. External film cooling and internal convection cooling are the two techniques researched and harnessed by most GT manufactures [92]. The resultant improvement in heat transfer performance makes higher TIT and increased cycle efficiency possible. However, the use of internal cooling has its own backlash. As pointed out by Young et al. [92], "increased cooling flowrates result in higher aerodynamic and thermodynamic losses which offset the beneficial effect of increase turbine inlet temperatures."

Despite the extensive application of cooling techniques within the GT industry, there has been no general agreement on how to model a cooled multi-stage turbine. Methodologies developed to account for the losses incurred by cooling and hence the cooled turbine efficiency are subject to interpretation. So far, different models have been proposed to capture the perplexing process happened in the turbine [92-97]. In this work, the cooling is modeled using the algorithm presented in a NASA technical memorandum [78]. The algorithm calculates "both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling air injection into the gas stream". It has been converted to a widely-used package that is formatted and implemented in NPSS environment. Given the turbine operating condition, the output of this algorithm includes the cooling flow fraction extracted from from compressor and total bleeding flow rate used for turbine bucket and nozzle cooling,

4.1.5 *On-Design Performance*

The GT cycle modeling starts with the on-design cycle analysis. In this case, the design point of the GT is known from published data, and this piece of information is used to calibrate the on-design performance of the model. The thermodynamic characteristics of each component on the fluid are then calculated starting at the inlet of the engine and working through, component by component, to the exit at the turbine. Note that the thermodynamic properties of the working fluid exiting one component become the inlet properties of the next component until the inlet and exit thermodynamic properties are known for all components [98].

In the NPSS environment, once the physics-based model with stage-level fidelity is assembled, it is ready for calibration. In the case of industrial GT PG6541B, the baseload (on-design) system metrics of baseline and the calibrated NPSS model are tabulated in Table 30. The designed pressure ratio, shaft speed, and turbine inlet temperature (TIT) are the inputs to this model. The NPSS then computes the solution subject to multiple solver pair relations, which are set-up at on-design condition. The solve pairs include varying the value of fuel-air ratio to match the TIT and varying the horsepower extraction from shaft to match the exhaust airflow pressure (set to the ambient pressure). The pressure ratios, adiabatic temperatures, and adiabatic efficiencies for each compressor or turbine stage are computed using **(Eq. 14)-(Eq. 25)** based on equal-work-per-stage assumption. It is observed that the heat rate has the largest calibration error, which stands at 2.58%. This magnitude of error is considered acceptable as the current stage-based NPSS model is still a zero-dimension thermodynamic model only dedicated to conceptual design study.

Table 30. Calibration Result for PG6541B at Base-Load

	Variable Type	Baseline	NPSS Model	Percentage Error
Pressure Ratio	Input	11.8	11.8	N/A
Shaft Speed (rpm)	Input	5,104	5,104	N/A
Turbine Inlet Temperature (°F)	Input	2,042	2,042	N/A
Mass Flow (lbm/s)	Output	309.72	310.3	0.19%
Turbine Exit Temperature (°F)	Output	1,005	1,030	2.49%
Power Output (MW)	Output	38.14	38.09	0.13%
Heat Rate (BTU/kW-hr)	Output	10,870	10,590	2.58%

4.1.6 *Off-design Performance*

As an indispensable and critical complement to the on-design performance simulation, the physics-based model built is able to simulate the gas turbine operation performance at its off-design condition. The data generated during the on-design cycle analysis are inputs for all off-design analysis [99]. As the engine's size has been fixed at this stage, the purpose of off-design analysis is to evaluate the GT's thermodynamic performance at operational conditions other than on-design. The performance of each component is no longer specified as in on-design cycle analysis but determined from engine component performance maps scaled around the design point [98]. For a given GT off-design operation condition, the corresponding location on each map and GT performance are obtained by an iterative process. The components must be 'matched' to determine the pressure ratio, rotor speed, and efficiency [100]. The design solution at the end of this iterative process must satisfy both mass (continuity) and energy conservation conditions. It is noted here that infusion of technology changes the characteristics of the component(s) in the GT model. The off-design analysis renders a necessary step to capture the corresponding system-level performance (CTQ) change enabled by the applied technology set. The topic of technology modeling at off-design condition is covered in the next section.

4.2 *Modeling Uprating Technologies*

Once the physics-based model is calibrated and the concept of growth is established, the uprating options of this product are evaluated. To make sure the model is capable of dealing with technology inputs behind the PIP compiled in the manual [9], each PIP option is summarized APPENDIX A – A SUMMARY OF GE MS6001 UPRATING OPTIONS AND TECHNOLOGIES so that the impacting mechanism is formulated. The goal is to model individual technology as close to its nature as possible and to make sure the GT model established is able to predict, with reasonable accuracy, the improvement in performance after different technology sets are applied to the baseline. In this work, the uprating options are grouped into multiple categories based on the change it brings to the GT system. Table 8 gives an example of how each technology is analyzed in terms of its immediate benefit and its impact on system-level performance. Those characterizations give insights into the nature of each technology and serve as a good reference when conducting categorization.

4.2.1 *Category 1: Inlet Guided Vane Improvement*

Industrial GTs often need to operate below their base-load conditions. Fuel control and guided vane control are the two distinctive methods deployed at part-loading operating condition [101]. Fuel control works by reducing the fuel flow into the burner until the desired load is met. Guided vane control reduces the air intake by the compressor by turning inlet guided vanes (IGVs) to a different angle. Uprating Option 1 and 2 improves IGVs for the baseline engine by either using an aerodynamically optimized blade design or enabling a larger angle turning. The direct impact of both options is the same - increased airflow into the compressor, which is indicative of additional power. During part-load operation, the angle of IGV is so controlled that the power output of the GT is lowered but a constant firing temperature is maintained [102,103].

From the perspective of modeling in NPSS environment, a “corrected weight flow audit scalar” is used to account for the IGV enabled mass flow increase in the compressor.

This parameter scales the compressor performance map in term of the corrected flow so that a new “match point” is found on this scaled map. The two key solver pairs used in this case are: varying the fuel-air-ratio to match the firing temperature and varying the horsepower extraction to match the exhaust pressure. Since the firing temperature is kept at constant while IGV is in use, it is set at the same value as in the on-design condition. The modeling information for this category is summarized below:

Uprating options: 1 and 2

Impacting k-factors: CMP25.s_WcAud

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horsepower extraction of the shaft;
2. Dependents: Firing temperature (same as on-design condition), exhaust pressure (set to ambient level).

4.2.2 *Category 2: Shaft Speed Increase*

One feature carried by MS6001 series is its capability to offer two different utility frequencies via a coupled gearbox. For this option, the shaft speed is increased to 5163 rpm accompanied by a load gearbox replacement. The faster rotor speed enables more airflow through the turbine and hence generates more power for a given ambient condition. For both compressor and turbine maps, the increase in shaft speed shifts the operating point to a higher speed line and a new “matched” point is found, which is indicative of changes in adiabatic efficiencies for both components. A similar rotor speed increase option is provided by GE for geared GT series MS5001, with the condition that the total torque input from the turbine being the same at the higher speed [104]. The benefit of keeping the same torque on the shaft ensure design margin is kept after the improvement, saving the effort to redesign and replace the existing shaft and bearing system. In the case of MS 6001, it is hence reasonable to assume that the torque constraint still holds for Option 3.

In the simulation environment, the shaft speed is varied to reflect the new RPM. Additionally, two efficiency adders are used to capture the efficiency drifts after the rotor speed increase for both compressor and turbine. Those two auditing factors work by scaling the individual component map until a new operating point is converged under the new shaft speed. The two solver pairs are set as follows: fuel-air-ratio is varied to match the total of torques coming into the shaft and horsepower extraction of the shaft is varied to zero out the net total of all torques on the shaft and losses. Note that the net torque in is kept at the same level as on-design condition in the first solver pair. The modeling information for this category is summarized below:

Uprating option: 3

Impacting k-factors: SHAFT1.Nmech, CMP25.a_effAud, TRB41.a_effAud

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horsepower extraction of the shaft;
2. Dependents: Total of all torques coming into the shaft (same as on-design condition), the net total of all torques on the shaft and losses (set to zero).

4.2.3 *Category 3: Sealing Technology Improvement*

Sealing technology is further improved and implemented to subside leakage throughout the GT system. High-pressure packing brush seals (Option 4) are applied as a replacement to traditional labyrinth seals to reduce the leakage of compressor discharge air between the stationary inner barrel and the compressor rotor aft stub shaft into the turbine first-forward wheelspace. In the turbine, the abradable coating (Option 5) allows tighter clearance between the Stage 1 bucket and shroud, minimizing the bucket tip leakage. Stage 1 shroud with cloth seals (Option 6) reduces leakage between shroud segments and between the Stage 1 shroud and Stage 1 nozzle. Stage 2 nozzle interstage brush seal (Option 7) curtails the flow leakage across the diaphragm and the turbine rotor from Stage 1 aft into Stage 2 forward wheel space. Stage 2 and 3 honeycomb shrouds (Option 8 and 9) are upgraded to further lessen leakage associated with hot gases that flow around the tips of the buckets. Addressing the existing leakage along the flow-path directly improves the adiabatic efficiency of the corresponding stage efficiency and benefits the performance of the entire component. The improvement in compressor and turbine leads to higher power output for the GT and better system-level cycle efficiency.

As all five options in this category have a specified stage of impact, the stage-level model is used in sealing-related applications. The improved efficiency at a given stage is captured by an efficiency difference factor corresponding to that stage. The new component adiabatic efficiency is then calculated based on equal-work-per-stage assumption. The component map is then scaled to account for that the component-level efficiency change and a different “match” point is obtained. The solver pairs in this category are set to vary the fuel-air-ratio to match the exhaust pressure and to vary the horsepower extraction of shaft to match the net total of all torques on the shaft. The modeling information for this category is summarized below:

Uprating options: 4,5,6,7,8,9

Impacting k-factors: TRB41.delta_eff_1, TRB41.delta_eff_2, TRB41.delta_eff_3;

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horsepower extraction of the shaft;
2. Dependents: exhaust pressure (set to ambient level), the net total of all torques on the shaft and losses (set to zero).

4.2.4 *Category 4: Advanced Aerodynamic Design Improvement*

Stage 3 nozzle and bucket in the turbine are redesigned (Option 10) using improved airfoils to provide efficiency boost for this stage. Similar to the modeling technique used in Category 5, this mounting stage-level efficiency is captured by an efficiency difference factor dedicated to Stage 3. Under the equal-work-per-stage assumption, the stage characteristic analysis is conducted to update the entire turbine efficiency. It is used to scale the performance map so that a new “match” point for the GT is located. The solver pairs in this category are set to vary the fuel-air-ratio to match the exhaust pressure and to vary the horse power extraction of shaft to match the net total of all torques on the shaft. The modeling information for this category is summarized below:

Uprating options: 10

Impacting k-factors: TRB41.delta_eff_3

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horse power extraction of the shaft;
2. Dependents: exhaust pressure (set to ambient level), the net total of all torques on the shaft and losses (set to zero).

4.2.5 *Category 5: Cooling Technology Improvement*

There are multiple ways to improve the efficiency and life of components located in the hot gas path of a GT. Upgraded materials, coated surface, and improved cooling techniques are the three prevalent methods used for uprating options to sustain mounting operating temperature in the turbine component. In Option 11, the new GTD-222 Stage 2 nozzle is coated with an aluminide coating to resist high-temperature oxidation. Additionally, several nozzle design changes are also in place to reduce the cooling air requirement. In the firing temperature uprating package, perimeter cooling accompanied with new airfoil geometry is applied to Stage 1 bucket to increase the efficiency of heat transfer from the bucket metal to the cooling air. For Stage 2 bucket, six radial cooling holes and new airfoil geometry provide more effective cooling to be used at uprated 2,084°F firing temperature condition.

In academia, the attempts to conduct better-cooled turbine modeling [92-95] and efficiency calculation [96,97] are still on-going research topics. To simulate the impact of cooling technology upon the turbine, "coolit" package included in NPSS is set up to capture the technology-enabled material property change and cooling effectiveness improvement. Following the algorithm behind this package, "the quantity of required cooling flow and the corresponding decrease in stage efficiency are calculated for each row of airfoils throughout the turbine…The calculations depend on both the type of cooling configuration and the value of cooling effectiveness" [78]. The allowable bulk metal temperature for each turbine stage (including both buckets and nozzles) are impacting factors that can reflect material and coating technology applied to parts installed on each stage. The information for upgraded material is available in [9]. The cooling technique improvement is reflected in the first stage (Del_xFactor1) as well as the remaining downstream stages (Del_xFactor) as a factor to a baseline cooling configuration (full cover film cooling). The "coolit" algorithm uses turbine adiabatic efficiency as input to calculate turbine cooled efficiency and the cooling flow required for each stage, which both contribute to the system-level performance of GT. The modeling information for this category is summarized below:

Uprating options: 11, 12(a), 12(b)

Impacting k-factors: Del_tMetal_S1B, Del_tMetal_S1N, Del_tMetal_S2B, Del_tMetal_S2N, Del_tMetal_S3B, Del_tMetal_S3N, Del_xFactor, Del_xFactor1,

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horsepower extraction of the shaft;
2. Dependents: Firing temperature (same as on-design condition), exhaust pressure (set to ambient level).

4.2.6 *Category 6: Firing Temperature Upgrade*

Increasing the firing temperature of a GT is an effective way to generate more power. Nevertheless, the additional power gain via this practice does come with substantial part improvements. From the combustor to the turbine, a list of critical components is upgraded to accommodate the upcoming temperature rise along the entire hot gas path. The package included in the publication encompasses six different items for post-combustion section, covering technical areas of cooling, coating, and sealing. Material change and coating treatment have been applied to Stage 3 buckets and nozzles. New cooling designs are deployed in the combustor as well as the first two stages of buckets in the turbine. The package is essentially a collection of “ingredients” required in place to push the new firing temperature to 2,084 ºF.

To model the package in the simulation environment, technology impacting factors relevant to the material, coating, and cooling are used. The allowable bulk metal temperatures used in “coolit” for each stage are used to capture the material upgrade and coating applied to buckets and nozzles. The cooling technique improvement is reflected in the first stage (Del_xFactor1) as well as the remaining downstream stages (Del_xFactor) as scaling factors to a baseline cooling configuration (fully cover film cooling). The modeling information for this package is summarized below:

Uprating options: 12

Impacting k-factors: TRB41.FS41.Tt ,Del_tMetal_S1B, Del_tMetal_S1N, Del_tMetal_S2B, Del_tMetal_S2N, Del_tMetal_S3B, Del_tMetal_S3N, Del_xFactor, Del_xFactor1,

Applicable solver pairs:

1. Independents: Fuel-air-ratio of the combustor, horsepower extraction of the shaft;
2. Dependents: Firing temperature (2,084 ºF), exhaust pressure (set to ambient level).

4.2.7 *Technology k-factor Matrix Generation*

Category-based technology modeling information is summarized in Table 32. Depending on the impacting mechanism, each technology category may include one or more NPSS-based variables that can be tuned during calibration for better technology modeling accuracy. Individual k-factor is established to account for each applicable NPSS variable used in different technology categories presented (Table 31). To calibrate those k-factors, published PG6541B uprates data from Table 51 is in use to obtain a full k-factor Technology Impact Matrix (TIM) to represent the PIP options available for this GT product. Technology Compatibility Matrix (TCM) is not required in this case as there is no compatibility issue between any pair of uprate options. The k-factor tuning process follows the steps below:

1. For technology category mapping to a single k-factor (i.e. Category I, III, and IV), the tuning process completes once the value of k-factor drives the power output toward the corresponding value as shown in **Table 51**. Note that Category III is considered as a single k-factor case as each uprating option is impacting only one of multiple-stage efficiencies. As such, the corresponding stage efficiency change is captured by a dedicated k-factor generated for that stage.
2. For technology category involves multiple k-factors (i.e. Category II, V, and VI), an underdetermined problem is present in this case as unknown k-factors outnumber the desired value to match (i.e. power). To address this challenge, extensive research into the existing literature has been conducted to find the appropriate k-factor values from credible published sources. For example, in Category V and VI, the upgraded material information used for each uprated stage of rotors and stators located in the hot gas path is obtained in [9]. The remaining k-factors are determined by adjusting their values based on the reasonable assumption(s), e.g. for Category II, in addition to account for the given shaft speed increase, equal efficiency change assumption has been applied to the k-factors to account for changes of efficiencies in the compressor and turbine.

Table 31. Map from k-factors to NPSS Variables for PG6541B Model

No.	k-factor	NPSS Variables	Component (Quantity) Affected
1	k_IGV	CMP25.s_WcAud	Compressor (air flow)
2	k_shaft_c	CMP25.a_effAud	Compressor (adiabatic efficiency)
3	k_shaft_t	TRB41.a_effAud	Turbine (adiabatic efficiency)
4	k_eff_c	CMP25.a_effAud	Compressor (adiabatic efficiency)
5	k_eff_t1	TRB41.delta_eff_1	Stage 1 of Turbine (adiabatic efficiency)
6	k_eff_t2	TRB41.delta_eff_2	Stage 2 of Turbine (adiabatic efficiency)
7	k_eff_t3	TRB41.delta_eff_3	Stage 3 of Turbine (adiabatic efficiency)
8	k_cool_t2n	Del_tMetal_S2N	Stage 2 Nozzle of Turbine (allowable bulk metal temperature)
9	k_cool_t3n	Del_tMetal_S3N	Stage 3 Nozzle of Turbine (allowable bulk metal temperature)
10	k_cool_t3b	Del_tMetal_S3B	Stage 3 Bucket of Turbine (allowable bulk metal temperature)
11	k_cool_t1	Del_xFactor1	Stage 1 of Turbine (cooling effectiveness)
12	k_cool_t	Del_xFactor	Stage 2 and 3 of Turbine (cooling effectiveness)

A sensitivity analysis is conducted to study how the output power of the GT model reacts to the changes in NPSS variables included in Table 31. This study can be used to better understand the relationships between technology inputs and power output in the model. The sensitivity result could serve as another way to validate the model setup and detect potential flaws herein. In this study, the magnitude of each variable is set to be 1% of its baseline value, which is translated to 1% increase in baseline compressor inlet flow rate, 1% increase in compressor adiabatic efficiency, or 1% increase in turbine stage efficiency and so on. Note that the sensitivity study is conducted when the model is set to off-design mode, which is consistent with the occasions when k-factors are applied for performance enhancement.

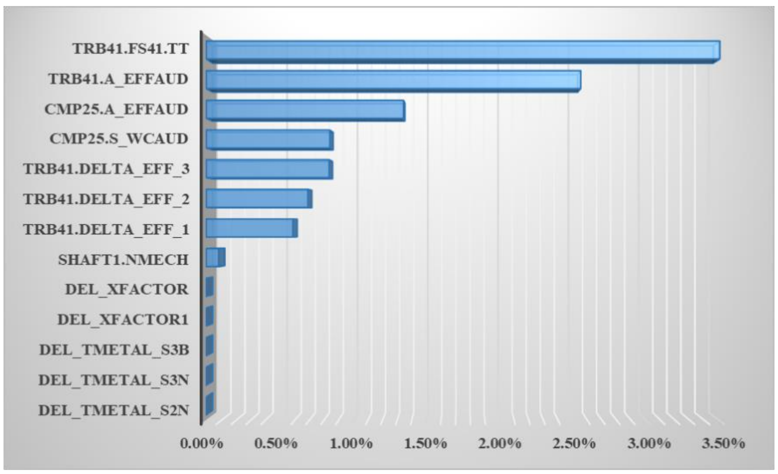


Figure 54. PG6541B Model Sensitivity Analysis Result

The result of the sensitivity study is presented in Figure 54 and variables are sorted by their impacts in decreasing order. The top three variables impacting the change of the power output are firing temperature, turbine adiabatic efficiency, and compressor adiabatic efficiency. 1% increase in firing temperature leads about a 3.5% increase in power, which makes it almost the most enticing knob to turn. Unfortunately, it is not the easiest one. The resulting higher temperature makes it the most expensive option as it is usually accompanied by the upgrade of materials and cooling techniques for most of the parts located in the hot gas path. The additional power benefit has to be weighed against the cost to realize a higher firing temperature once the firing temperature is considered as a potential knob. It is interesting to see that the efficiency change of the 3rd turbine stage has the largest impact compared to the first two turbine stages. This is due to the observation that the baseline stage-efficiency is different from stage to stage. As the last stage has the highest stage efficiency, 1% change leads to more efficiency improvement in the turbine component level. For variables with negligible impact on the power (Del_xFactor, Del_xFactor1, Del_tMetal_S2N, Del_tMetal_S3B, Del_tMetal_S3N), these improvements in either cooling or material aim to extend the life of parts used in the turbine section and enhance the maintainability of the engine.

Once the sensitivity study is complete, the GT modeled and technologies emulated established in this chapter are then used to derive a k-factor vector for each individual uprating option dedicated to industrial GT PG6541B. The result is displayed in Table 33 and Table 34. Note that Option 1 is not included in the table as this uprate option is not compatible with PG6541B product. The first table shows the gas turbine performance obtained after taking a k-factor vector used to model each technology option. The output power values from the simulated model are compared with the reported power data from [9]. Other significant system-level performance indices are also listed, including heat rate, efficiency, firing temperature, and pressure ratio. The % error column in Table 33 consistently shows a small percentage modeling error after tuning as a result of careful selection of k-factor values. Table 34 presents the constructed technology impact matrix. Note that the value in this table represents a relative change with respect to the datum model (PG6541B) and that the unit in the table depends on the corresponding quantity impacted in the constructed NPSS model.

Table 32. NPSS Solver Pairs Used for Technology Modeling

No.	Technology Category	Impacting factor
I	**IGV**	CMP25.s_WcAud
II	**Shaft Speed**	SHAFT1.Nmech, CMP25.a_effAud, TRB41.a_effAud
III	**Sealing**	TRB41.delta_eff_1, TRB41.delta_eff_2, TRB41.delta_eff_3
IV	**Aero**	TRB41.delta_eff_1, TRB41.delta_eff_2, TRB41.delta_eff_3
V	**Cooling**	Del_tMetal_S1B, Del_tMetal_S1N, Del_tMetal_S2B, Del_tMetal_S2N, Del_tMetal_S3B, Del_tMetal_S3N, Del_xFactor, Del_xFactor1
VI	**Firing Temperature Package**	TRB41.FS41.Tt, Del_tMetal_S1B, Del_tMetal_S1N, Del_tMetal_S2B, Del_tMetal_S2N, Del_tMetal_S3B, Del_tMetal_S3N, Del_xFactor, Del_xFactor1

Table 33. k-factor Tuning Result for PG6541B Model

Option	Category	Published MW	Modeled MW	%Error for Power	Heat Rate (BTU/kW-hr)	Efficiency	Firing Temperature in °C	Pressure Ratio
1	I	38.14	38.1087	0.08%	10596.7	32.19%	1116.67	11.8
2	II	38.293	38.3033	-0.03%	10591.6	32.21%	1116.67	11.8662
3	III	38.560	38.5026	0.15%	10581.2	33.23%	1116.67	11.9376
4	III	38.426	38.418	0.02%	10537.6	32.40%	1116.67	11.8007
5	III	38.407	38.4177	-0.03%	10515.7	32.39%	1116.96	11.8013
6	III	38.540	38.5531	-0.03%	10490.4	32.47%	1117.77	11.8048
7	III	38.521	38.4919	0.08%	10501.3	32.45%	1117.42	11.8033
8	III	38.273	38.2148	0.15%	10553.8	32.23%	1115.74	11.796
9	IV	38.235	38.2169	0.05%	10553.5	32.33%	1179.61	11.8022
10	V	38.521	38.5078	0.04%	10498.8	32.50%	1117.5	11.8036
11	VI	38.521	38.5727	-0.13%	10489.5	32.53%	1115.71	11.8431

Table 34. k-factor Technology Impact Matrix for Uprating Technologies (PG6541B)

Option	Category	k_IGV	k_shaft_c	k_shaft_t	k_eff_c	k_eff_t1	k_eff_t2	k_eff_t3	k_cool_t2n	k_cool_t3n	k_cool_t3b	k_cool_t1	k_cool_t
1	I	0.60%											
2	II		0.80%	0.80%									
3	III				0.6%								
4	III					1.30%							
5	III					1.40%							
6	III						1.30%						
7	III						0.50%						
8	III							0.50%					
9	IV							0.90%					
10	V								70 ºR				-0.2
11	VI									90 ºR	70 ºR	-0.01	-0.01

4.3 *Growth Quantification for GT Products*

Within the same GT architecture, newer products are developed and infused with recently matured technologies, which are integrated to realize growth that was previously built in the same architecture. In the meantime, a subset of compatible technologies is included in the list of uprating options dedicated to previous generations of GT products [9-11]. This practice equips those operating GTs the capability to unleash the built-in growth to improve thermodynamic performance, saving a costly flange-to-flange replacement for the plant. As such, those published technology PIP packages shed light on the amount of potential growth for the architecture. The case study to be conducted in this section looks into the available uprating options and use that to obtain the growth behind those packages.

4.3.1 *Background of Case Study Part I*

In 1997, GE decided to uprate its current production of MS6001 products to the 5,163 RPM turbine speed [9]. Output and efficiency improvements were also improved by increasing firing temperature, reducing leakage in the hot gas path, minimizing inlet and exhaust pressure losses. Those efforts finally led to the production of PG6581B in 2000. A thorough comparison between PG6581B and its predecessor, PG6541B, is included in [105] published by GE in 2006. The information from the source is summarized in Table 35, which lists all the hardware differences between these two GT products within MS6001 architecture. It is discovered that those differences in major components of GTs are almost all accounted for in the list of PIP packages available for products of MS6001 earlier generations (**Table 51**). The last column of Table 35 shows the individual PIP package available that can be used for PG6541B to be uprated to the same hardware used in PG6581B.

Table 35. Hardware Differences between PG6581B and PG6541B [10, 119]

Component Impacted	PG6581B	PG6541B	PIP Item
Stage 1 Shroud	HR-120 Material with 'Pumpkin Tooth'	310 SS with 'Pumpkin Tooth'	Stage 1 Shroud with Cloth Seals
Stage 1 Nozzle	FSX-414, Improved Cooled	FXS-414, not Improved Cooled	Improved Cooling Stage 1 Nozzle
Stage 1 Bucket	GTD-111, Perimeter	GTD-111, 12-hole	Included in 2084°F Package
Stage 2 Shroud	Honeycomb shroud	Non-Honeycomb Shroud	Stage 2 Honeycomb Shroud
Stage 2 Nozzle	GTD-222 material	FSX-414 material	GTD-222 Stage 2 Nozzle
Stage 2 Bucket	IN738, 7-hole, cutter tooth design	IN738, 4-hole, non-cutter tooth	Improved Cooling Stage 2 Bucket
Stage 3 Shroud	Honeycomb shroud	Non-Honeycomb Shroud	Stage 3 Honeycomb Shroud
Stage 3 Nozzle	GTD-222 material	FSX-414 material	GTD-222 Stage 3 Nozzle
Stage 3 Bucket	IN738, cutter tooth design	U500, non-cutter tooth design	Advanced aero stage 3 bucket and nozzle
Compressor	HPPS with brush seal	Labyrinth seal	High-pressure packing brush seal
Inlet Guide Vane Angle	GTD-450 material, 86° maximum angle	403 SS material, 84° maximum angle	86° IGV Setting
Transition Piece	Nimonic-263 body and aft-frame with TBC	Hast-X body and aft-frame with TBC	Included in 2084°F Package
Combustor Liner	Standard combustion design with TBC	Standard combustion design w/o TBC	Included in 2084°F Package
Load Gear Limit	5163 rpm load gear	5094 rpm load gear	5163 rpm load gear
Firing Temperature	2084°F	2042°F	Increase Tfire to 2084°F

Given a set of matured technologies, the goal of the first part of case study in this section is to quantify the growth of existing architecture and use it toward new product development in the same architecture. The baseline GT model and technology information developed earlier in this chapter are used in this part of case study.

4.3.2 *Growth Quantification for an Existing GT Product*

The first part is to quantify the existing growth for product PG6541B using the technology k-factor matrix obtained in Table 34. Under the stackable assumption, the cumulative impact of all technologies can be modeled by superimposing corresponding k-factors on top of each other. Since there is no compatibility issue between any pair of uprating options, the equivalent technology k-factor vector representing the entire list of options is obtained. The all-in-one uprating package includes system-level improvement such as increased shaft speed and higher firing temperature, as well as component-level performance enhancement such as turbomachinery stage-based material upgrades. Using the tuned PG6541B model as a baseline, the uprated version's performance is obtained as outputs of the established simulation environment. The growth quantification for PG6541B is present in Table 36. The column PG6541B+ is the maximum growth enabled by the published uprating packages.

Table 36. Growth Quantification for PG6541B

	PG6541B	PG6541B+ (Simulated)	Growth Range	% Change
Power (MW)	38.14	42.86	4.72	12.38%
Heat Rate in BTU/kW-hr	10,900	9,982	918	- 8.42%
Pressure Ratio	11.8	12.1	0.3	2.54%
Firing Temperature (°F)	2,042	2,084	42	2%

.

It is observed that the uprated engine is expected to have a growth of 12.38% in power and 8.42% improvement in heat rate. By operating at a higher firing temperature and a slightly increased pressure ratio, Brayton cycle parameters have been changed. By maintaining the same hot gas path geometry, this upgrade is enabled by redesigning and replacing multiple parts. This significant redesign efforts and implementation cost are justified by contributing 30% of the total growth in power. For all other uprate options, since they do not involve cycle upgrade, all of them have contributed around or below 10% of the total growth in power. A complete pie chart in Figure 55 shows the slice of each individual option contributing to the total power increase.

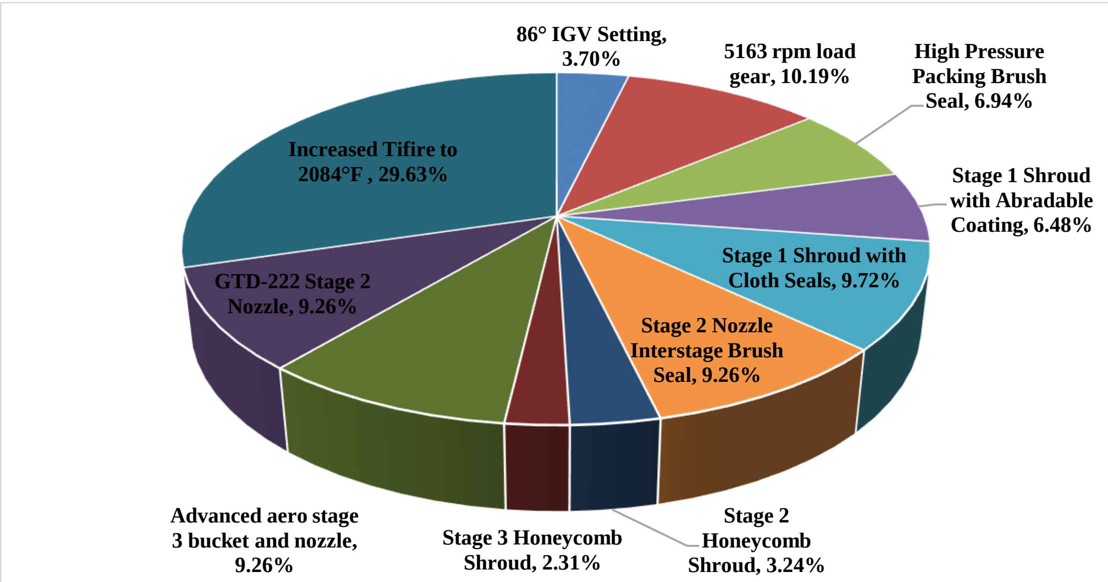


Figure 55. Percentage Contribution to Maximum Growth in Power

4.3.3 *Performance Prediction Using Modeled Technology Inputs*

The second part of the case study is to use technical information to predict a newer GT product's performance. The product evolution is another form of growth realization within the same architecture, i.e. instead of replacing existing parts with improved ones, the newer version is a design "born" with updated features that can be found in the list of PIP packages provided for earlier GT products (Table 35). Using the technology k-factor matrix obtained in Table 34, the performance of PG6581B can be modeled using the baseline PG6541B along with technology package inputs. Based on the list of differences summarized in Table 35, 12 out of 14 uprating options are taken in as technical inputs to account for the improved features equipped in PG6581B. To be specific, "Stage 1 Shroud with Abradable Coating" and "Stage 2 Nozzle Interstage Brush Seal" are not included. The 3 CTQs of the simulated PG6581B is tabulated in Table 37.

Table 37. PG6581B Performance Prediction

	PG6581B	PG6581B (Simulated)	% Error
Power (MW)	42.1	42.18	0.19%
Heat Rate in BTU/kW-hr	10,724	10,040	6.38%
Pressure Ratio	12.2	12.1	0.82%
Firing Temperature (°F)	2,084	2,084	N/A

Given the firing temperature at 2084 ºF, it is observed that the GT model is able to use the tuned technology matrix in Table 34 to provide a close estimate of the power, heat rate, and pressure ratio for PG65821B product. The percentage error is listed for each CTQ output by the model. The power and pressure both have errors lower than 1%, which are considered a pretty good estimate. The heat rate of the GT has a percentage error slightly above 6%. This is still acceptable considering the fidelity of the model obtained for the conceptual study in this research, despite further improvement is possible once more published information about this new product is available.

4.3.4 *Result Discussion*

Note that the purpose of this part of case study is to quantify the growth behind the technology-enabled uprate options and then uses this information to guide future product and technology development. By looking at performance data obtained from Table 36 and Table 37, the latest matured technology packages are able to uptick the power above 42 MW for products within MS6001 series. It is worth noting that the newest product in this series, i.e., PG6581B, already show signs of getting sufficiently close to the maximum growth by those packages. As such, future products development for this product is expected to rely on further technology evolution and/or breakthrough. The former choice is to push E-class technology further so that the CTQs of future MS6001 products can be improved further. The latter one is to investigate the possibility of introducing the step-changing F-class technology into this product series so that a new architecture is designed for F-class technology with surfacing needs from the market in mind. The remaining case study in the next section look into the topic of how new architecture of GT products are designed with growth in mind.

4.4 *New Architecture Design Using Growth Concept*

In this part of case study, a real design scenario in history for MS6001 series is visited and a new GT architecture is to be developed in this context using the designed-in growth approach presented in Figure 49. Various prevalent GT product design and development techniques are used in this process. The newly designed architecture is anticipated to rely on emerging technology information to address both short-term design requirement and predict product growth for this architecture.

4.4.1 *Background of Case Study Part II*

In 1987, GE GT product PG6541B was introduced [9] as an uprated version of its predecessor, PG6531B. The newer product features 2.25% more power and 0.28% more efficient in terms of thermal efficiency (Table 49). Almost during the same time, F-class technology was being nurtured, which "represented a quantum leap in the operating temperature, cooling technology, and aerothermal performance of heavy-duty gas turbines" [107]. Per GE's terminology, F-class products are expected to operate at a firing temperature between 2,300°F and 2,600°F (Figure 6). From classical thermodynamics, a higher firing temperature in a Brayton cycle leads to a higher mass-specific power output if the pressure ratio of the cycle remains unchanged **(Eq. 7)**. Therefore, given the same mass air flowing through the system, the GT product with F-class technology is expected to produce more power. The temperature increase in the hot gas section is driven primary by advancement in material, combustion, and cooling technologies, which are developed along with GT product's evolution.

4.4.2 *Establish Product Requirements*

From its inception, MS6001 is a product series targeting the market of light-duty and features dual utility frequencies operation via a load gearbox (Figure 5). By the year of 1990, MS6001 had been evolving through four different generations and the product series covered power range from 31 MW (MS6431A) up until 38.14 MW (PG6541B). Market analysis prediction then conducted by the company indicated a potential strong need for this type of product in the market of 70MW and above [107] in the next 5 to 10 years. Since there was no such product in the existing product family, the design problem was handed over to the GT design team to come up with a solution on how to develop the existing MS6001 product series so that its power can be upgraded to 70MW and above to meet this predicted market expectation.

For this design challenge, there is no doubt that the solution cannot be unique. Using the architecture-based approach formulated in this work (Figure 25), the first option is to look into the growth potential of existing product architecture. If the uprated product is expected to exceed 70-MW threshold, the PIP option is a preferred way forward with minimized design effort and development cost. However, in case the PIP is not able to reach the desired requirement, the option of launching a new architecture would be the best bet. When considering launching a new architecture, countless design efforts and resources are expected to pour in. As such, the expectation of the product is high and the design team is looking for a long-term solution that will lead to a brand-new architecture not only meets the immediate needs in 5 years but also envisions the architecture growth for the next 10 years and possibly beyond.

4.4.3 *PIP Option Investigation*

E-class technology was developed in 1972 and had since been integrated to all evolving 6B product series from MS6431A to PG6541B. The E-class technology features a firing temperature from 2,000°F and 2,300°F (Figure 6). As a feasibility investigation for PIP, the potential growth space of the existing architecture is predicted based on two possible options:

1. Increase the firing temperature to the upper limit of E-class technology, i.e. 2,300 °F. This assumes that the existing hot gas path parts are able to sustain the temperature hike enabled by maturing material, cooling, and coating technologies.
2. Increase the specific mass flow rate by 9%. This can be achieved by further opening up the inlet guided vane and/or improving aerodynamics of the compressor blades. Rangland [13] states that high flowing a compressor is “limited to under 10%”. As such, a 9% increase in flow rate is implemented.

Table 38 lists the simulated performance data of PG6541B and its derivatives. PG6541B+ is the uprated version PG6541B after all applicable PIP options are in place (Table 36). Using the NPSS model developed in this chapter, the performance of PG6541B with 2,300 °F firing temperature (Option 1) is obtained, which ends up with raising the power to 46.4 MW. On top of that, if high flowing a compressor is also deployed, the product would further reach a power output of 53 MW. Despite the substantial growth in the output, it is observed that the 70MW design requirement still cannot be fulfilled by the PIP option. As such, the NAI option is activated and a new architecture seems inevitable in this case.

Table 38. Growth Space for Products Developed under Existing Architecture

Product	Power (MW)	Tfire (ºF)	Mass Flow (lbm/s)
PG6541B	38.11	2,042	310.3
PG6541B+	42.86	2,084	312.1
PG6541B+ & Option 1	46.4	2,300	311.82
PG6541B+ & Option 1 and 2	53	2,300	334.05

4.4.4 *Identify Emerging Technologies*

Shortly after PG6541B was introduced to the market, F-class technology entered the arena. The introduction of F-class technology around 1990 "was impelled by the concurrent need to press the limits on aerothermal performance, meet drastically lowered emissions standard, and succeed in a fiercely competitive market that was paying 20% and 40% less per installed power" [107]. In this design scenario, the possibility of including F-class technology is considered one ingredient to further mount the output power to the 70 MW threshold.

The technology prediction provided by Zachary [108] in Figure 56 shows his estimation on the growth potential of F technology class. The prediction time window spans from 1991 until the sunset of F-class technology. It is observed that the 300°F firing temperature increase during the entire time span is consistent with GE's firing temperature-based technology class definition (Figure 6). In addition, Zachary forecasts up to 5% in compressor mass flow rate increase. Performance-wise, the power of the F-class GT products is expected to produce up to 30% more power and operate up to 10% more efficiency, which are to be validated later this part of case study. This chart helps give an idea of how much growth potential F-class technology can render to the existing GT products. In this case, it is presumed that 300°F in firing temperature and 5% increase in compressor inlet mass flow rate are the growth potential to be designed in the new architecture, hereby named Architecture 6F for abbreviation. Let Model **6F1** be the very first product in this architecture (initial design) and Model **6FN** be the last one (fully-grown design). Architecture 6F is a product family to be active from the inception of F-class to its end, 6F1 being an entry-level F- class product and 6FN being integrated with the “ultimate” F-class technology by design.

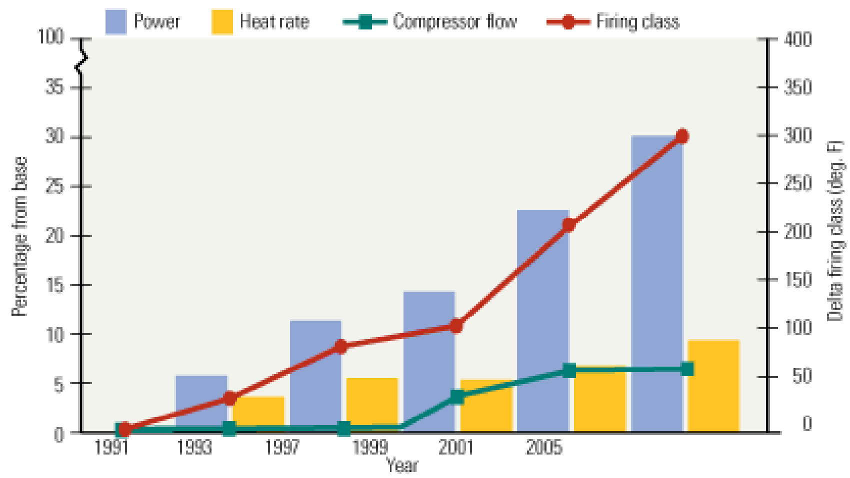


Figure 56.Prediction of F-class Technology Evolvement [108]

In addition to technology-class-enabled growth capability, there are other emerging technologies that are potential performance improvement contributors during the evolvement of Architecture 6F. One feature they share in common is that they do not fundamentally alter the operating cycle of the GT, which is defined by firing temperature at the turbine inlet and pressure ratio of the compressor. Technology category I through V in Section 4.2 cannot serve better examples of those technologies (Table 39). They are categorized so that their impact can be modeled by dedicating k-factors established earlier.

Table 39. Emerging Technology Categories

Option	Category	Specification
1	I	Inlet Guided Vane Improvement
2	II	Shaft Speed Increase
3	III	Sealing Technology Improvement
4	IV	Advanced Aerodynamic Design
5	V	Cooling Technology Improvement

4.4.5 *Size Architecture-based Design*

In this step, the growth is to be designed in the new architecture. Prevalent GT product development practices such as geometric scaling and zero-staging, are used to size the new architecture. The sizing process determines Brayton cycle parameters, inlet mass flow into the compressor, and the scale factor. Geometric scaling concept and its benefits have been introduced in Section 2.4.2. It is preferred by GT manufacturers to conduct faster and reliable GT product development. In this design scenario, the new product is expected to be doubled in power with respect to PG6541B, which happens to be the most recent family member of MS6001 series at that time. Conducting geometric scaling on the baseline product compressor and turbine so that the scaled version will be close to the targeted power level is justifiable from both design and cost perspective. On top of that, F-class technology is designed into the products to make the new architecture more competitive

Table 40 summarizes the pertaining information for this design problem. Based on the predicted market analysis, the initial design of this new architecture (6F1) is expected to have a power output of at least 70 MW. The fully-grown design (6FN) will be more powerful while the value is yet to be determined after design. The firing temperature and inlet compressor mass flow rate take into account the forecasted performance evolvement of F-class technology in Figure 56. In other words, the designed-in growth of 300°F in firing temperature and 5% in inlet mass flow rate are to be included in the new architecture development.

Table 40. Architecture-based Design Problem Set-up

Parameter	Model 6F1	Model 6FN	Designed-in Growth	Comment
Power (MW)	70	TBD	TBD	Initial design requirement
Tfire (°F)	2,300	2,600	300	F-class technology
Inlet Flow Rate	Wc	1.05Wc	5%	Scaling from PG6541B
Pressure Ratio	TBD	TBD	TBD	Zero-staging

As another prevalent GT upgrade technique, the pressure ratio of the compressor is further improved by zero-staging, i.e. adding an extra stage of stator and rotor in front of the first stage, as shown in Figure 9. The inlet design will need to be adjusted accordingly. The pressure ratio of Model 6FN is selected to improve cycle efficiency. Figure 57 shows a series of curves depicting how cycle efficiency changes with pressure ratio under a given temperature ratio T_4/T_2 = 5.5, where T_4 is the firing temperature and T_2 is the compressor inlet temperature. It is assumed that the inlet condition of the compressor is at ISO condition (59 °F). As an approximation, the average temperature ratio for F-class engine is around 5.5 (Figure 56). Additionally, the estimated component efficiency of compressor and turbine for MS6001 series products at that time stand at about 85% [109]. The pressure ratio for zero stage is assumed to be 1.1 for simplicity. Based on the rules of scaling listed in Table 5, the compressor pressure ratio hardly changes before and after geometric scaling. Thus, the new zero-staged compressor will have 18 stages. The designed pressure ratio of 6FN increases from 11.8 to 13. The new cycle efficiency is expected to be improved per Figure 57.

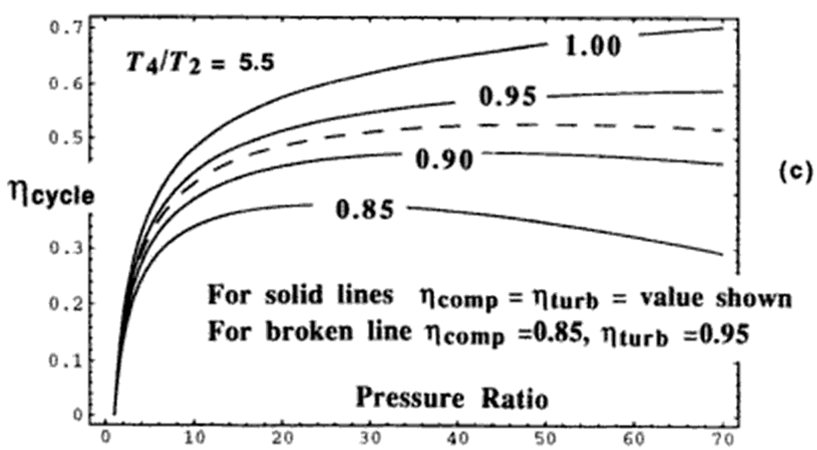


Figure 57. Cycle Efficiency vs. Pressure Ratio for an Idealized Gas Turbines [111]

So far, the cycle parameters have been determined in the new architecture. The next step is to derive the scale factor and the inlet flow rate. This is done by running Model 6FN at on-design mode and 6F1 at off-design mode in the NPSS simulation environment, which makes sure the flow-path geometry and dimensions of those two products do not change. When the inlet flow rate of PG6541B is scaled up, the scale factor is tuned until the output of Model 6F1 hits 70 MW threshold at 2,300°F firing temperature. This is to ensure the minimum power requirement is to be met for 6F1. Then the inlet flow rates for both products are fall-outs in this process. So are the pressure ratio of 6F1 and the power of 6FN. The entire break-down for architecture 6FA development approach is illustrated in Figure 58. **Error! Reference source not found.** shows the results for the two designs after the scaling. The linear dimension scale factor from PG6541B to Architecture 6F turns out to be 1.3. From the result, the technology class infusion uprates the power of 6F1 to 70MW and 6FN to 88.15MW, preparing the architecture 25.3% further power growth as the product evolves from the first generation into the most advanced F-class version, which is consistent with the prediction given in Figure 56.

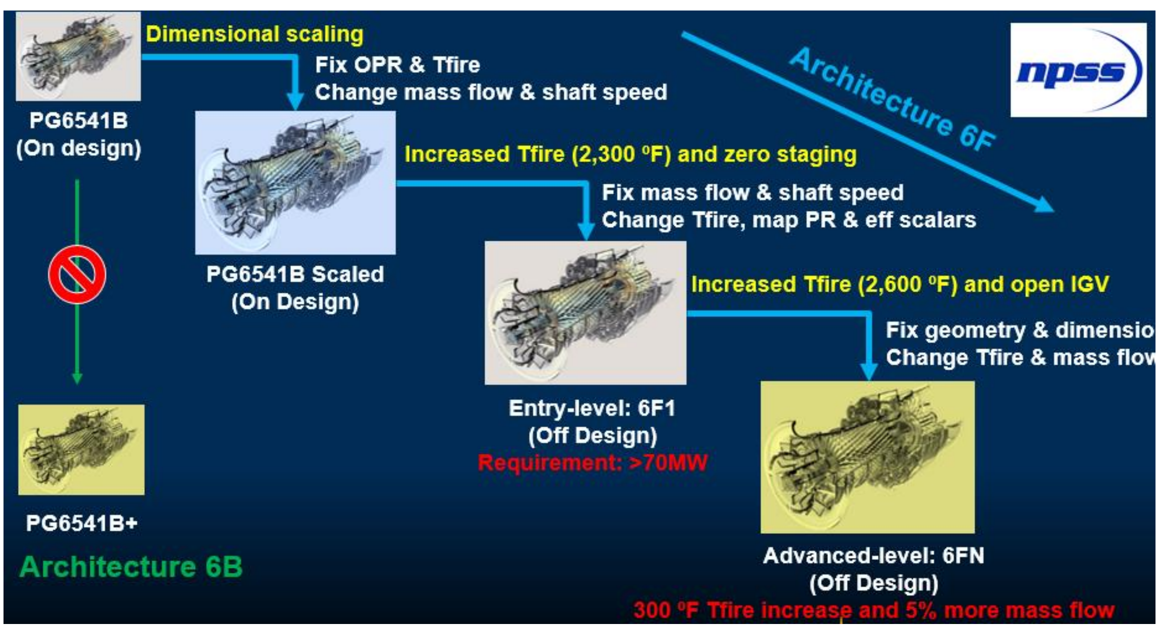


Figure 58. Architecture 6F Development Break-down

4.4.6 *Generate Technology Matrices*

Once the F-class technology sets the stage for the architecture, the next step in the process is to identify other emerging technologies and quantify their impact in terms of changes with respect to baseline (Model 6F1) in the form of technology metrics. Technology models are categorized and modeled in Section 4.2. New technology categories are created if the emerging technology does not fit into any of the established categories. A set of 10 technologies applicable to the 6F architecture is selected for analysis in this study. These 10 technologies consisted of 2 compressor technologies, 7 turbine technologies, and 1 shaft speed increase. The specific set of technologies are selected by the technology development team as the technology maturity date for all of them will fall between the development cycles of architecture 6F products. Table 42 tabulated the information of each individual technology and their forecasted impact upon maturity. It is presume that there is no compatibility issue between any pair of technologies in this table.

Table 41. List of 6FA vs. PG6541B Differences [105, 109]

Component Impacted	6FA	PG6541B	PIP Item
Stage 1 Nozzle	FSX-414, Improved Cooled	FXS-414, not Improved Cooled	Improved Cooling Stage 1 Nozzle
Stage 1 Bucket	GTD-111DS	GTD-111, 12-hole	Included in 2084°F Package
Stage 2 Nozzle	GTD-222 material	FSX-414 material	GTD-222 Stage 2 Nozzle
Stage 2 Bucket	GTD-111 material	IN738, 4-hole, non-cutter tooth	Improved Cooling Stage 2 Bucket
Stage 3 Shroud	Honeycomb shroud	Non-Honeycomb Shroud	Stage 3 Honeycomb Shroud
Stage 3 Nozzle	GTD-111 material	FSX-414 material	GTD-222 Stage 3 Nozzle
Stage 3 Bucket	GTD-111, cutter tooth design	U500, non-cutter tooth design	Advanced aero stage 3 bucket and nozzle
Compressor	HPPS with brush seal	Labyrinth seal	High-pressure packing brush seal
Firing Temperature	2,300°F	2,020°F	F-class

Table 42. Emerging Technology Impact Forecast

No.	Category	k_eff_c	k_eff_t2	k_eff_t3	k_cool_t2n	k_cool_t3n	k_cool_t3b	k_cool_t1	k_cool_t
1	III	0.60%							
2	III		1.30%						
3	III		0.50%						
4	III			0.50%					
5	IV			0.90%					
6	V				70 ºR				-0.2
10	VI					90 ºR	70 ºR	-0.01	-0.01

4.4.7 *Obtain Full-grown and Initial GT Designs*

Once the technology information is in place, the architecture-level growth is can be evaluated by integrating the uprating technology into the baseline model (6F1). It is assumed that the technology impact is stackable. As such, the performance of model 6FN can be simulated by inputting the cumulative technology impact from Table 42. The final performance parameters are summarized in Table 43.

The development path for Architecture 6FA is hence established with one initial product 6FA and one ultimate product 6FN. For this architecture, it is observed that the initial design requirement for power is met by 6FA. In addition, the predicted technology set could further push the power to 95.48 MW while make the architecture operate more efficiently. On the other hand, the growth of 300 °F increase in firing temperature and 4.9% hike in mass flow rate has been designed in as intially planned. As F-class technology matures, this portion of growth will be fully realized once 6FN is in production, which could be 10 years or even longer from the inception of the new architecture. The development path gradually paves the way to a series of competitive F-class product for the manufacturer during this time frame.

Table 43. Initial Design and Fully-grown Design for Architecture 6F

Parameter	6F1	6FN	% Growth	Growth Range
Tfire in °F	2,300	2,600	13.04%	300
Mass Flow Rate in 10^3 lbm/s	517.7	542.84	4.9%	24.14
Power in MW	70.4	95.48	35.6%	25.08
Heat Rate in BTU/kW-hr	11,447	10,047	12.2%	1,400
Pressure Ratio	12.48	13.85	11%	1.37

4.4.8 *Product Development Path*

The purpose of the second part of case study uses the design-in growth concept to plan a “new” GT architecture for MS6001 series. The time dates back to late 1980s when

PG6541B just went into production. The then "new" architecture was triggered by the power requirement from the niche market and takes advantage of the rising of F-class technology at that time. The realization of this part of growth depends on both the evolvement of F-class technology and other emerging technologies to be matured in the same time frame. Using the approach presented in Figure 49, the initial product and fully-grown product performance parameters are obtained.

Table 44. Design-in Growth GTs vs. Actual GTs by GE

Parameter	6F1	6FN	MS6001FA	6F.03
Power (MW)	70.36	95.48	70.1	88
Inlet Flow Rate in 10^3 lbm/s	517.7	542.84	427.7	471,79
Heat Rate in BTU/kW-hr	11,447	10,737	10,530	9,277
Firing Temperature in °F	2,300	2,600	2350	N/A
Pressure Ratio	12..48	13.85	14.9	16.1
Number of Compressor Stages	18	18	18	18
Number of Turbine Stages	3	3	3	3

Table 44 includes information from GE regarding the actual development path they took for MS6001 series products amid F-class technology rising. MS6001FA was the first product in this architecture. Instead of scaling from an MS6001 product, it was scaled from MS7001F, which is from a completely different product series [109]. The product was designed for a 70 MW power requirement and it went to production in 1996. The product has an 18-stage compressor and a 3-stage turbine, which are the same as the designed 6FA architecture presented in the second part of case study. The mass flow rate is smaller compared to 6F1, but it has a higher firing temperature and pressure ratio. The most recent product rolled out in this architecture is 6F.03, which has 88 MW in power output, but the firing temperature remains unavailable to the public so far. It's interesting to observe and compare the performance of architecture 6F as well as the real architecture manufactured. GE is continuing upgrading this architecture and it remains to be seen how far the performance can be pushed further with F-class technology.

4.4.9 *Technology Development Cost Consideration*

So far, focus has been given to the thermodynamic gains brought by infusing newer technologies. However, in addition to those added benefits, technology in the real world always comes with a development cost. This price tag should be also factored in when a new product or architecture is being designed. This would help identify those technologies that are both thermodynamically and economically competitive. In this section, technology development cost is included for designing and developing the new 6FA architecture.

As a measurement of technology maturity, technology readiness level (TRL) has a wide variety of uses in aerospace systems engineering and project management [112]. A higher TRL is always desirable as it indicates the technology is closer to maturity. From a cost perspective, a technology with higher TRL would incur lower future development cost. To account for this TRL-dependent cost, there is a need to create a map from a given TRL to a future technology development cost. In literature, Conrow [112] coined a concept called technology readiness coefficients, which permits the generation of TRL values for use in mathematical operations. His work was extended and adapted in [113] based on the assumption that the TRL coefficients could be an indicator of future development cost. Figure 59 displays an empirical curve that mapping TRL to the % maturity (which is also equivalent to % development cost per [113]). It is observed that at a higher TRL, more capital is required to elevate the technology from one base TRL to its next level.

The establishment of this mapping from TRL to % development cost is useful as it makes the evaluating the cost aspect of a new technology possible. In this context, a relative cost index is created (Table 45) based upon the work of [112, 113]. It is presumed that it takes one unit of capital to develop any technology from TRL = 0 to TRL = 9. At a given

TRL, there is still a fraction of that unit capital required (amount indicated in Table 45) to fully mature that technology.

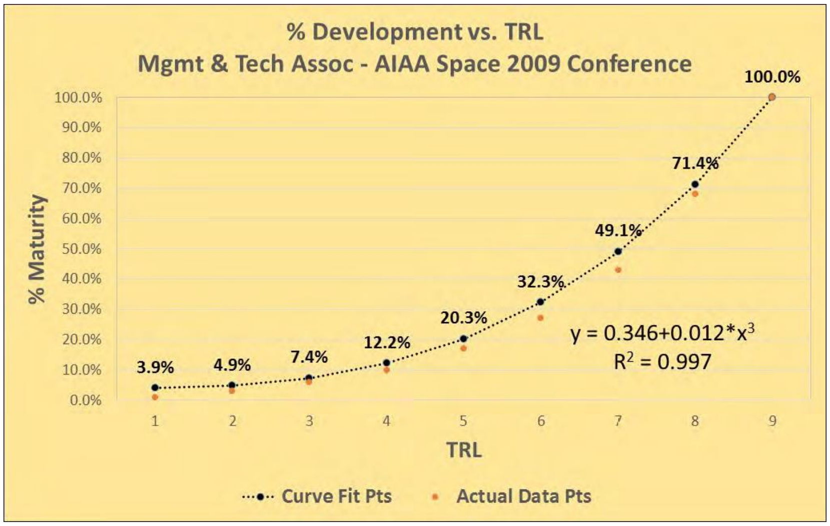


Figure 59. % Maturity vs. TRL Curve [112, 113]

Table 45. TRL vs. Relative Cost Index

TRL	% Maturity	Relative Cost Index
0	0	1
1	0.039	0.961
2	0.049	0.951
3	0.074	0.926
4	0.122	0.878
5	0.203	0.797
6	0.323	0.677
7	0.491	0.509
8	0.714	0.286
9	1	0

In this scenario, 10 new technologies are potential candidates to put on baseline 6F1 products for evaluation and comparison. They are presumably a shortlist of PIP technologies available for Architecture 6E and could potentially form $2^{10} = 1024$ different combinations. The technology impact matrix is obtained from Table 34 with each technology categorized (Table 46). Each technology of interest comes with a TRL, specifying the relative degree of maturity for its development stage. In practice, TRL information is obtained either by consulting a technology specialist or looking into a well-established technology database. A relative cost index is tagged based on individual technology's TRL in Table 47. The cost index is standardized to represent the amount of capital to be invested to bring that technology into full maturity. It is presumed that there is no incompatibility between any pair formed from that 10 technologies of interest.

Once the context has been specified, the technology selection approach presented in Figure 32 is deployed in this case. The simulated 6F1 model built in NPSS environment is used to capture the impact of different technology combinations. The system-level metrics of interest are power and total technology development cost. As such, the optimization problem is formulated as: Maximize the power of a new GT product subject to the available budget constraint. The introduction of economical constraint limits the number of technologies used for performance improvement.

Considering the binary nature of technology vector ("on" or "off"), genetic algorithm (GA) is called upon to solve the constrained optimization problem. The implementation procedure of GA is summarized in APPENDIX B. Population size is selected to be 40 per generation. Mutation rate and cross-over rate are set to 0.04 and 0.7 respectively. GA is observed to have fast convergence and the results are presented in Table 48 for selected budget constraints. There are several observations to be made here:

1. A hefty budget leads to better GT performance as a larger number of technologies are allowed to participate in performance enhancement.
2. By looking into the individual technology making up the top combination across different budget values, T5 technology is identified to be the most competitive, followed by T2. On the other hand, T10 is observed to be the least competititve.

The results of this part of case study help the development team to identify technologies that are both thermodynamically enticing and economically competitive. Technologies selected and developed from this process are more likely to contribute to the future success of a new product development program for industrial GT manufacturer.

Table 46. k-factor Technology Impact Matrix for Emerging Technologies for Architecture 6F

No.	Technology	Category	k_IGV	k_shaft_c	k_shaft_t	k_eff_c	k_eff_t1	k_eff_t2	k_eff_t3	k_cool_t2n	k_cool_t
1	IGV Design Improvement	I	0.60%								
2	Shaft Speed Increase	II		0.80%	0.80%						
3	HPP Brush Seal	III				0.6%					
4	S1 Shroud with Abradable Coating	III					1.30%				
5	S1 Shroud with Cloth Seals	III					1.40%				
6	S2 Nozzle Interstage Brush Seal	III						1.30%			
7	S2 Honeycomb Shroud	III						0.50%			
8	S3 Honeycomb Shroud	III							0.50%		
9	Advanced Aero S3 Bucket and Nozzle	IV							0.90%		
10	GTD-222 S2 Nozzle	V								70 ºR	-0.2

Table 47. Emerging Technologies TL and Relative Cost

No.	Technology	Category	Technology Level	Relative Cost
1	IGV Design Improvement	I	6	0.677
2	Shaft Speed Increase	II	7	0.509
3	HPP Brush Seal	III	7	0.509
4	S1 Shroud with Abradable Coating	III	8	0.286
5	S1 Shroud with Cloth Seals	III	8	0.286
6	S2 Nozzle Interstage Brush Seal	III	7	0.509
7	S2 Honeycomb Shroud	III	8	0.286
8	S3 Honeycomb Shroud	III	8	0.286
9	Advanced Aero S3 Bucket and Nozzle	IV	6	0.677
10	GTD-222 S2 Nozzle	V	7	0.509

Table 48. Top Technology Combinations with Given Budgets

Budget	Heat Rate (BTU/kW-hr)	Power (MW)	Cost	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
0.5	11022.5	88.91	0.286	0	0	0	0	1	0	0	0	0	0
1	10742.8	91.43	0.795	0	1	0	0	1	0	0	0	0	0
1.5	10609.4	92.49	1.367	0	1	0	1	1	0	0	1	0	0
2	10509.6	93.28	1.876	0	1	0	1	1	1	0	1	0	0
2.5	10454.9	93.9	2.385	0	1	1	1	1	1	0	1	0	0
3	10392	94.22	2.839	0	1	0	1	1	1	1	1	1	0
3.5	10337.3	94.84	3.348	0	1	1	1	1	1	1	1	1	0
4	10366.3	95.08	3.739	1	1	1	1	1	1	0	1	1	0
4.5	10327.4	95.39	4.025	1	1	1	1	1	1	1	1	1	0

4.5 *Summary of the Case Study*

This section chapter implements the entire product growth approach (Figure 25) in two parts of case study. The first part of case study quantifies the built-in growth behind the uprating options and uses the growth to predict future products' performance. The second part of case study combines prevalent GT product design techniques and designed-in growth concept to plan the product evolvement of a new architecture. The cost of technology development is also taken into consideration. The approach and results presented from this case study help to answer the overarching research question posed at the beginning of this work and induce the thesis statement of this research:

Overarching Research Question: Given a set of available technologies and existing industrial gas turbine architectures, how can the capability of product growth management in a GT architecture be used to enable an informed decision upon its future product development path?

Thesis Statement: The architecture-based product growth approach presented in this work uses the concept of growth as a key metric to design future GT products. If this framework is implemented, it would enable GT designers to have a structural and transparent decision-making process to perform product improvement and plan for future GT product's development path.

CHAPTER V

CONTRIBUTIONS AND FUTURE WORK

In this work, an industrial GT product conceptual design and development methodology is presented to decipher the proprietary and often subjective product development decision-making process. This new architecture-based growth approach is formulated with the intention to:

1. Understand **past** industrial GT products' performance evolvement;
2. Interpret the **prevalent** GT product improvement practices;
3. Use the concept of growth to enable a scientific and structured decision-making process for **future** industrial GT products' development.

For industrial GT products, the pursuit of higher power output, efficiency, reliability, and availability has never been put to an end by the GT designing team. At the same time, the operation cost and emission have been descending to make the power plant operation more affordable and environmentally friendly. In this work, the process behind this continuous performance upgrade and product development has been investigated with details. For existing GT products, a list of uprating options is offered so that the performance of industrial GT can be improved without introducing a new product. For a prospective power plant, new industrial GTs integrated with recent technologies are rolled out by the designer one after another, equipped with enhanced system-level capability and characteristics. However, the two aforementioned GT product upgrade practices are often deployed for different purposes.

PIPs are intended to improve the overall performance of existing product architecture via technology infusion and partial redesign. This architecture-based design concept enables products to "grow" with minimized product life cost and risk by recycling the existing design and production resources. In other words, the growth of the product is realized with the help of those technologies that shape the uprating options. The majority of newer GT designs have undergone this process and become the derivatives of previous generations within the same architecture. The uprated products are expected to meet various operators' economic requirements as well as external environmental compliance. The traditional conceptual design tools mainly have focused on product-level design optimization and technology selection, with little attention being rendered to multi-product or architecture-level. To overcome this limitation, this growth-based approach uses an existing technology evaluation approach with augmented capabilities to address technology selection and prioritization process at architecture-level so that valuable resources are expected to be invested in those technologies that can tap into the growth for the most performance improvement.

Despite less common and possibly more costly, NAI expands the existing product variety by unveiling a completely different architecture with noticeable performance improvement enabled by a breakthrough in technology class. The structured approach presented in this work designs growth into the new architecture by sizing the gas turbine technologies at future level but then "adjusting" its performance to the current technology level. The initial design may not work at its optimal operating condition with its present hardware design as it is sized with respect to a future technology level. However, the long-term payback is significant compared to the product following a PIP path. A retrofit-based case study clearly shows both the short-term and the long-term benefits of such a new architecture from a plant operator's perspective. However, a thorough cost analysis is still needed to further justify this move. A decision like this is so critical as it directly impacts the directions and flexibility of the company's product development in the next decade or even longer.

The product growth framework established uses the built-in growth and the design-in growth formulated in this work for creating a product roadmap for near-term product upgrade (PIP) or long-term product development (NAI). The framework of growth includes technology modeling, growth quantification (for existing products), and growth infusion (for new architecture). As growth space is highly dependent on the technology level, an augmented technology evaluation approach is presented to reasonably model and capture technologies' joint impact on baseline GT products. With technology inputs established, the built-in growth quantification is thus enabled and so is the designed-in growth. If implemented, this architecture-based growth approach is expected to render concrete simulated results to support the new product decision-making process, providing a second opinion to complement the existing proprietary GT development process.

5.1 *Research Questions and Hypotheses*

Overarching Research Question: Given a set of available technologies and existing industrial gas turbine architectures, how can the capability of product growth management in a GT architecture be used to enable an informed decision upon its future product development path?

Thesis Statement: The architecture-based product growth approach presented in this work uses the concept of growth as a key metric to design future GT products. If this framework is implemented, it would enable GT designers to have a structural and transparent decision-making process to perform product improvement and plan for future GT product's development path.

This statement is concluded from the case study: The approach flow presented in Figure 25 is followed to conduct the deployment of the full approach in CHAPTER IV. The experiment fully demonstrates the capability of using real-world engine performance and technology data to conduct technology modeling, growth quantification, and growth infusion, which are the three pillars of product growth framework.

Research Question 1: How to identify competitive technologies that will be integrated into future GT product development?

Hypothesis 1: For a given set of technologies, the application of TIES is able to identify competitive technologies that bring performance benefits to products within the same GT architecture.

Research Question 2: How to account for the built-in growth of the GT architecture included in its dedicated PIP?

Hypothesis 2: For a given industrial GT architecture, its built-in growth can be quantified by evaluating feasible technology combinations provided in the PIP with respect to system-level metrics of interest.

Hypotheses 1 and 2 are confirmed in Section 3.3.4. In this example, both product-level and architecture-level growth space are quantified and represented with appropriate growth metrics. The information collected is then used to shape the capability envelope of this architecture for a given set of technologies. The mastering of this knowledge facilitates a faster decision-making process of the manufacturer. This capability is always valued during a competition or bidding event for new power plant project procurement. The technology selection process presented enables the company to identify those technologies with a wider spectrum of impact on its products. Given emerging technology information, this elite-selection process is able to prioritize future technology development and achieve a smart resources allocation mechanism for the company.

Research Question 3: How to design growth into a new GT architecture given forecasted information about emerging technologies?

Hypothesis 3: The product growth can be designed into the new industrial GT architecture by sizing the design for technologies at a future technology level and then adjust its performance to its current technology level.

Research Question 4: What are advantages of using designed-in growth when launching a new architecture?

Hypothesis 4: If a new architecture is developed using a designed-in growth path, the architecture benefits from more performance gain throughout its planned horizon when compared to the path of a PIP.

Hypotheses 3 and 4 are confirmed in Section 3.4.3. In this case study, a process showing how to infuse designed-in growth into a new architecture is unfolded. This path features an unusual reverse design sequence, with the purpose of taking advantage of predicated technology information from a future technology level. A fully-grown design is established first using the predicted technology inputs, followed by the initial design and its potential performance improvement roadmap. The case study concludes that the reverse order design procedure used for designing growth into new architecture is a feasible practice conceptually and proves its potentially added value by comparing its economic performance with a PIP in the context of a retrofit scenario.

5.2 *Summary of Contributions Made*

The principal contributions of this thesis include are:

1. The development of quantifiable growth metrics in the context of industrial GT product development. Although, the growth concept has been introduced amid aircraft engine conceptual design [27-32], it has been enriched substantially in this research and tailored to entertain needs from industrial gas turbine design and development. In particular, this adaption and extension of this notion turn out to be

instrumental in understanding and interpreting the product performance improvement trajectory of past products and the prevalent product upgrade techniques utilized by the top manufacturers. As such, the "growth" metric itself is an innovation for the conceptual design of industrial GT products.

2. The establishment of product growth framework for industrial GT product development decision-making. This idea of using growth metrics as indicators to guide product development path provides an alternative approach for the GT designers to come up with new and competitive products. As an enabler to product growth realization, the technology evaluation and selection procedure can help identify and down-select technologies that are considered key contributors to growth fulfillment in the present or for the future.
3. The approximation of a stage-by-stage GT model. Uprating technologies used for compressor and turbine existing GT products may have impacts stage-level improvement to those components. The establishment of this capability equips the model to emulate those impacts and help the design team to evaluate the corresponding stage-relevant performance with sufficient confidence.
4. Category-based Technology Modeling. Technologies available for GT performance uprating usually fall into several categories, including cooling, material, and sealing. Using a category-based technology modeling, each technology is first classified and then linked to a set of k-factors already established in that category. This technique facilitates a faster modeling cycle and saves the time for re-establish the impact factors every time an emerging technology surfaces. New technology category is required if the new technology does not fit into any of the existing category.

5.3 *Recommendation for Approach Future Enhancement*

The architecture-based growth approach articulated in this thesis intends to provide a different angle to look at the existing development process for the industrial GT. One design philosophy presented in this work is that there is almost always room for improvement for a designed product. There is no surprise that the same philosophy applies to the gap-bridging approach formulated in this thesis. There are potential parts that can be added on top of the existing work to enhance the capability and breadth coverage of this approach:

1. The cost consideration. There is a list of factors to account for before a company decides to launch a new architecture. Those considerations may include the cost of conducting new product research, development and field-testing activities. Moreover, the cost to initiate a new product line (software and hardware) should also be in the equation. These types of evaluation often require empirical regression model and historical data from the past so that a reasonable estimate can be established with sufficient confidence.
2. The risk consideration. The successful introduction of a new product depends on multiple factors. The risk consideration of all applicable factors inside and outside the company is often considered a daunting task for a business. Inside the company, the risk on the list may include project delay, insufficient funding, and technology performance gap. Outside the company, the product may face fierce competition with similar products from other manufacturers. Considering the magnitude of investment for a new industrial GT architecture, a thorough risk assessment and mitigation plan should be carried out beforehand to maximize the likelihood of success after rolling out a new architecture.
3. Uncertainty consideration in emerging technologies. The prediction of future technologies' impact is not easy. The deterministic treatment of technology is the first but not the ideal step to deal with emerging technology, whose impact

is subject to change until it finally matures. This uncertainty in impact should be factored in and analyzed in full when conducting technology selection and product performance evaluation for future products. In this case, a probabilistic design method should be introduced into the approach when designing and developing future products using lower *TL* technologies.

APPENDIX A – A SUMMARY OF GE MS6001 UPRATING OPTIONS AND TECHNOLOGIES

MS6001 series gas turbines were first introduced by General Electric back in 1978 for both 50 Hz and 60 Hz markets. Over the time span of four decades, incremental performance gains have been pursued and realized thanks to constant advances in materials, coating, cooling, sealing, and design. Those improvements help "enhance performance, extend life, and provide economic benefits through increased reliability and maintainability of operating MS6001 turbines" [9]. As a result, there are observed trends of increasing in thermodynamic performance (higher power output and lower heat rate) and operational performance (reliability, availability, and emission). The evolution of thermodynamic performance for this product series is tabulated in Table 49, clearly showing this trend during its first two-decade [9].

Table 49. Evolution of the MS 6001 Gas Turbine (1978 – 2000) [9]

Model	Ship Dates	Firing Temperature (°F)	Output (MW)	Heat Rate (BTU/kW-hr)	Exhaust Flow (10^3 lb/hr)	Exhaust Temperature (°F)
MS6431A	1978	1850	31.05	11,220	1,077	891
MS6441A	1979	1850	31.8	11,250	1,112	901
MS6521B	1981	2020	36.73	11,120	1,117	1017
PG6531B	1983	2020	37.3	10,870	1,115	1005
PG6541B	1987	2020	38.14	10,900	1,117	999
PG6551B	1995	2020	39.12	10,740	1,137	1003
PG6561B	1997	2020	39.62	10,740	1,145	989
PG6571B	1997	2077	40.59	10,600	1,160	1005
PG6581B	2000	2084	41.46	10,724	1,166	1016

The most recent model of MS6001 series gas turbines in production and their specifications are tabulated in Table 50 below. It is evident that they have more enticing performance metrics compared to their predecessors earlier thanks to continuous technology advancement and specifically, integration of F technology class.

Table 50. Latest MS6001 Series Production Line [106]

Model*	Output (MW)	Heat Rate (BTU/kW-hr)	Exhaust Flow (10^3 lb/hr)	Exhaust Temperature (°F)
6B.03	44	10,740	1,152	548
6F.01	52	9,369	1,001	603
6F.03	82	9,991	1,692	613

*GE adopted a different model designation scheme in the first decade of 21st century

For MS6001 series uprates, there is a list of developed technologies that are compatible with the designated platforms and their impacts typically are grouped under the following categories [9]:

1. Increase air flow
2. Increase firing temperature
3. Performance output and heat rate improvements
4. Increase turbine speed
5. Reduce parasitic leakage and cooling flows
6. Extend inspection intervals
7. Improve availability and reliability
8. Parts life extension
9. Reduce emissions

In this research, a subset of representative technologies plus one featured uprate package are selected for a calibrated gas turbine model. Technologies behind those uprating option are analyzed for their impacts on the system. 18 uprating options are summarized along with its impact on the baseline model. The uprating options and their individual impact on power output, heat rate, and exhaust energy of multiple existing products have been tabulated in GE's published literature [9]. Table 51 reproduces the percentage performance change as a result of deploying each available option.

Uprating Option 1: GTD-450 High Flow Reduced Camber Inlet Guide Vanes

Inlet guided vanes (IGVs) are located in front of the first stage of the compressor and they are used to direct the air onto the compressor at a desirable angle. With redesigned aerodynamics, this flatter and thinner unit provides more inlet flow while remains dimensionally interchangeable with the original one. Fabricated with precipitation hardened martensitic stainless steel GTD-450, this uprate option enhances the material performance in corrosion, crack, and fatigue resistance.

Uprating Option 2: 86° IGV Setting

GTD-450 material replaces AISI 403SS in IGV for higher tensile strength and superior corrosion resistance. The increase in IGV angle allows more air flow through the compressor and therefore yields a higher power output. However, this option also comes with a slight heat rate penalty due to compressor efficiency decrease.

Uprating Option 3: 5163 RPM Load Gear

This uprate option increases the shaft speed from 5104 rpm to 5163 rpm. For a ground-based gas turbine, a higher speed is always desired since it translates to higher air flow and hence more power output. However, this speed is limited by the physical size of the gas turbine since the tip speed of the buckets must be kept in subsonic regime to avoid any losses incurred by shock waves.

Uprating Option 4: High Pressure Packing Brush Seal

Brush seals are a pack of fine metallic wires (or bristles) held in a fame. They are designed to reduce the leakage of compressor discharge air between the stationary inner barrel and the compressor aft sub shaft into the turbine first-forward wheel-space. They are used in the newly developed gas turbine products as replacements or additions to labyrinth seals which have failed to maintain their desired sealing levels after a number of transient radial excursions. A tighter and consistent sealing level provided by this uprate option yields the capability to control bypass airflow to the minimum levels required for cooling the turbine first-forward wheel-space. As such, there is less chargeable cooling air required for the turbine hot section, which results in more chargeable air available to perform work in the cycle.

<u>Uprate Option 5: Stage 1 Shroud Abradable Coating Uprate</u>

The abradable coating used in turbine, which is a 47-mil layer made of GT-50 material, is applicable to the inner circumference of the stage 1 shroud blocks. This coating is designed to wear away without removing any bucket tip material under conditions such as rotor misalignment and casing out of roundness. This yields a consistently tighter clearance between the bucket and shroud, which is translated to less bucket tip leakage and hence an improvement in turbine section efficiency.

<u>Uprate Option 6: Stage 1 Shroud with Cloth Seals</u>

The improved stage 1 shroud in turbine brings in improvement to its predecessor in both material and design. Compared to 310SS, the new material HR-120 is a solid solution strengthened alloy that features improved low cycle fatigue life and allows operation at higher 2084°F firing temperature. The new shroud design focuses on reducing leakage between shroud segments as well as between the stage 1 shrouds and stage 1 nozzle. This is achieved by using a new spline seals to replace the original pumpkin teeth design. The turbine performance upticks as a result of a drop in the amount leakage of compressor discharge air into the hot gas path.

<u>Uprate Option 7: Stage 2 Nozzle Inter-stage Brush Seal</u>

Similar to the previous option, the inter-stage brush seal is introduced as an enhancement to the radial high-low labyrinth seal included in the current 2^{nd} stage nozzle/diaphragm assembly. The labyrinth seal, when combined with the new unit, would further reduce the flow leakage between the diaphragm and the turbine rotor in the stage 2 forward wheel-space area. According to GE's testing result, the sealing efficiency of the new combination is found to be 10 times that of a labyrinth seal under similar condition. The reduction in cooling airflow losses allows more air to flow through the combustion system, thereby improving overall gas turbine performance.

Uprating Option 8 and 9: Stage 2 and 3 Honeycomb Shroud Blocks Uprates

Modernization of the flow-through section by installing seals with a honeycomb surface is an effective way to reduce bucket tip leakage. With greater rub tolerance, this option renders relatively tighter clearances between Stage 2 and Stage 3 bucket-tips and casing shroud during steady-state operation. The reduction in tip leakage for both stages contributes to a higher overall system output and efficiency.

Uprate Option 10: Advanced Aero Stage 3 Bucket and Nozzle

The third stage of turbine section has been redesigned with advanced aerodynamic airfoil shapes. The new configuration of the stage 3 nozzle provides significant reduction in hub Mach number and improved angle of attack distribution exiting nozzle. The original IN-738 material has been replaced with GTD-741 for its outstanding strength at the high uprate temperature. The new bucket design features "cutter teeth" on the bucket tip shroud rails, which renders improved stage efficiency and local creep life. The bucket has a significantly thinner airfoil and a closed airfoil throat to reduce stage losses and improve efficiency.

Uprating Option 11: GTD-222+ Stage 2 Nozzle Uprate

FSX-414 material is replaced by more creep-resistant GTD-222+ in stage 2 nozzle of the turbine section. As the original nozzle is more susceptible to downstream deflection caused by hostile environment such as high gas loading and extreme metal temperature, frequent repairs must be conducted to restore creep-deflection induced nozzle axial position and unit clearance. The new nozzle is made of nickel-based superalloy and comes with an aluminide coating to resist high-temperature oxidation. In addition, the modification of internal core plug within the nozzle design makes the cooling more effective. As such, less amount cooling airflow is required, and the turbine yields an increase in output power.

Uprate Option 12: Firing Temperature Uprate to 2084°F Package

In 1978, the first generation of MS 6001 series, MS6431A, was rolled out with a firing temperature at 1850°F. Since then, every attempt to attain a higher firing temperature has been an uphill battle. The current uprate option is no exception. To increase the firing temperature to 2084°F, improvements are required throughout the entire flowpath, from compressor to turbine. As such, this is a package option which engages synergy of multiple uprate technologies. Two of those technologies have been introduced in the previous sections, i.e. Option 1 and Option 2. The remaining on the list are summarized in the following paragraphs. Note that they have to be applied jointly to achieve the expected higher firing temperature.

GTD-111DS perimeter cooled stage 1 bucket uses directionally solidified (DS) GTD-111 material with GT-33 IN coating and 16 cooling holes to replace the original stage 1 bucket material. Unlike IN-738, the oriented grain structure of DS GTD-111 material eliminates the transverse grain boundaries. This adds creep and rupture into bucket structure and extends the life of this part. GT-33 material takes place of previous GT-29 for the bucket coating, making the bucket less susceptible to cracking. The newly designed bucket has 16 cooling holes located around the "perimeter" of the bucket, of which 13 holes include "turbulators" on the internal surfaces of the cooling holes to increase the efficiency of heat transfer. In additional, a new airfoil profile is deployed for the bucket to achieve better aerodynamic efficiency.

Improved Cooling 6-hole stage 2 bucket is the latest development for the stage 2 bucket to be compatible with the operation at a higher firing temperature. The new bucket structure includes 6 repositioned radial cooling holes – four of which are turbulated to improve cooling of the bucket – leading to reduced bulk metal temperature. In addition, “cutter teeth” on each bucket tip shroud rails are deployed to ensure a better sealing and less tip leakage.

IN-738 Stage 3 Bucket replaces the original U-500 in material due to its superior hot corrosion resistance and outstanding strength at the high uprate temperature. “Cutter teeth” on the bucket tip shroud rails are added for better sealing purposes.

GTD-222(+) Stage 3 Nozzle, like the stage 2 nozzle, uses the GTD-222+ material to replace previous FSX-414 to eliminate the nozzle downstream creep deflection. The chord of the nozzle has been lengthened to reduce overall airfoil stress level within the unit. In addition, an internal airfoil rib is added to the body to provide additional stability and buckling strength. The combination of materials change and redesign work have made the nozzle more reliable compared to its predecessor.

Uprate Transition Piece with Cloth Seals deals with the connecting piece between the combustor and the turbine. Due to the hostile environment (high temperatures and stresses) in this passage, transition piece currently made of Hastelloy-X alloy is subject to substantial creep distortion, which results in aft seal disengagement, causing an undesirable change in gas temperature profile into the turbine. As an uprate option, transition piece fabricated with Nimonic 263 has been selected to replace the Hastelloy-X alloy as the new nickel-based material. The new alloy is precipitation-strengthened and features higher creep strength capability. In addition, cloth seals are designed to reduce the leakage between the transition piece and the first stage nozzle as well as wear rate to improve inspection intervals and part life.

TBC Coated Combustion Liner applies a thermal barrier coating to combustion liner to reduce the underlying base metal temperature, which enables operations at higher temperature environment. It also helps extend maintenance interval by alleviating cracking and thermal stresses.

Table 51. Changes in Gas Turbine Performance as a Result of Each Uprating Option [10]

		Output Change in % Baseline				Heat Rate Change in % Baseline				Exhaust Energy Change in %			
#	Option	PG6531B	PG6541B	PG6551B	PG6561B	PG6531B	PG6541B	PG6551B	PG6561B	PG6531B	PG6541B	PG6551B	PG6561B
1	GTD-450 reduced camber IGV (84°)	1.5				-0.3				0.9	0.9	0.9	0.9
2	86° IGV Setting	0.4	0.4			0.2	0.2			0.7	0.7	0.7	0.7
3	High Pressure Packing Brush Seal	0.75	0.75	0.75	0.75	-0.7	-0.7	-0.7	-0.7	0.2	0.2	0.2	0.2
4	Advanced Aero Stage 3 Bucket and Nozzle	1	1	1	1	-1	-1	-1	-1	-0.5	-0.5	-0.5	-0.5
5	5163 RPM Load Gear	1.1	1.1	1.1	0.5	-0.07	-0.07	-0.07		1	1	1	1
6	Stage 1 Shroud Abradable Coating	0.7	0.7	0.7	0.7	-0.5	-0.5	-0.5	-0.5				
7	Stage 1 Shroud with Cloth Seals	1.05	1.05	1.05	1.05	-0.45	-0.45	-0.45	-0.45	-0.3	-0.3	-0.3	-0.3
8	Stage 2 Nozzle Inter-stage Brush Seal	1	1	1	1	-0.5	-0.5	-0.5	-0.5	0.4	0.4	0.4	0.4
9	GTD-222(+) Stage 2 Nozzle	1	1			-0.4	-0.4			0.5	0.5	0.5	0.5
10	Stage 2 Honeycomb Shroud	0.35	0.35			-0.35	-0.35			-0.2	-0.2	-0.2	-0.2
11	Stage 3 Honeycomb Shroud	0.25	0.25			-0.25	-0.25			-0.2	-0.2	-0.2	-0.2
12	*Package: Increase Tfire to 2084°*	3.2	3.2	3.2	3.2	-0.2	-0.2	-0.2	-0.2	2.9	2.9	2.9	2.9
	All options above included	**12.3**	**10.8**	**8.8**	**8.2**	**-4.52**	**-4.22**	**-3.42**	**-3.35**	**5.4**	**5.4**	**5.4**	**5.4**

APPENDIX B – GENETIC ALGORITHM STEPS [70]

1. Create a random population

2. Calculate all finesses $\tilde{F}_i(X) = \bar{F}_i^{max}(X) - \bar{F}_i(X)$.

3. Get their sum $F_{sum} = \sum \tilde{F}_i\,(X)$.

4. Construct a roulette wheel, with each string occupying an area on the wheel in proportion to the ratio $\tilde{F}_i/F_{sum}$.

5. Use a random number 0-1 to pick pairs on the wheel as "mating pairs" that will reproduce.

6. Perform crossover. Use a weighted coin toss to pick the probability of cross-over.

7. If crossover is dictated, pick two integer numbers between 1 and string length (the length of the binary string) to establish the starting and ending crossover locations. Exchange values in the string between two parents.

8. Perform the mutation operation on the child. Use a weighted coin toss to pick the probability of mutation. If mutation is dictated, pick an integer number between 1 and string length to establish the mutation location. Exchange the 0 and 1 in the string

9. Repeat the process until convergence is achieved.

APPENDIX C – TECHNOLOGY CANDIDATE DATABASE

In this section, a technology candidate database prototype is established per ERD in Figure 33. The prototype engages 3 dummy GT products, 14 dummy technologies, 11 technology k-factors, and 2 design variables. SQLite Studio is used in this example to establish and support the database. This idea of technology database is easily scalable as most GT manufacturers deal with a substantial list of technology candidates. In addition to SQLite Studio, the database can also be created in other commercial or state-of-the-art platform such as cloud database. The first part of this example shows the process to retrieve information and create a simple technology-technology compatibility matrix (TCM) and product-based technology impact matrix (TIM) using queries conducted on the platform of SQLite Studio. The second part presents the procedure to use the created matrices in the first example to generate Design of Experiments (DoE) for purposes of subsequent design space exploration or surrogate modeling. MATLAB is used in the second part and the actual script is also included for reference. Other programming languages can also be used to achieve this goal, such as Python and JMP.

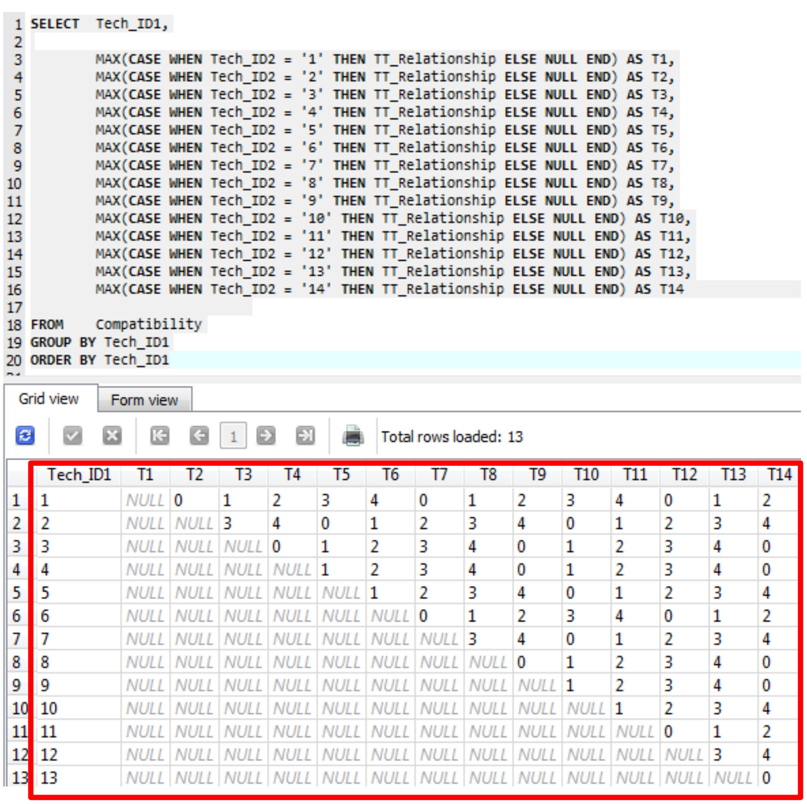
C.1 Technology Information Retrieval and Processing

For presentation purpose, technologies are simply assigned ID from 1 to 14 and k-factors (TechX) are assigned ID from 1 to 12 in this case. Once the organized information is tabulated into all 8 entities and inter-entity relations are established using primary and foreign keys as shown in Figure 33, the database prototype is in shape. The SQL script below is used to generate compatibility matrix using all 14 technologies:

```
SELECT Tech_ID1,
        MAX(CASE WHEN TECH_ID2 = '1' THEN TT_Relationship ELSE NULL END) AS T1,
        MAX(CASE WHEN TECH_ID2 = '2' THEN TT_Relationship ELSE NULL END) AS T2,
        MAX(CASE WHEN TECH_ID2 = '3' THEN TT_Relationship ELSE NULL END) AS T3,
        MAX(CASE WHEN TECH_ID2 = '4' THEN TT_Relationship ELSE NULL END) AS T4,
```

```
MAX(CASE WHEN TECH_ID2 = ‘5’ THEN TT_Relationship ELSE NULL END) AS T5,
MAX(CASE WHEN TECH_ID2 = ‘6’ THEN TT_Relationship ELSE NULL END) AS T6,
MAX(CASE WHEN TECH_ID2 = ‘7’ THEN TT_Relationship ELSE NULL END) AS T7,
MAX(CASE WHEN TECH_ID2 = ‘8’ THEN TT_Relationship ELSE NULL END) AS T8,
MAX(CASE WHEN TECH_ID2 = ‘9’ THEN TT_Relationship ELSE NULL END) AS T9,
MAX(CASE WHEN TECH_ID2 = ‘10’ THEN TT_Relationship ELSE NULL END) AS T10,
MAX(CASE WHEN TECH_ID2 = ‘11’ THEN TT_Relationship ELSE NULL END) AS T11,
MAX(CASE WHEN TECH_ID2 = ‘12’ THEN TT_Relationship ELSE NULL END) AS T12,
MAX(CASE WHEN TECH_ID2 = ‘13’ THEN TT_Relationship ELSE NULL END) AS T13,
MAX(CASE WHEN TECH_ID2 = ‘14’ THEN TT_Relationship ELSE NULL END) AS T14
FROM Compatibility
GROUP BY Tech_ID1
ORDER BY Tech_ID1
```

The script would return the result as shown in the red square box in Figure 60, Note that 0, 1,2,3, and 4 are five fictitious compatibility relations used in this example.



```
SELECT  Tech_ID1,

        MAX(CASE WHEN Tech_ID2 = '1' THEN TT_Relationship ELSE NULL END) AS T1,
        MAX(CASE WHEN Tech_ID2 = '2' THEN TT_Relationship ELSE NULL END) AS T2,
        MAX(CASE WHEN Tech_ID2 = '3' THEN TT_Relationship ELSE NULL END) AS T3,
        MAX(CASE WHEN Tech_ID2 = '4' THEN TT_Relationship ELSE NULL END) AS T4,
        MAX(CASE WHEN Tech_ID2 = '5' THEN TT_Relationship ELSE NULL END) AS T5,
        MAX(CASE WHEN Tech_ID2 = '6' THEN TT_Relationship ELSE NULL END) AS T6,
        MAX(CASE WHEN Tech_ID2 = '7' THEN TT_Relationship ELSE NULL END) AS T7,
        MAX(CASE WHEN Tech_ID2 = '8' THEN TT_Relationship ELSE NULL END) AS T8,
        MAX(CASE WHEN Tech_ID2 = '9' THEN TT_Relationship ELSE NULL END) AS T9,
        MAX(CASE WHEN Tech_ID2 = '10' THEN TT_Relationship ELSE NULL END) AS T10,
        MAX(CASE WHEN Tech_ID2 = '11' THEN TT_Relationship ELSE NULL END) AS T11,
        MAX(CASE WHEN Tech_ID2 = '12' THEN TT_Relationship ELSE NULL END) AS T12,
        MAX(CASE WHEN Tech_ID2 = '13' THEN TT_Relationship ELSE NULL END) AS T13,
        MAX(CASE WHEN Tech_ID2 = '14' THEN TT_Relationship ELSE NULL END) AS T14

FROM    Compatibility
GROUP BY Tech_ID1
ORDER BY Tech_ID1
```

Grid view | Form view

Total rows loaded: 13

	Tech_ID1	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
1	1	NULL	0	1	2	3	4	0	1	2	3	4	0	1	2
2	2	NULL	NULL	3	4	0	1	2	3	4	0	1	2	3	4
3	3	NULL	NULL	NULL	0	1	2	3	4	0	1	2	3	4	0
4	4	NULL	NULL	NULL	NULL	1	2	3	4	0	1	2	3	4	0
5	5	NULL	NULL	NULL	NULL	NULL	1	2	3	4	0	1	2	3	4
6	6	NULL	NULL	NULL	NULL	NULL	NULL	0	1	2	3	4	0	1	2
7	7	NULL	NULL	NULL	NULL	NULL	NULL	NULL	3	4	0	1	2	3	4
8	8	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	1	2	3	4	0
9	9	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	1	2	3	4	0
10	10	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	1	2	3	4
11	11	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	1	2
12	12	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	3	4
13	13	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0

Figure 60. Technology Compatibility Matrix Generated from Querying Database

The SQL script below is used to generate impact matrix for all 14 technologies:

```
SELECT TechX_ID,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '1', THEN DeltaLowerBound ELSE NULL END) AS T1,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '2', THEN DeltaLowerBound ELSE NULL END) AS T2,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '3', THEN DeltaLowerBound ELSE NULL END) AS T3,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '4', THEN DeltaLowerBound ELSE NULL END) AS T4,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '5', THEN DeltaLowerBound ELSE NULL END) AS T5,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '6', THEN DeltaLowerBound ELSE NULL END) AS T6,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '7', THEN DeltaLowerBound ELSE NULL END) AS T7,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '8', THEN DeltaLowerBound ELSE NULL END) AS T8,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '9', THEN DeltaLowerBound ELSE NULL END) AS T9,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '10', THEN DeltaLowerBound ELSE NULL END) AS T10,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '11', THEN DeltaLowerBound ELSE NULL END) AS T11,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '12', THEN DeltaLowerBound ELSE NULL END) AS T12,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '13', THEN DeltaLowerBound ELSE NULL END) AS T13,
        MAX(CASE WHEN Product_ID = '2'  AND Tech_ID = '14', THEN DeltaLowerBound ELSE NULL END) AS T14
FROM Compatibility
GROUP BY Tech_ID1
ORDER BY Tech_ID1
```

The script would return the result as shown in the red square box in Figure 61, which is descriptive of the relation between k-factor (showing lower bound) and each individual technology. In this case, the values of k-factor are fictitious and are used only for demonstration purpose.

```sql
SELECT  TechX_ID,

        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '1' THEN DeltaLowerBound ELSE NULL END) AS T1,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '2' THEN DeltaLowerBound ELSE NULL END) AS T2,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '3' THEN DeltaLowerBound ELSE NULL END) AS T3,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '4' THEN DeltaLowerBound ELSE NULL END) AS T4,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '5' THEN DeltaLowerBound ELSE NULL END) AS T5,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '6' THEN DeltaLowerBound ELSE NULL END) AS T6,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '7' THEN DeltaLowerBound ELSE NULL END) AS T7,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '8' THEN DeltaLowerBound ELSE NULL END) AS T8,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '9' THEN DeltaLowerBound ELSE NULL END) AS T9,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '10' THEN DeltaLowerBound ELSE NULL END) AS T10,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '11' THEN DeltaLowerBound ELSE NULL END) AS T11,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '12' THEN DeltaLowerBound ELSE NULL END) AS T12,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '13' THEN DeltaLowerBound ELSE NULL END) AS T13,
        MAX(CASE WHEN Platform_ID = "2" AND Tech_ID = '14' THEN DeltaLowerBound ELSE NULL END) AS T14

FROM    ApplicationValues
GROUP BY TechX_ID
ORDER BY TechX_ID
```

Grid view | Form view

Total rows loaded: 11

	TechX_ID	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
1	1	1.57	1.68	1.79	1.9	2.01	2.12	2.23	2.34	2.45	2.56	2.67	2.78	2.89	3
2	2	1.58	1.69	1.8	1.91	2.02	2.13	2.24	2.35	2.46	2.57	2.68	2.79	2.9	3.01
3	3	1.59	1.7	1.81	1.92	2.03	2.14	2.25	2.36	2.47	2.58	2.69	2.8	2.91	3.02
4	4	1.6	1.71	1.82	1.93	2.04	2.15	2.26	2.37	2.48	2.59	2.7	2.81	2.92	3.03
5	5	1.61	1.72	1.83	1.94	2.05	2.16	2.27	2.38	2.49	2.6	2.71	2.82	2.93	3.04
6	6	1.62	1.73	1.84	1.95	2.06	2.17	2.28	2.39	2.5	2.61	2.72	2.83	2.94	3.05
7	7	1.63	1.74	1.85	1.96	2.07	2.18	2.29	2.4	2.51	2.62	2.73	2.84	2.95	3.06
8	8	1.64	1.75	1.86	1.97	2.08	2.19	2.3	2.41	2.52	2.63	2.74	2.85	2.96	3.07
9	9	1.65	1.76	1.87	1.98	2.09	2.2	2.31	2.42	2.53	2.64	2.75	2.86	2.97	3.08
10	10	1.66	1.77	1.88	1.99	2.1	2.21	2.32	2.43	2.54	2.65	2.76	2.87	2.98	3.09
11	11	1.67	1.78	1.89	2	2.11	2.22	2.33	2.44	2.55	2.66	2.77	2.88	2.99	3.1

Figure 61. Technology Impact Matrix Generated from Querying Database

C.2 Design of Experiment Generation

It has been shown that a master TCM and a master TIM can be generated using SQL queries from a well-established technology database. A MATLAB script is coded to take in this information and generate DoE for design space exploration or surrogate modeling. A user needs follow several steps to generate a customized DoE for later use. This is completed in 5 steps:

1. Technology Information Setup: Technologies of interest, number of impacting factors, baseline values of impacting factors, name of TIM and TCM files generated from previous queries;
2. TIM Extraction: Range of TIM table extracted;
3. TCM Extraction: Range of TCM table extracted;
4. DoE Setup: Number of DoE Points and DoE Type (uniform or Latin Hyper Cube);
5. Technology k-factors' Ranges.

Once all the inputs are specified, the script is expected to use them to generate a customized DoE per user's request and the complete MATLAB script is as follows:

```
%% SQL DoE Generator %%
%% Haoyun Fu %%
%% Aerospace Systems Design Laboratory %%
%% Georgia Institute of Technology %%

%% This MATLAB file extracts technology information from two SQL
exported csv files (TCM and TIM) and transform it into a form TIES can
utilize (Tailored TIM and TCM). It calculates ranges of each impacting
factors and outputs DOE for simulation %%


clc
clear all
close all

%% User Specifications

% Step 1: Specify technology related parameters

TechNo = [1 2 4 5 6 7 9 10 11 12 13]; % Select a subset of technolgies
of interest
N_IntX = 11; % Number of intermediate variables (impacting factors)
Baseline = [0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0]; % Baseline value for
intermediate variables if available
filename1 = 'Master_TIM.csv'; % Name of csv file for TIM
filename2 = 'Master_TCM.csv'; % Name of csv file for TCM

% Stpe 2: Select and Import Technology Impact Matrix

xlRange1 = 'B1:O11'; % Range of table extracted
TIM_0 = xlsread(filename1,xlRange1);

% Step 3: Select and Import Technology Compatibility Matrix

xlRange2 = 'C1:O13'; % Range of table extracted
TC = xlsread(filename2,xlRange2);

% Step 4: Specify DoE related parameters

N_DoE = 100; % Number of DoE points to be generated
DoE_Type = 2; % 1. Uniform Space Filling 2. Latin Hyper Cube

% Step 5: Select whether to specify ranges of impacting factors

Range_Q = 1; % 1: Using TIM to determine ranges, 2: User specify ranges
in the next two rows
Range_Upper = []; % Upper bounds for all impacting factors in the order
shown in the imported table
```

```
Range_Lower = []; % Lower bounds for all impacting factors in the order
shown in the imported table

%% Tailored TIM Generation

N_T = size(TechNo,2);    % Number of technologies

TIM = zeros(N_IntX, N_T);

for i = 1:N_T
    TIM(:,i) = TIM_0(:,TechNo(i));
end

%% Tailored TCM Generation

% Complete the TCM

TCM_0 = zeros(size(TC,1)+1, size(TC,2)+1);

for i = 1:size(TC,1)
    for j = i:size(TC,2)
        TCM_0 (i,j+1) = TC(i,j);
    end
end

TCM_0 = TCM_0' + TCM_0;

for i = 1:size(TCM_0,1)
    for j= i+1:size(TCM_0,2)
        if TCM_0(i,j) == 3
            TCM_0(i,j) = 4;
        else if TCM_0 (i,j) == 4
                TCM_0(i,j) = 3;
            end
        end
    end
end

for i = 1:size(TCM_0,1)
    TCM_0 (i,i) = 1;
end

% Complete Tailored TCM

TCM = zeros(N_T, N_T);

for i = 1:N_T
    for j = i+1:N_T-1
        TCM(i,j) = TCM_0(TechNo(i),TechNo(j));
    end
end

TCM = TCM' + TCM;
```

```
for i = 1:size(TCM,1)
    for j= i+1:size(TCM,2)
        if TCM(i,j) == 3
            TCM(i,j) = 4;
        else if TCM(i,j) == 4
                TCM(i,j) = 3;
            end
        end
    end
end

for i = 1:size(TCM,1)
    TCM (i,i) = 1;
end


%% Range Calculator for Impact Factors (based on TIM and TCM)

if Range_Q == 1

    Range_Upper = zeros (1,N_IntX);
    Range_Lower = zeros (1,N_IntX);

% Option 1: User Specified (Already defined if this option is selected)

% Option 2: TIM Based

    for i = 1:N_IntX
        Max_IntX = max(TIM(i,:));
        Min_IntX = min(TIM(i,:));
        Sum_IntX_M = zeros(1,N_T);

        if Max_IntX * Min_IntX >= 0 && Max_IntX + Min_IntX >= 0
            Range_Lower(i) = Min_IntX;
            for j = 1:N_T
                Sum_IntX = 0;
                for k = j:N_T
                    if TCM(j,k) ~= 0
                        Sum_IntX = Sum_IntX + TIM(i,k);
                    end
                end
                Sum_IntX_M(j) = Sum_IntX;
            end
            Range_Upper(i) = max(Sum_IntX_M);
        end

        if Max_IntX * Min_IntX >= 0 && Max_IntX + Min_IntX < 0
            Range_Upper(i) = Max_IntX;
            for j = 1:N_T
                Sum_IntX = 0;
                for k = j:N_T
                    if TCM(j,k) ~= 0
                        Sum_IntX = Sum_IntX + TIM(i,k);
                    end
                end
```

```
                Sum_IntX_M(j) = Sum_IntX;
            end
            Range_Lower(i) = min(Sum_IntX_M);
        end

        if Max_IntX * Min_IntX < 0
            for j = 1:N_T
                Sum_IntX = 0;
                for k = j:N_T
                    if TCM(j,k) ~= 0 && TIM(i,j)*TIM(i,k)>0
                        Sum_IntX = Sum_IntX + TIM(i,k);
                    end
                end
                Sum_IntX_M(j) = Sum_IntX;
            end
            Range_Upper(i) = max(Sum_IntX_M);
            Range_Lower(i) = min(Sum_IntX_M);
        end
    end

end

%% DOE Generator

Diff_M = Range_Upper - Range_Lower;
Delta_M = zeros(N_DoE,N_IntX);
DoE_M = zeros(N_DoE,N_IntX);
BaselineM = [];

% Construct Baseline Matrix
for i = 1:N_DoE
BaselineM = [BaselineM; Baseline'];
end

% Option 1: Random Space Filling

if DoE_Type == 1
    Rand_M = rand(N_DoE,N_IntX);
    for i = 1:N_DoE
        Delta_M(i,:) = Range_Lower + Diff_M.*Rand_M(i,:);
        DoE_M(i,:) = Baseline' + Delta_M(i,:);
    end
end

% Option 2: Latin Hyper Cube

if DoE_Type == 2
    Rand_M = lhsdesign(N_DoE,N_IntX);
    for i = 1:N_DoE
        Delta_M(i,:) = Range_Lower + Diff_M.*Rand_M(i,:);
        DoE_M(i,:) = Baseline' + Delta_M(i,:);
    end
end
```

```
%% Export Design of Experiment

dlmwrite('DOE_Table.txt',DoE_M,'delimiter','\t','precision','%.3f');


%% End of Script
```

APPENDIX D – GROWTH-BASED TECHNOLOGY SELECTION

Table 52. Technology Compatibility Matrix for PG7241FA and PG7231FA

Tech	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
T1	1	1	1	1	1	1	0	0	1	1	1	1
T2	1	1	0	0	0	1	1	1	0	1	1	1
T3	1	0	1	1	1	1	1	1	1	1	1	1
T4	1	0	1	1	1	1	1	1	1	1	0	1
T5	1	0	1	1	1	1	1	1	1	1	1	1
T6	1	1	1	1	1	1	1	1	1	1	1	1
T7	0	1	1	1	1	1	1	1	1	1	1	1
T8	0	1	1	1	1	1	1	1	1	1	1	1
T9	1	0	1	1	1	1	1	1	1	0	0	1
T10	1	1	1	1	1	1	1	1	0	1	0	1
T11	1	1	1	0	1	1	1	1	0	0	1	1
T12	1	1	1	1	1	1	1	1	1	1	1	1

Table 53. Variable Used in Technology Impact Matrix

Variable Name	Variable Specification
Comp_delta_effPoly	Compressor Polytropic Efficiency Change
Comp_delta_FSPRmax	Compressor Fist Stage Pressure Ratio Change
Turb_delta_desVaneTemp	Turbine Designed Vane Temperature Change
Turb_delta_Stator_rho	Turbine Stator Material Density Change
Turb_delta_desBladeTemp	Turbine Designed Blade Temperature Change
Turb_delta_filmc_eff	Turbine Film Cooling Efficiency Change
Turb_delta_internalc_eff	Turbine Internal Colling Efficiency Change
Turb_delta_effPoly	Turbine Polytropic Efficiency Change
Cost_delta_RDT	RD&T Cost Change

Table 54. Technology Impact Matrix for PG7241FA

Technology	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	Unit	Baseline
Comp_delta_effPoly	0.03						0.02	0.04					NA	0.87
Comp_delta_FSPRmax	0.6						0.3	0.6					NA	1.367
Turb_delta_desVaneTemp		35	50	25					80	60	40		R	2100
Turb_delta_Stator_rho		-0.09	0.024										lb/in3	0.29 (GTD111)
Turb_delta_desBladeTemp		35	50	25					80	60	40		R	2100
Turb_delta_filmc_eff					0.1								NA	0.6
Turb_delta_internalc_eff					0.05								NA	0.7
Turb_delta_effPoly						0.02				0.01		0.03	NA	0.90
Cost_delta_RDT	20	10	20	5	20	15	15	30	20	30	20	25	M$	12.4
Impacted Component	Comp.	Turb.	Turb.	Turb.	Turb.	Turb.	Comp.	Comp.	Turb.	Turb.	Turb.	Turb.		

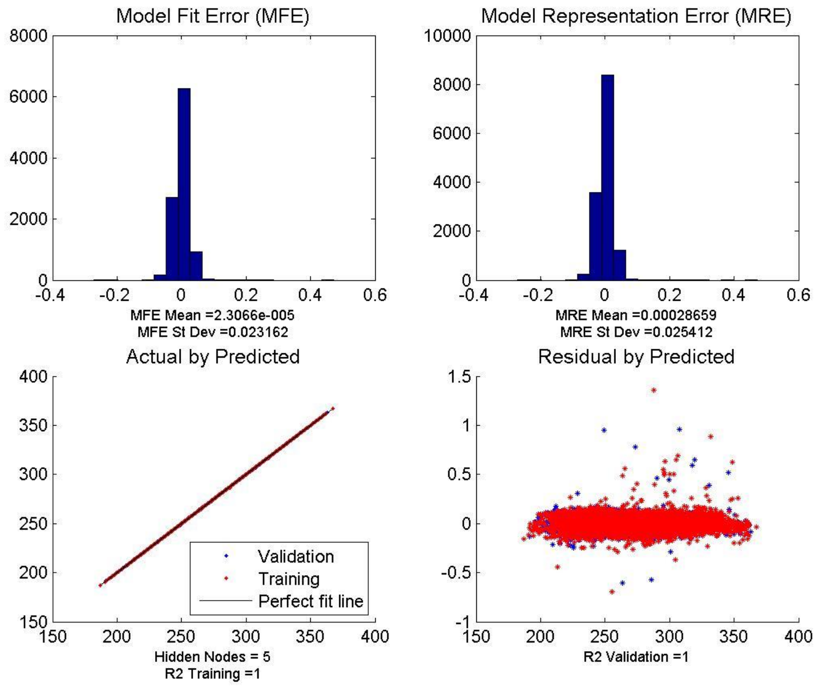


Figure 62. Neural Network Training Result for Power Output

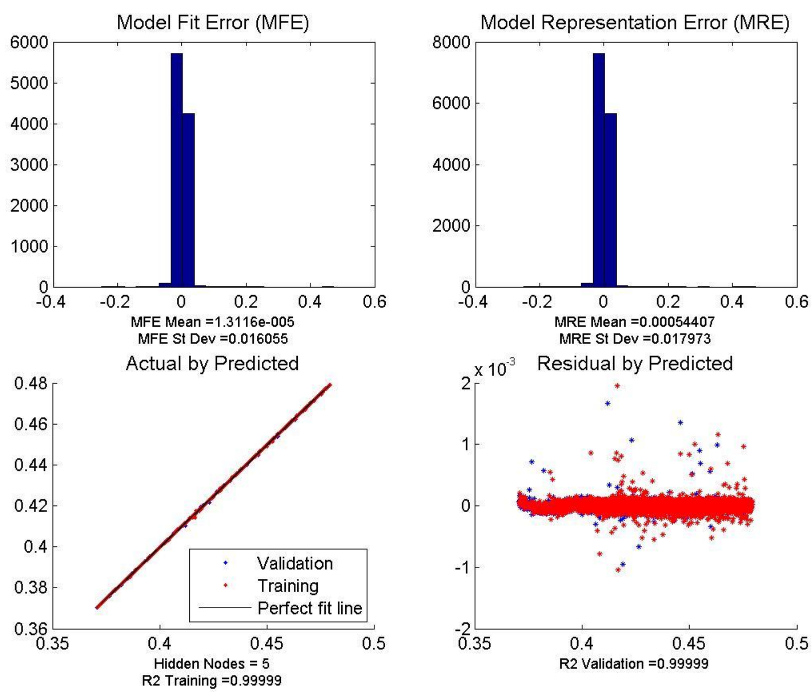


Figure 63. Neural Network Training Result for Cycle Efficiency

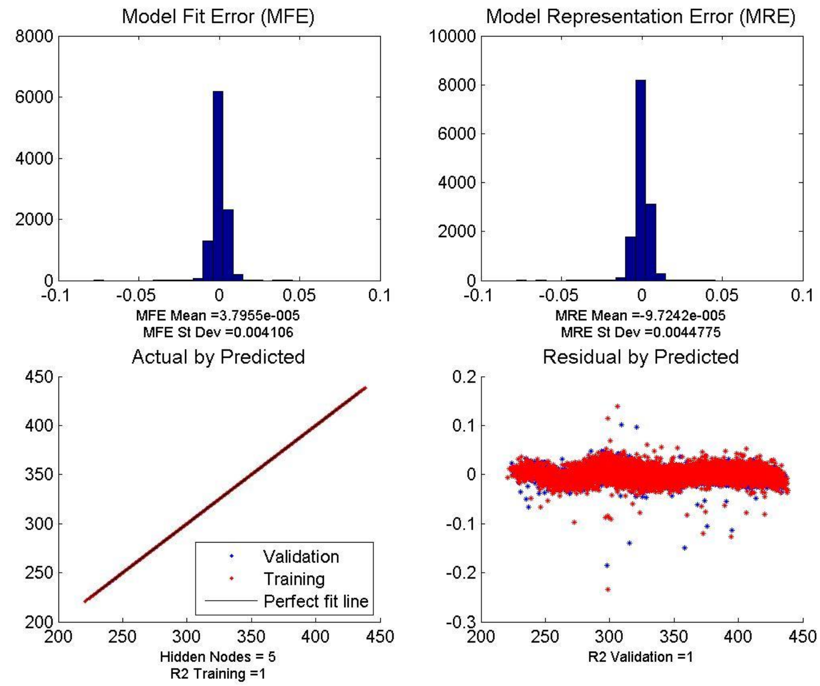


Figure 64. Neural Network Training Result for Sum of Acquisition Cost and Change of R&D Cost

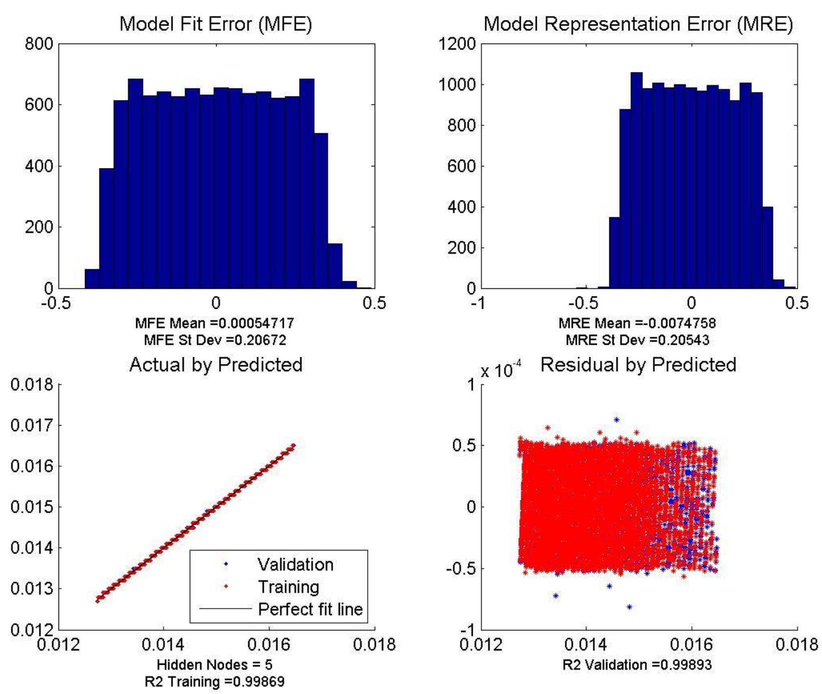


Figure 65. Neural Network Training Result for Sum of Fuel Cost and Operation/Maintenance Cost

Table 55. Technology Impact Matrix for PG7231FA

Technology	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	Unit	Baseline
Comp_delta_effPoly	0.03						0.02	0.04					NA	0.87
Comp_delta_FSPRmax	0.8						0.3	0.6					NA	1.367
Turb_delta_desVaneTemp		45	50	25					100	60	40		R	2100
Turb_delta_Stator_rho		-0.09	0.024										lb/in3	0.29 (GTD111)
Turb_delta_desBladeTemp		45	50	25					100	60	40		R	2100
Turb_delta_filmc_eff					0.1								NA	0.6
Turb_delta_internalc_eff					0.05								NA	0.7
Turb_delta_effPoly						0.02				0.02	0.05	0.03	NA	0.90
Cost_delta_RDT	20	10	20	5	20	15	15	30	20	30	20	25	M$	12.4
Impacted Component	Comp.	Turb.	Turb.	Turb.	Turb.	Turb.	Comp.	Comp.	Turb.	Turb.	Turb.	Turb.		

Genetic algorithm used for optimization

"GA_7FA.m" written in MATLAB

```
clear all
close all
clc
%% Initial Setup

%Dimension for decimal variables
Dim=3;
%Resolusion for decimal variables
R=10;
%X Uppeer Limit for decimal variables
Xup=[15.5 2420 900];
%X Lower Limit for decimal variables
Xlow=[15.5 2420 900];
%Range of X
r=Xup-Xlow;
%Range Division for decimal variables
d=2^R-1;

%Number of technologies
NT=12;
%Technology impact matrix for PG7241FA
% TIM=[
%     0.03,0,0,0,0,0,0.02,0.04,0,0,0,0;
%     0.6,0,0,0,0,0,0.3,0.6,0,0,0,0;
%     0,35,50,25,0,0,0,0,80,60,40,0;
%     0,-0.09,0.024,0,0,0,0,0,0,0,0,0;
%     0,35,50,25,0,0,0,0,80,60,40,0;
%     0,0,0,0,0.1,0,0,0,0,0,0,0;
%     0,0,0,0,0.05,0,0,0,0,0,0,0;
%     0,0,0,0,0,0.02,0,0,0,0.01,0,0.03;
%     20,10,20,5,20,15,15,30,20,30,20,25
%     ];

%Technology impact matrix for PG7231FA
TIM=[
    0.03,0,0,0,0,0,0.02,0.04,0,0,0,0;
    0.8,0,0,0,0,0,0.3,0.6,0,0,0,0;
    0,45,50,25,0,0,0,0,100,60,40,0;
    0,-0.09,0.024,0,0,0,0,0,0,0,0,0;
    0,45,50,25,0,0,0,0,100,60,40,0;
    0,0,0,0,0.1,0,0,0,0,0,0,0;
    0,0,0,0,0.05,0,0,0,0,0,0,0;
    0,0,0,0,0,0.02,0,0,0,0.02,0.05,0.03;
    20,10,20,5,20,15,15,30,20,30,20,25
    ];

Compatibility_Index = 1;

TCM =[
        1,1,1,1,1,1,0,0,1,1,1,1;
        1,1,0,0,0,1,1,1,0,1,1,1;
```

```
        1,0,1,1,1,1,1,1,1,1,1,1;
        1,0,1,1,1,1,1,1,1,1,0,1;
        1,0,1,1,1,1,1,1,1,1,1,1;
        1,1,1,1,1,1,1,1,1,1,1,1;
        0,1,1,1,1,1,1,1,1,1,1,1;
        0,1,1,1,1,1,1,1,1,1,1,1;
        1,0,1,1,1,1,1,1,1,0,0,1;
        1,1,1,1,1,1,1,1,0,1,0,1;
        1,1,1,0,1,1,1,1,0,0,1,1;
        1,1,1,1,1,1,1,1,1,1,1,1
        ];


%Total String Length
L=Dim*R+NT;
%Population Size
n=3*L; % n is even
%Iteration Number
I_num=0;
I_num_max=100;
Z_elite_Mixed=[];

%% Initialize the population

% Decimal Variables
X1=round(rand(n,R));
Y1=zeros(n,1);
for i=1:n
    Y1(i,1)=0;
    for j=1:R
        Y1(i,1)=Y1(i,1)+X1(i,R-j+1)*2^(j-1);
    end
    Z1(i,1)=r(1)/d*Y1(i,1)+Xlow(1);
end

X2=round(rand(n,R));
Y2=[];
for i=1:n
    Y2(i,1)=0;
    for j=1:R
        Y2(i,1)=Y2(i,1)+X2(i,R-j+1)*2^(j-1);
    end
    Z2(i,1)=r(2)/d*Y2(i,1)+Xlow(2);
end

X3=round(rand(n,R));
Y3=[];
for i=1:n
    Y3(i,1)=0;
    for j=1:R
        Y3(i,1)=Y3(i,1)+X3(i,R-j+1)*2^(j-1);
    end
    Z3(i,1)=r(3)/d*Y3(i,1)+Xlow(3);
end
```

```
% Binary Variables

X_T=round(rand(n,NT));

% Convert to Intermediate Variables for Transfer Function Evaluation
Z_T=X_T*TIM';

Z4=Z_T(:,1);
Z5=Z_T(:,2);
Z6=Z_T(:,3);
Z7=Z_T(:,4);
Z8=Z_T(:,5);
Z9=Z_T(:,6);
Z10=Z_T(:,7);
Z11=Z_T(:,8);
Z12=Z_T(:,9);


%% Algorithm Starts

elite=0;
OEC_M=[];
GT_Per_M=[];

% Weighting factor each objective
W_eta=0.4;
W_MW=0.1;
W_AC=0.1;
W_OMC=1-W_eta-W_MW-W_AC;

%Calculate fitness for each indivitual

 while (elite<=5)

eta=[];
MW=[];
AC=[];
OMC=[];
OEC=[];


% Baseline value for PG7141FA
% eta_BL=0.4209;
% MW_BL=180.3653;
% AC_BL=264.8302;
% OMC_BL=0.0159;

% Baseline value for PG7131FA
eta_BL=0.4207;
MW_BL=167.3825;
AC_BL=266.7857;
OMC_BL=0.0159;

for k=1:n
```

```
    %ZM=[Z1(k) Z2(k) Z3(k) Z4(k) Z5(k) Z6(k) Z7(k) Z8(k) Z9(k) Z10(k)
Z11(k) Z12(k)];

    % Neural network models are created for all 4 obejctives

    eta=[eta 0.3464261346090 +  0.1259956252387 * 1/(1+exp(-
1*( 6.1861395873430 + -0.0848481678275 * Z1(k)+ -0.0004561621843 *
Z2(k)+  0.0000226942161 * Z3(k)+  7.6486602905038 * Z4(k)+ -
1.0903538566400 * Z5(k)+ -0.0002485303366 * Z6(k)+  7.2311487161738 *
Z7(k)+  0.0002012055653 * Z8(k)+ -10.8324721197274 * Z9(k)+ -
1.9765925315860 * Z10(k)+ -15.7032814059370 * Z11(k)+  0.0005925434657
* Z12(k)))) + -0.3411588823170 * 1/(1+exp(-1*( 1.2642282046972 +
0.0257150315096 * Z1(k)+  0.0000155794807 * Z2(k)+  0.0000094846265 *
Z3(k)+  7.7728387086125 * Z4(k)+ -0.5391746100074 * Z5(k)+
0.0011009790998 * Z6(k)+ -7.8950524673882 * Z7(k)+ -0.0007978486560 *
Z8(k)+ -7.6020846773839 * Z9(k)+ -26.6497375488845 * Z10(k)+ -
5.5851657224066 * Z11(k)+  0.0041620051276 * Z12(k)))) + -
0.0001677327232 * 1/(1+exp(-1*( 8.7035829004984 +  0.1233705045419 *
Z1(k)+ -0.0032941169267 * Z2(k)+ -0.0029493585470 * Z3(k)+
3.8668132714144 * Z4(k)+  0.1638129007731 * Z5(k)+ -0.0008182911614 *
Z6(k)+  0.7013697626381 * Z7(k)+ -0.0012175809463 * Z8(k)+ -
11.2757397956194 * Z9(k)+ -3.2624371338755 * Z10(k)+  9.0164297052073 *
Z11(k)+ -0.0031632554370 * Z12(k)))) +  0.0791450688704 * 1/(1+exp(-
1*( 3.6487509121363 +  0.0684146317499 * Z1(k)+ -0.0011379381011 *
Z2(k)+ -0.0000020205447 * Z3(k)+ -5.3090561800166 * Z4(k)+
0.1349631709982 * Z5(k)+  0.0000860270700 * Z6(k)+  8.3168617463388 *
Z7(k)+ -0.0005321979961 * Z8(k)+ 12.4552373856113 * Z9(k)+
20.3479996585880 * Z10(k)+ 24.4433455973081 * Z11(k)+ -0.0023745778819
* Z12(k)))) +  0.1814179234607 * 1/(1+exp(-1*(-1.7889218673385 +
0.0990917781723 * Z1(k)+  0.0012525150526 * Z2(k)+  0.0000104351993 *
Z3(k)+ -7.0332872740045 * Z4(k)+  0.7022040764554 * Z5(k)+ -
0.0009421832246 * Z6(k)+  8.8837221048368 * Z7(k)+  0.0010424246832 *
Z8(k)+ -1.8646287368362 * Z9(k)+ -20.9959872479349 * Z10(k)+
17.6973268103580 * Z11(k)+ -0.0029573350436 * Z12(k))))];

    MW=[MW 69.7494585606720 + 272.7163465819585 * 1/(1+exp(-1*(-
3.8869380819586 + -0.0010547703643 * Z1(k)+  0.0014790803563 * Z2(k)+
0.0009500503915 * Z3(k) + -0.0842690254961 * Z4(k) + -0.0044926346097 *
Z5(k) + -0.0000068294510 * Z6(k) + -0.0617137815607 * Z7(k) + -
0.0000068765687 * Z8(k) + -0.0676328718191 * Z9(k) + -0.1349272613989 *
Z10(k) + -0.1281602512444 * Z11(k) + -0.0000355790933 * Z12(k)))) +
692.1706814938842 * 1/(1+exp(-1*(-6.7625456422727 +  0.0049076915207 *
Z1(k)+  0.0013075008892 * Z2(k)+  0.0014551481120 * Z3(k) +
0.3815408723683 * Z4(k) +  0.0230864974361 * Z5(k) +  0.0000331032531 *
Z6(k) +  0.3053627274578 * Z7(k) +  0.0000329890502 * Z8(k) +
0.3395621039776 * Z9(k) +  0.7025617902310 * Z10(k) +  0.5690776737300
* Z11(k) +  0.0001547018851 * Z12(k)))) + 32.9461533773161 * 1/(1+exp(-
1*( 9.2825966853698 +  0.0846619704826 * Z1(k)+ -0.0028385855539 *
Z2(k)+ -0.0017017176491 * Z3(k) +  6.5898330222836 * Z4(k) +
0.3948281549947 * Z5(k) +  0.0005648517067 * Z6(k) +  5.1941864293962 *
Z7(k) +  0.0005639710842 * Z8(k) +  5.9256773663553 * Z9(k) +
11.8487497639059 * Z10(k) +  9.8790368709049 * Z11(k) +
0.0026910593586 * Z12(k)))) + -303.1840579008305 * 1/(1+exp(-1*(-
2.8247524548311 +  0.0050445460149 * Z1(k)+  0.0012434431197 * Z2(k)+ -
0.0020115443689 * Z3(k) +  0.3831915288637 * Z4(k) +  0.0232636291033 *
```

```
Z5(k) +  0.0000336153421 * Z6(k) +  0.3024821026519 * Z7(k) +
0.0000332651126 * Z8(k) +  0.3453421176047 * Z9(k) +  0.7044518577004 *
Z10(k) +  0.5885151580782 * Z11(k) +  0.0001566568556 * Z12(k)))) + -
157.4105924975287 * 1/(1+exp(-1*( 1.0144404632527 + -0.0151792560704 *
Z1(k)+ -0.0003475059329 * Z2(k)+  0.0008678176324 * Z3(k) + -
1.1773713867105 * Z4(k) + -0.0712455780835 * Z5(k) + -0.0001008844360 *
Z6(k) + -0.9340876917020 * Z7(k) + -0.0001013856214 * Z8(k) + -
1.0631761387292 * Z9(k) + -2.1309658413063 * Z10(k) + -1.7635793642434
* Z11(k) + -0.0004806991612 * Z12(k))))];

    AC=[AC 272.5386608707586 + 487.5530401582189 * 1/(1+exp(-1*(-
2.5551993584550 +  0.0151516276957 * Z1(k)+  0.0002153625558 * Z2(k)+ -
0.0000395585842 * Z3(k) +  1.1784486150267 * Z4(k) +  0.0707063311352 *
Z5(k) +  0.0001010096441 * Z6(k) +  0.9303707548445 * Z7(k) +
0.0001010116365 * Z8(k) +  1.0606085027820 * Z9(k) +  2.1211983459326 *
Z10(k) +  1.7676749633299 * Z11(k) +  0.0004821019648 * Z12(k)))) + -
272.2495747327707 * 1/(1+exp(-1*( 1.3304398756818 +  0.0031856862406 *
Z1(k)+ -0.0005211581229 * Z2(k)+ -0.0000809159324 * Z3(k) +
0.2477753696068 * Z4(k) +  0.0148668130017 * Z5(k) +  0.0000212384480 *
Z6(k) +  0.1956064481614 * Z7(k) +  0.0000212385533 * Z8(k) +
0.2230045226628 * Z9(k) +  0.4459597833745 * Z10(k) +  0.3716457701418
* Z11(k) +  0.0001013597919 * Z12(k)))) + 294.3644194151447 *
1/(1+exp(-1*( 0.6297403905368 +  0.0220635567708 * Z1(k)+ -
0.0002027661667 * Z2(k)+  0.0000766524044 * Z3(k) +  1.7160747817948 *
Z4(k) +  0.1029636128841 * Z5(k) +  0.0001470919774 * Z6(k) +
1.3548012205007 * Z7(k) +  0.0001470918754 * Z8(k) +  1.5444579163894 *
Z9(k) +  3.0888939761828 * Z10(k) +  2.5740976018494 * Z11(k) +
0.0007020300599 * Z12(k)))) + -296.0713475855246 * 1/(1+exp(-1*(-
0.2713786237185 +  0.0029487820067 * Z1(k)+  0.0001576814431 * Z2(k)+
0.0014655194908 * Z3(k) +  0.2293439447234 * Z4(k) +  0.0137591245001 *
Z5(k) +  0.0000196579534 * Z6(k) +  0.1810578184062 * Z7(k) +
0.0000196590070 * Z8(k) +  0.2064045491814 * Z9(k) +  0.4128195621716 *
Z10(k) +  0.3439934279969 * Z11(k) +  0.0000938126294 * Z12(k)))) +
435.7361556848939 * 1/(1+exp(-1*( 0.6083959332603 +  0.0101188709991 *
Z1(k)+ -0.0007183011933 * Z2(k)+ -0.0000105991382 * Z3(k) +
0.7870129019399 * Z4(k) +  0.0472222077091 * Z5(k) +  0.0000674594256 *
Z6(k) +  0.6213207422680 * Z7(k) +  0.0000674577086 * Z8(k) +
0.7083109894262 * Z9(k) +  1.4166338226170 * Z10(k) +  1.1805021464137
* Z11(k) +  0.0003219639575 * Z12(k))))];

    OMC=[OMC 0.0152930579634 +  0.0024133285345 * 1/(1+exp(-1*(-
1.8544529899460 + -0.0158548139599 * Z1(k)+  0.0006469272031 * Z2(k)+
0.0009868755654 * Z3(k) + -1.2162334500764 * Z4(k) + -0.0745045294698 *
Z5(k) + -0.0001049483910 * Z6(k) + -0.9861250372679 * Z7(k) + -
0.0001058509678 * Z8(k) + -1.0717599892608 * Z9(k) + -2.2547725058652 *
Z10(k) + -1.8577653833542 * Z11(k) + -0.0005116189154 * Z12(k)))) + -
0.0013067344261 * 1/(1+exp(-1*( 0.5602914672137 +  0.0012174886584 *
Z1(k)+ -0.0008724648564 * Z2(k)+  0.0015708089359 * Z3(k) +
0.0526250809067 * Z4(k) +  0.0053548087215 * Z5(k) +  0.0000053054187 *
Z6(k) +  0.0674942592936 * Z7(k) +  0.0000037066209 * Z8(k) +
0.0861951136418 * Z9(k) +  0.1605933570091 * Z10(k) +  0.1404371551716
* Z11(k) +  0.0000400839051 * Z12(k)))) +  0.0023917308927 * 1/(1+exp(-
1*( 4.5887470532260 + -0.0236070456070 * Z1(k)+ -0.0021227108418 *
Z2(k)+ -0.0000175955707 * Z3(k) + -1.8003163221992 * Z4(k) + -
0.1106031964404 * Z5(k) + -0.0001551471346 * Z6(k) + -1.4556038077592 *
Z7(k) + -0.0001580549049 * Z8(k) + -1.6149148961954 * Z9(k) + -
```

```
3.3094803001485 * Z10(k) + -2.7283960558702 * Z11(k) + -0.0007310283665
* Z12(k)))) + -0.0042489283133 * 1/(1+exp(-1*(-1.6926315809914 +
0.0260573655312 * Z1(k)+  0.0001970793098 * Z2(k)+  0.0000709639233 *
Z3(k) +  2.0509685050238 * Z4(k) +  0.1242887964021 * Z5(k) +
0.0001770457480 * Z6(k) +  1.6238501076449 * Z7(k) +  0.0001786615318 *
Z8(k) +  1.8310461510189 * Z9(k) +  3.7410780965490 * Z10(k) +
3.0424885333942 * Z11(k) +  0.0008365070620 * Z12(k)))) +
0.0029800276730 * 1/(1+exp(-1*(-2.1744199500949 + -0.0718640072718 *
Z1(k)+  0.0006263507545 * Z2(k)+  0.0001049129594 * Z3(k) + -
5.5716572347016 * Z4(k) + -0.3316625785053 * Z5(k) + -0.0004747490882 *
Z6(k) + -4.3915229137136 * Z7(k) + -0.0004753626889 * Z8(k) + -
4.9931671760395 * Z9(k) + -10.0678258114312 * Z10(k) + -8.3303019023227
* Z11(k) + -0.0022871482230 * Z12(k))))];

    % Overall Evaluation Criteria collased 4 objectives into one single
objective based on assigned weightings

    OEC=[OEC
eta(k)];%(W_eta*eta(k)/eta_BL+W_MW*MW(k)/MW_BL)/(W_AC*AC(k)/AC_BL+W_OMC
*OMC(k)/OMC_BL)];

end

% Penalize the infeasible tech set

if Compatibility_Index == 1

    TIncSM = [];
    TIncS =[];

    for Ti = 1:NT-1
        for Tj = Ti+1:NT
          TIncS = X_T(:,Ti)+X_T(:,Tj);
          TIncSM = [X_T(:,Ti) X_T(:,Tj)];
          if TCM(Ti,Tj) == 0
              for TC = 1:n
                  if TIncS(TC) == 2
                      OEC(TC) = 0.001;
                  end
              end
           end
        end
    end

end


[C,I]=max(OEC);

OEC_M=[OEC_M; max(OEC)];

if (elite>=1) && Z_elite(1)-Z1(I)+Z_elite(2)-Z2(I)+Z_elite(3)-
Z3(I)+Z_elite(4)-Z4(I)+Z_elite(5)-Z5(I)+Z_elite(6)-Z6(I)+Z_elite(7)-
Z7(I)+Z_elite(8)-Z8(I)...
```

```
        +Z_elite(9)-Z9(I)+Z_elite(10)-Z10(I)+Z_elite(11)-
Z12(I)+Z_elite(12)-Z12(I) == 0
    elite=elite+1;
else elite=0;
end

if elite==0

Z_elite=[Z1(I);Z2(I);Z3(I);Z4(I);Z5(I);Z6(I);Z7(I);Z8(I);Z9(I);Z10(I);Z
11(I);Z12(I)];
end

X_T_elite=X_T(I,:);

Sum=sum(OEC);

OEC_n=OEC./Sum;

Cum_OEC=OEC_n(1);

for l=2:n
    Cum_OEC=[Cum_OEC sum(OEC_n(1:l))];
end

%Reproduce selected individuals to form a new population using roulette

A=rand(n,1);
B=[];
C2=[];
for m1=1:n
    for m2=1:n-1
    if A(m1)<=Cum_OEC(1)
        B=[Y1(1);Y2(1);Y3(1);X_T(1,:)'];
    else if A(m1)>Cum_OEC(m2) && A(m1)<=Cum_OEC(m2+1)
            B=[Y1(m2+1);Y2(m2+1);Y3(m2+1);X_T(m2+1,:)'];
        end
    end
    end
    if m1==1
        C2=B;
    else
        C2=[C2 B];
    end
end

C_bi1=[dec2bin(C2(1,:),R)];
C_bi2=[dec2bin(C2(2,:),R)];
C_bi3=[dec2bin(C2(3,:),R)];
C_Tech=C2(4:end,:)';


%Perform cross over for design variables
Pcrx=0.7;
%p=1;
C_bi11=C_bi1;
```

```
C_bi21=C_bi2;
C_bi31=C_bi3;
C_Tech1=C_Tech;

 for p=1:2:n-1
    rd=rand(1);
    if rd>=Pcrx
    crx=floor((R+1)*rand(1,2));

    if crx(2)>crx(1)
        C_int=C_bi1(p,crx(1)+1:crx(2));
        C_bi11(p,crx(1)+1:crx(2))=C_bi1(p+1,crx(1)+1:crx(2));
        C_bi11(p+1,crx(1)+1:crx(2))=C_int;

    else if crx(2)<crx(1)
            C_int1=C_bi1(p,:);
            C_bi1(p,:)=C_bi1(p+1,:);
            C_bi1(p+1,:)=C_int1;
            C_int2=C_bi1(p,crx(2)+1:crx(1));
            C_bi11(p,crx(2)+1:crx(1))=C_bi1(p+1,crx(2)+1:crx(1));
            C_bi11(p+1,crx(2)+1:crx(1))=C_int2;

        end
    end
    else
        C_bi11(p,:)=C_bi1(p,:);

    end
 end

 for p=1:2:n-1
    rd=rand(1);
    if rd>=Pcrx
    crx=floor((R+1)*rand(1,2));

    if crx(2)>crx(1)
        C_int=C_bi2(p,crx(1)+1:crx(2));
        C_bi21(p,crx(1)+1:crx(2))=C_bi2(p+1,crx(1)+1:crx(2));
        C_bi21(p+1,crx(1)+1:crx(2))=C_int;

    else if crx(2)<crx(1)
            C_int1=C_bi2(p,:);
            C_bi2(p,:)=C_bi2(p+1,:);
            C_bi2(p+1,:)=C_int1;
            C_int2=C_bi2(p,crx(2)+1:crx(1));
            C_bi21(p,crx(2)+1:crx(1))=C_bi2(p+1,crx(2)+1:crx(1));
            C_bi21(p+1,crx(2)+1:crx(1))=C_int2;

        end
    end
    else
        C_bi21(p,:)=C_bi2(p,:);

    end
 end
```

```
 for p=1:2:n-1
    rd=rand(1);
    if rd>=Pcrx
    crx=floor((R+1)*rand(1,2));

    if crx(2)>crx(1)
        C_int=C_bi3(p,crx(1)+1:crx(2));
        C_bi31(p,crx(1)+1:crx(2))=C_bi3(p+1,crx(1)+1:crx(2));
        C_bi31(p+1,crx(1)+1:crx(2))=C_int;

    else if crx(2)<crx(1)
            C_int1=C_bi3(p,:);
            C_bi3(p,:)=C_bi3(p+1,:);
            C_bi3(p+1,:)=C_int1;
            C_int2=C_bi1(p,crx(2)+1:crx(1));
            C_bi31(p,crx(2)+1:crx(1))=C_bi3(p+1,crx(2)+1:crx(1));
            C_bi31(p+1,crx(2)+1:crx(1))=C_int2;

        end
    end
    else
        C_bi31(p,:)=C_bi3(p,:);

    end
 end

% Perform cross over for Tech Variables

 for p=1:2:n-1
    rd=rand(1);
    if rd>=Pcrx
    crx=floor((R+1)*rand(1,2));

    if crx(2)>crx(1)
        C_int=C_Tech(p,crx(1)+1:crx(2));
        C_Tech1(p,crx(1)+1:crx(2))=C_Tech(p+1,crx(1)+1:crx(2));
        C_Tech1(p+1,crx(1)+1:crx(2))=C_int;

    else if crx(2)<crx(1)
            C_int1=C_Tech(p,:);
            C_Tech(p,:)=C_Tech(p+1,:);
            C_Tech(p+1,:)=C_int1;
            C_int2=C_Tech(p,crx(2)+1:crx(1));
            C_Tech1(p,crx(2)+1:crx(1))=C_Tech(p+1,crx(2)+1:crx(1));
            C_Tech1(p+1,crx(2)+1:crx(1))=C_int2;

        end
    end
    else
        C_Tech1(p,:)=C_Tech(p,:);

    end
 end
```

```
% Peform mutation for design variables

Pmu=0.06;

for q1=1:n
    rd1=rand(1,R);
    for q2=1:R
        if rd1(q2)<=Pmu
            if C_bi11(q1,q2)==0
                C_bi11(q1,q2)='1';
            else
                C_bi11(q1,q2)='0';
            end
        end
    end
end

for q1=1:n
    rd2=rand(1,R);
    for q2=1:R
        if rd2(q2)<=Pmu
            if C_bi21(q1,q2)==0
                C_bi21(q1,q2)='1';
            else
                C_bi21(q1,q2)='0';
            end
        end
    end
end

for q1=1:n
    rd2=rand(1,R);
    for q2=1:R
        if rd2(q2)<=Pmu
            if C_bi31(q1,q2)==0
                C_bi31(q1,q2)='1';
            else
                C_bi31(q1,q2)='0';
            end
        end
    end
end

% Perform mutation for Tech Variables

for q1=1:n
    rd2=rand(1,R);
    for q2=1:R
        if rd2(q2)<=Pmu
            if C_Tech1(q1,q2)==0
                C_Tech1(q1,q2)=1;
            else
                C_Tech1(q1,q2)=0;
            end
```

```
        end
    end
end

% Go back and iterate
for i=1:n
Y1=bin2dec(C_bi11);
Z1(i,1)=r(1)/d*Y1(i,1)+Xlow(1);
Y2=bin2dec(C_bi21);
Z2(i,1)=r(2)/d*Y2(i,1)+Xlow(2);
Y3=bin2dec(C_bi21);
Z3(i,1)=r(3)/d*Y2(i,1)+Xlow(3);

X_T=C_Tech1;
Z_T=X_T*TIM';
Z4=Z_T(:,1);
Z5=Z_T(:,2);
Z6=Z_T(:,3);
Z7=Z_T(:,4);
Z8=Z_T(:,5);
Z9=Z_T(:,6);
Z10=Z_T(:,7);
Z11=Z_T(:,8);
Z12=Z_T(:,9);
end

% Elitiest approach

Z1(I)=Z_elite(1);
Z2(I)=Z_elite(2);
Z3(I)=Z_elite(3);
Z4(I)=Z_elite(4);
Z5(I)=Z_elite(5);
Z6(I)=Z_elite(6);
Z7(I)=Z_elite(7);
Z8(I)=Z_elite(8);
Z9(I)=Z_elite(9);
Z10(I)=Z_elite(10);
Z11(I)=Z_elite(11);
Z12(I)=Z_elite(12);

X_T(I,:)=X_T_elite;

if elite==0
elite=elite+1;
end
Z_elite;
Z_elite_Mixed=[Z_elite_Mixed Z_elite X_T_elite'];
GT_Per=[eta(I);MW(I);AC(I);OMC(I)];
GT_Per_M=[GT_Per_M GT_Per];
Output=[max(OEC);GT_Per;Z_elite(1:3);X_T_elite']';
I_num=I_num+1;

if I_num>I_num_max
    break
```

```
end

 end

 [C,I]=max(OEC_M);
 Output=[Output I];  % Convergence Step

% Plot OEC Convergence

I_num_M=1:101;
plot(I_num_M, OEC_M);


 %% End of Code %%
```

End of GA_7FA.m written in MATLAB

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VITA

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