

CRANFIELD UNIVERSITY

MOSAB WAEEL ALRASHED

MECHATRONICS NUMERICAL MODELLING FOR INTEGRATED
TURBO-ELECTRIC TECHNO-ECONOMIC ENVIRONMENTAL RISK
ASSESSMENT

PhD Full Time
Academic Year: 2019 - 2020

Supervisors: Doctor Theoklis Nikolaidis
Professor Pericles Pilidis

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ABSTRACT

Long-term targets from the aerospace administration are to have cleaner, cost-efficient, and more performance-efficient transportation. The National Aeronautics and Space Administration (NASA) has proposed several solutions to hybrid technology, of which the turbo-electric distributed propulsion (TeDP) model is one of the latest promising models. This research project presents numerical modelling of the integrated TeDP model through the method of assisting technical performance, considering the economic and environmental risks. The contribution to numerical modelling is an integrated electrical module on the academic multidisciplinary Cranfield University gas-turbine TurboMatch® simulation tool with the projected method. In piloting this project, the outcome of this work advances the knowledge of TeDP and the future technology of aviation-distributed propulsion.

Moreover, a proper simulation tool to assist TeDP and ‘more electric aviation’ has been upgraded in TurboMatch. In addition, an integrated development environment (IDE) extension for TurboMatch was developed to investigate the electrical grid in TeDP. This work presents a toolkit for assessing the power and efficiency profiles of the electrical network specified for TeDP. From the given level of thrust, the methodology was used to evaluate and optimise the electrical network. A number of integration electric propulsion models were developed to demonstrate the assisting method for redundancy and reliability improvement. The total goal was to initialise the features of the TeDP mechatronics and electrical grid with the best technical, economic, and environmental solutions for the greatest efficiency.

The implication of this research is to understand the concept of TeDP using the use-case study of NASA’s N3-X conceptual proposal for project progress validation. The contribution knowledge lies in the area of the numeric model and the method to assist TeDP using the devised techno-economic environmental risk assessment (TERA) concept. The project inputs focus on future long-term goals for intelligent TeDP.

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KEYWORDS

Turboelectric, Turboelectric distributed propulsion, Energy simulation, Numerical modelling, Hybrid electrified system, TurboMatch, GridMatch, Quantification risk analysis, Economic add value, Techno-economic environmental risk assessment, Key performance indicators, Turboelectric power, Hybrid aircraft engines, Numerical modelling and simulation, Futuristic propulsion systems, More electric aviation.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ACARE	Advisory Council for Aviation Research and Innovation in Europe
AEA	All-Electric Aircraft
AI	Artificial Intelligence
ATM	Air Traffic Management
BLI	Boundary-Layer Ingestion
CAEP	Committee on Aviation Environmental Protection
CDF	Cumulative Distribution Function
CESTOL	Cruise Efficient Short Take-Off and Landing
CFD	Computational Fluid Dynamics
CGF-1	Cranfield Generator Fan -1
CGShaft-1	Cranfield Generator Shaft -1
CIT	Cranfield Institution of Technology
CM	Carbon Monoxide
CMF-1	Cranfield Motor Fan -1
DC	Direct Current
DEAP	Distributed Electrical Aerospace Propulsion
DFA	Deterministic Finite Automaton
DP	Design Point
EAV	Economic Added Value
EV	Electric Vehicle
FAA	Federal Aviation Administration
FPR	Fan Pressure Ratio
GE	General Electric®
GM	GRIDMATCH (software tool)
GUI	Graphical User Interface
HELFM	Holomorphic Embedded Load Flow Method
HELM	Holomorphic Embedding Load Flow Method
HPC	High Pressures Compressor
HPT	High Pressures Turbine
HTS	High-Temperature Superconductor
HWB	Hybrid Wing Body
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization

IDE	Integrated Development Environment
IPC	Intermediate Pressures Compressor
IPT	Intermediate Pressure Turbine
IRR	Internal Rate of Return
KCL	Kirchhoff's Current Law
KPI	Key Performance Indicators
KVA	Kilo Volt Ampere
KVAR	Kilo Volt Ampere Reactive
KVL	Kirchhoff's Voltage Law
KW	Kilowatt
LH	Latin Hypercube
LMA	Levenberg-Marquardt algorithm
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
LRC	Langley Research Centre
LTO	Landing and Take-Off
MC	Monte Carlo
MEA	More Electric Aircraft
MIP	Mixed-Integer Programming
MIT	Massachusetts Institute of Technology
MVA	Megavolt amps
MW	Megawatt
NASA	National Aeronautics and Space Administration
NFA	Non-Deterministic Finite Automaton
NGRC	NASA Glenn Research Center
NME	Numerical Modelling Environment
NO	Nitric Oxide
NOPAT	Net Operating Profit After Tax
NOPLAT	Net Operating Profit Less Adjusted Taxes
NPV	Net Present Value
OPF	Optimal Power Flow
PEGS	Propulsion Electric Grid Simulator
PEM	Proton Exchange Membrane
PF	Power Factor
PI	Performance Indicators
PP	Payback Period

RBCC	Reverse-Brayton Cycle Cryocooler
RI	Results Indicators
RTO	Rolling to Take-Off
SAF	Sustainable Aviation Fuels
SDL	Specification and Description Language
SLS	Space Launch System
STARC-ABL	Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer propulsor
SUGAR	Subsonic Ultra Green Aircraft Research
TCC	Total Capital Cost
TeDP	Turboelectric Distributed Propulsion
TERA	TechnoEconomic Environmental Risk Assessment
TET	Technology, Economic, and Environmental Triangle
TM	TurboMatch (software tool)
TO	Take-Off
UB	Upper Bound
UHB	Ultra-High Bypass Ratio
UML	Unified Modelling Language
USD	United State Dollar
WACC	Weighted Average Cost of Capital
XIRR	Excel Internal Rate of Return

LIST OF NOMENCLATURE

C_a	Net Annual Cash Inflow
C_o	Initial Cash Flow
C_t	Future Cash Flow
I_o	The Initial Investment
Sp_{ED}	Specific Power
x_n	Point or Value
x_{n+1}	Next Point or Value
x_o	Represents Initial Cash Flow or Initial Outlay
x_t	Represents Future Cash Flows
ΔV	Voltage Drop
CO_2	Carbon Di Oxide
J	Jacobian Matrix
K_e	Back Electromotive Constant
K_t	Torque Constant
NO_x	Oxides of Nitrogen
r	Residual Vector
R	The Discount Factor
t	The Total Period
t	The Total Period
V_a	Watts, Actual, Active, or Real Power
V_i	Back Electromotive Force
V_r	Volt-Amperes Reactive or Reactive Power
V_t	Apparent Power
δ	Initial Guess Adjustment
λ	Damping Parameter
ω	Angular Velocity
Ω	Resistance with The Unit Ohm
COP	Coefficient of Performance
I	Electrical Current
L	Inductance
R	Resistance
$f(x_n)$	Valued Function
$f'(x_n)$	Line Slope or Derivative Of The Function

r	The Discount Rate
η	Efficiency

CHAPTER 1

INTRODUCTION OF THE RESEARCH PROJECT

Introduction

The evolution of the aircraft industry is reaching a revolutionary stage where research and development are taking place for improving aircraft efficiency, fuel burn, and acoustic noise. Electric and hybrid technology has gained more interest during the last few years, and novel tools and assessments have been developed that will go into service by 2025–2050. Turboelectric propulsion is one of the nearer promising technologies that are relevant in terms of reality and availability. This chapter will introduce the research evolution strategy for civil propulsion power and the challenges, contribution motivation, aims, objectives, and knowledge.

1.1 Evolutionary Distributed Propulsion

The design and development of distributed propulsion with novel achievements began in order to reach efficient performance. During this time, inventions aimed to reach the point of high performance and capability because of the unstable oil prices due to the economic changes affecting the critical elements. Then, the emergence of technology and economic (techno-economic) factors gained attention. After that period of growth, nature has suffered, and lobbyists have called for cleaner distributed propulsion to cover or at least cut down the increase of environmental effects [1]. The goals and strategies were set to rebuild the triangle of the new revolutionary distributed propulsion, as shown in the following Figure 1.1-1 with the following main points: technology (performance and efficiency), economic, and environment [2,3].

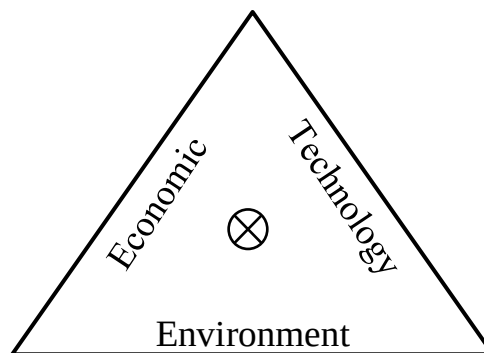


Figure 1.1-1: Technology, economic, and environmental triangle (TET).

Novel ideas are generated and developed to meet the three triangle criteria needed for the revelation of distributed propulsion using non-petroleum-based fuels to produce the power density. Moreover, hybrid vehicles aim for a more efficient energy source that is environmentally friendly.

1.1.1 Enhancement of Technologies

Application technologies proposed for research and development for distributed propulsion seem more applicable in the next generation. The gap between electric and mechanical becomes closer as the term *electromechanical and mechatronics* were established [4–6]. The challenge in technology was how to provide a high power density that can cover the baseline power generators. Moreover, the efficiency should have great value in terms of energy, sustainability, and economy, which electric promises to deliver. Although the physical technologies have not improved, the simulation and modelling technologies have upgraded to a level of having almost a negligible error percentage. That helps in finding the ideal points of the technology, economic, and environmental triangle (TET) in the simulated model [7,8].

1.1.2 Challenges Area of Economic Value

Since the 1960s, civil aircraft demand has grown [9]. The aviation industry's economic value of passenger transportation investment is expected to grow between 3.8% and 4.2% per year in the next years [10–12]. This expansion means that there are more costs in airports, traffic, energy, operations, maintenance, and even environmental costs if continuing with the same baseline fleet and energy generation [13]. Figure 1.1-2 represents the historical and expected forecast for the passenger numbers, which are translated as the number of commercial customers [14].

Measuring the benefits driven by the baseline aviation technology and comparing them with alternative novel technologies for the interim, short term, and long-term will show the limitation of the financial expense. Estimating the vehicle lifecycle, including research, development, manufacture, operation, maintenance, and policy fees should be of value to reduce costs and waste to be within the breakeven point. Due to the economic risk and market trading capacity variation during 2010–2017 with the oil prices ranging from \$70 to \$50 per barrel, new methods for future cost valuation terms, such as for the electric vehicle, have been studied. According to the published data, cost-cutting is needed on both technologies (lithium-ion batteries and electrical power), and the gasoline

production price affects the adjustment timespan for the lifecycle of electric energy [15]. Figure 1.1-3 shows the uncertainty of the modernised relationship between the technology costs for electric vehicles and the gasoline production price. Also, the Figure shows that from the red line, \$150 is the point where the fully electric vehicle should take the place of the legacy vehicle and the period for establishing a hybrid vehicle estimated to be in the year 2027 [16]. Furthermore, the future forecast demonstrates a decrease in electrify costs, which supports more electricity in transportation technology.

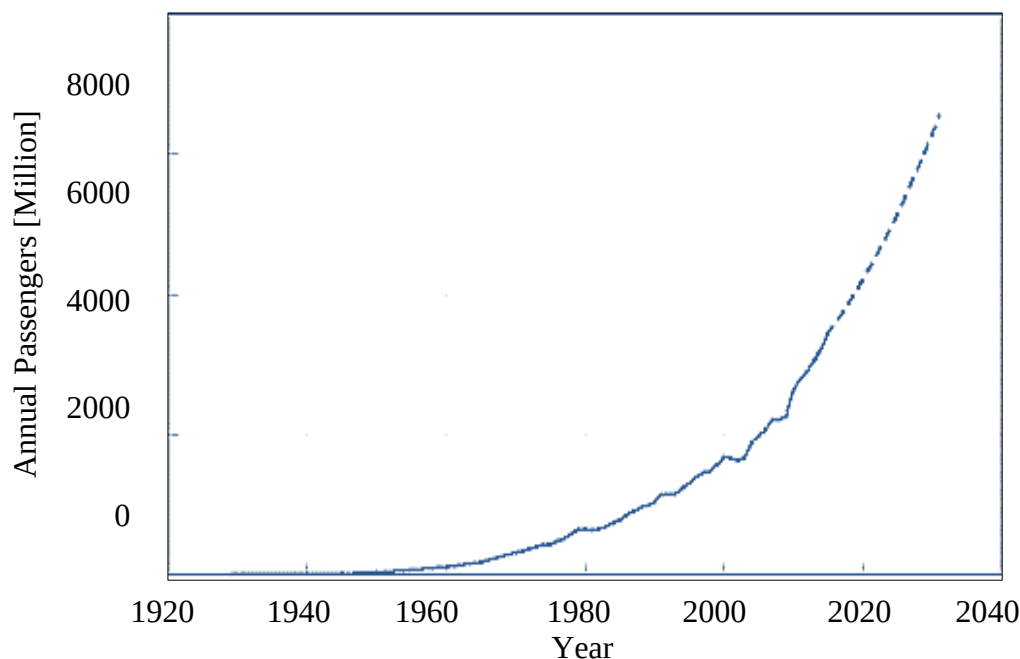


Figure 1.1-2: Annual demand of air traffic passengers [14].

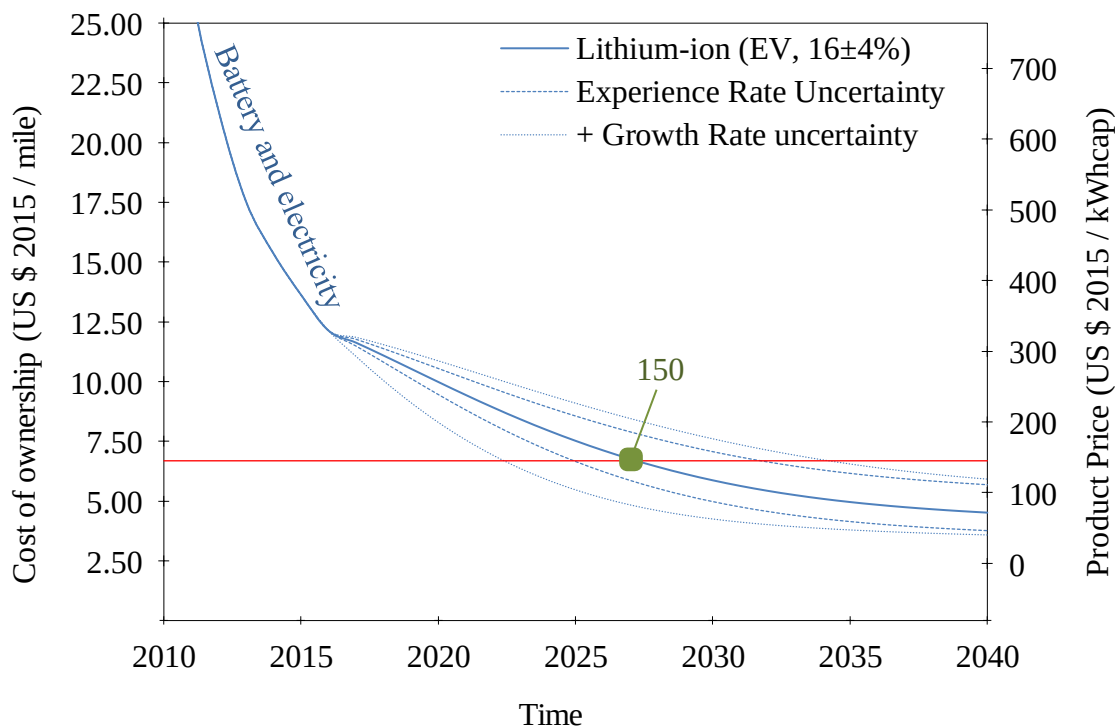


Figure 1.1-3: Forecast cost analyses for an electric vehicle with an average gasoline price [16].

1.1.3 Environmental Sustainability

After the global call for sustainability regarding the future expected risks concerning natural resources due to the radical changes in the environment, such as global warming, researchers have worked to determine how to reduce the short-term and long-term damage to sustainability by providing more environmentally efficient alternatives to the current fleet [17]. The three concerns to address are 1) reducing the consumption of energy in general and specifically fuel burn, 2) dropping the CO₂ and NO_x emission levels, and 3) reducing acoustic noise [18,19]. The National Aeronautics and Space Administration (NASA) pushed forward the timeline for a greener and practical aeronautics and space fleet by providing goals that need to be accomplished in the next 30 years [20]. These targets consist of technology and ideas that could solve more areas that are restricted. Their objectives and contributions are in Table 1.1-1.

Table 1.1-1: NASA's subsonic goal for airliner technology enhancement. [21–23]

Emissions	N+2 (~2020) (relative to B777/GE90)	N+3 (~2025)
Noise	-42 dB	-71 dB
LTO NO _x	-75%	-80%
Cruise	-70%	-80%
Fuel Burn	-50%	-60%

Furthermore, in Europe, for example, the Clean Sky project helps to reduce emissions within the European aviation industries. The Advisory Council for Aviation Research in Europe (ACARE) also targeted its vision for 2020 and 2050 with greener goals. Table 1.1-2 shows the target percentage goals for both Clean Sky and ACARE for reduced emissions relative to the 2000 emission levels as the set time goals [24–26].

Table 1.1-2: ACARE and Clean Sky emission reduction target. [24–26]

Emissions	ACARE (2020) (relative to 2000)	ACARE (2050) (relative to 2000)	Clean Sky (2020)	Clean Sky 2 (2050)
Noise	-10 dB (one half of average levels)	-65%	-75%	-65%
NO _x	-80%	-90%	-60%	-90%
CO ₂	-50%	-75%	-26%	-75%

The noble target from aviation leaders was to find newly distributed propulsion that can achieve the power densities needed with fewer environmental effects, which is critical. One of the excellent promising alternatives is electrical energy because of its availability

to provide the needed power densities. Besides, this new revolution is more realistic during the next years to accomplish and implement it affordably.

1.1.3.1 Committee on aviation environmental protection

In 1983, a technical committee was established within the International Civil Aviation Organization (ICAO) council Committee on Aviation Environmental Protection (CAEP). Establishing CAEP replaced both the Committee on Aircraft Noise (CAN) and the Committee on Aircraft Engine Emissions (CAEE), which performed for 13 and 6 years, respectively. This committee frames new policies, standards, and recommendations related to aircraft environmental emissions. Based on CAEP studies and the measurement outcomes, the ICAO council defined the environmental protection policies and targets. Figure 1.1-4 illustrates the CAEP levels regarding engine certification [27,28].

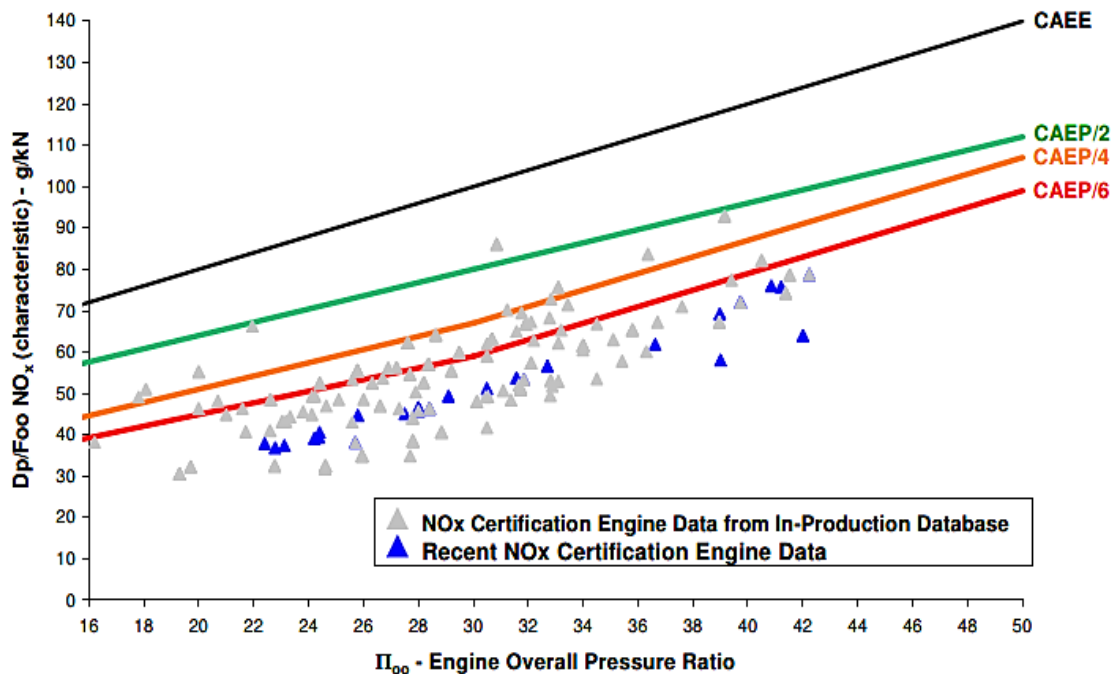


Figure 1.1-4: Engine certifications related to CAEP level [29].

The CAEP aims to reduce the levels from 45% to 60% of level six before 2026. For each level, CAEP has an assessment work cycle to collect data, analyse them, and then state their new standards. From the last level, the CAEP/10 standard (2016), the environmental assessment duration cycle for the CAEP/11 level, will start to deliver the new standards within the next two years (2019) [10,29].

1.2 Integrated Turboelectric Distributed Propulsion

Since full electric or partial electric, as a hybrid has improved the efficiency of several transport applications, including trains and cars, it is time for aircraft to be redesigned to fit electric propulsion. This integration of mechatronics eliminates the losses in legacy propulsion systems. The next chapter of this thesis discussed the overview of introducing electrical power to the aviation sector with comparison and analysis.

1.3 Research Motivation

The increasing destruction of the environmental atmosphere through various types of contaminants, noises, emissions, fuel burns, and consumption of non-renewable resources leads to the need to find alternative efficient power sources that are cleaner and cost-efficient for distribution propulsion systems [30]. According to the International Air Transport Association (IATA) and the Federal Aviation Administration (FAA), aircraft demand is growing more than 5% yearly with the expectation of doubling for 2025 [31,32]. This growth has two consequences: commuters and logistics services will benefit in terms of competition and availability, and unfortunately, growth in emissions, fuel consumption, and air traffic will occur. Figure 1.3-1 represents the size emission reduction in CO₂ for proposed opportunities includes baseline with the same technologies used nowadays, intermediate-generation aircraft, air traffic management (ATM), next-generation aircraft and retrofits. Moreover, exceeding the cost-effective could be done by early replacements, airline operational strategies and biofuels. The main scope of this research is to study next-generation aircraft technology represents in the blue triangle within the same figure.

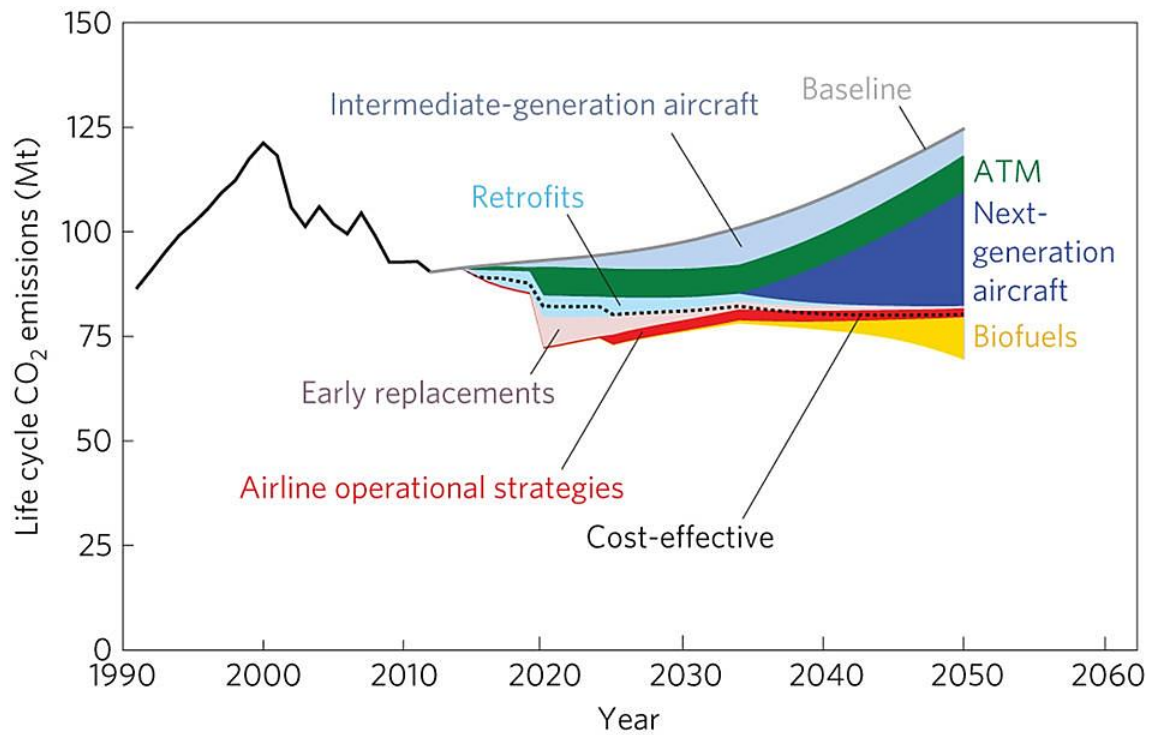


Figure 1.3-1: Lifecycle CO₂ emissions, the historical trend (1991–2012), and future projections (2013–2050) of the mitigation potential by category of measures [33].

1.4 Research Aim and Objectives

This section presents the aim, goal and objectives of this research, which been covered through the thesis chapters.

1.4.1 Aim

The research project aims to develop a numerical model of the integrated Brayton Cycle turbo-electric design so that quantitative estimates of an increasingly integrated turbo-electric system performance can be encompassed in a comprehensive techno-economic environmental risk assessment (TERA).

1.4.2 Goal

The goal is to develop an advanced numerical modelling environment that estimates the turbo-electric system performance, economic efficiency, and environmental impact based on the TERA method.

1.4.3 Objectives

1. Model the turbo-electric distributed propulsion (TeDP) with the primary electric systems (generator and motor), then the secondary auxiliary elements (buss, power converter) as needed for the effects on the numerical evaluation.
2. Identify the current modelling methodologies for TeDP with the different electrical power classes.
3. Integrate a method for TeDP numerical modelling, including electrical machines using TERA.
4. Develop a numerical simulation for TeDP systems based on the TurboMatch simulation tool, which provides comprehensive facilities for analysing electric systems parts.
5. Integrate the techno-economic vital elements (performance, economic added value, net present value, internal rate of return, and payback) to the developed numerical modelling environment (NME).
6. Include the environmental impact assessment for the TeDP system on the developed NME.
7. Conduct TERA for TeDP on NME and evaluate the results with authentic NASA published data.

1.5 Knowledge Contribution

1. An integrated numerical tool for an electrical network of TeDP performance with the capability to assess multiple types of TeDP applications.
2. A method to assist an integrated hybrid aviation distributed propulsion technology within the TET, considering the ideal points that been explained in figure 1.1-1.
3. Provide an economic added value (EAV) analysis to optimise the TeDP model with the trade-off techno-economic relationship.
4. Introduce techno-economic and environmental key performance indicators (KPIs) for TeDP MW-class systems.

Figure 1.5-1 illustrates the research contribution to knowledge percentage based on the specific area of development. Moreover, the figure represents the junction gaps bridged as numbered in Venn chart.

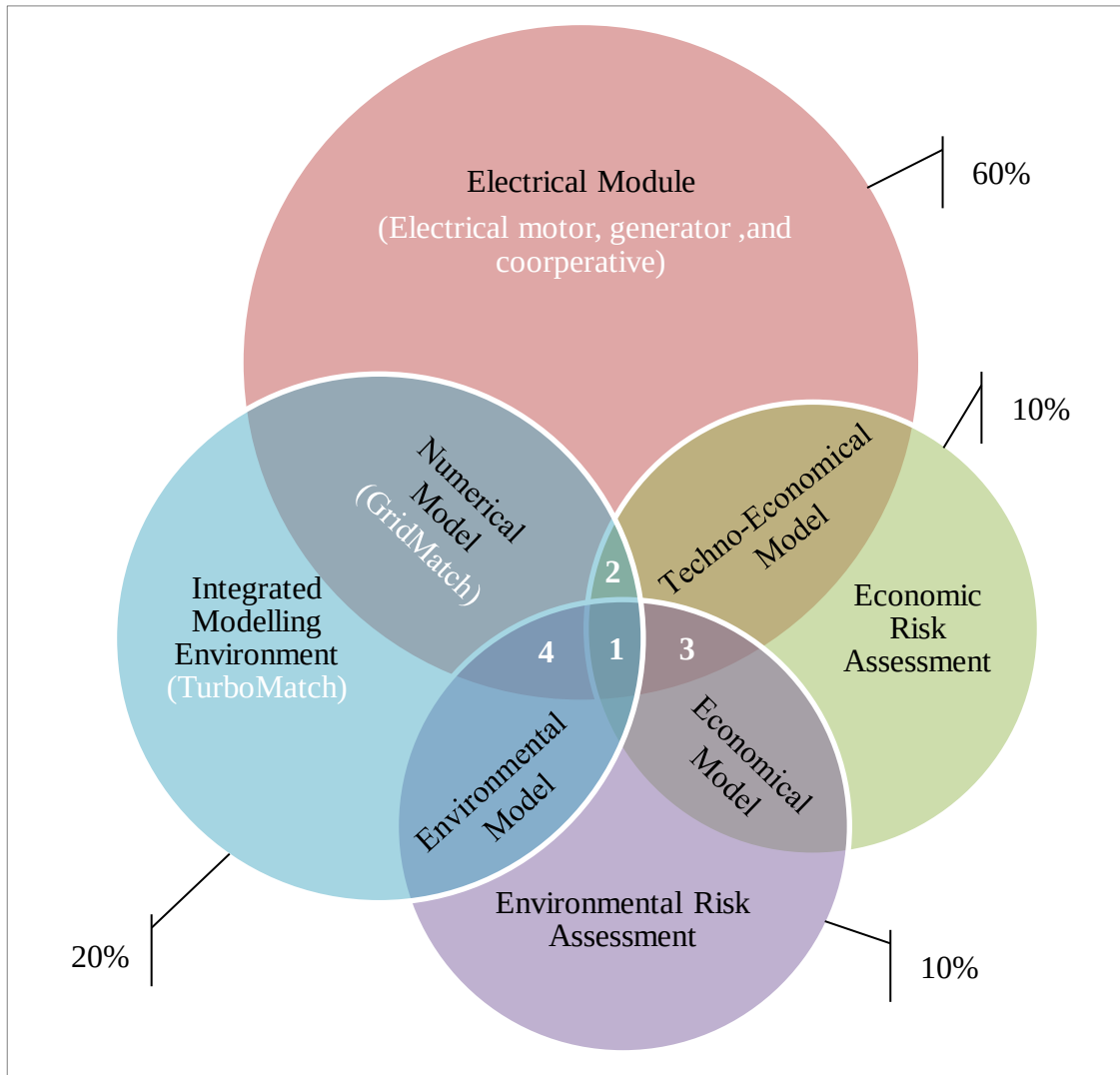


Figure 1.5-1: Knowledge contribution Venn chart

1.6 Thesis Structure

This study contributes in developing, modelling, assessing, and optimising the electrical elements to implement a power solution for performance enhancement in TeDP systems. It consists of assimilating TERA method by using numerical modelling. These research principles were contributed in nine chapters, as demonstrated in Table 1.6-1 and Figure 1.6-1. The chapters from 3 to 7 contribute to the lack of work for TeDP core development and study.

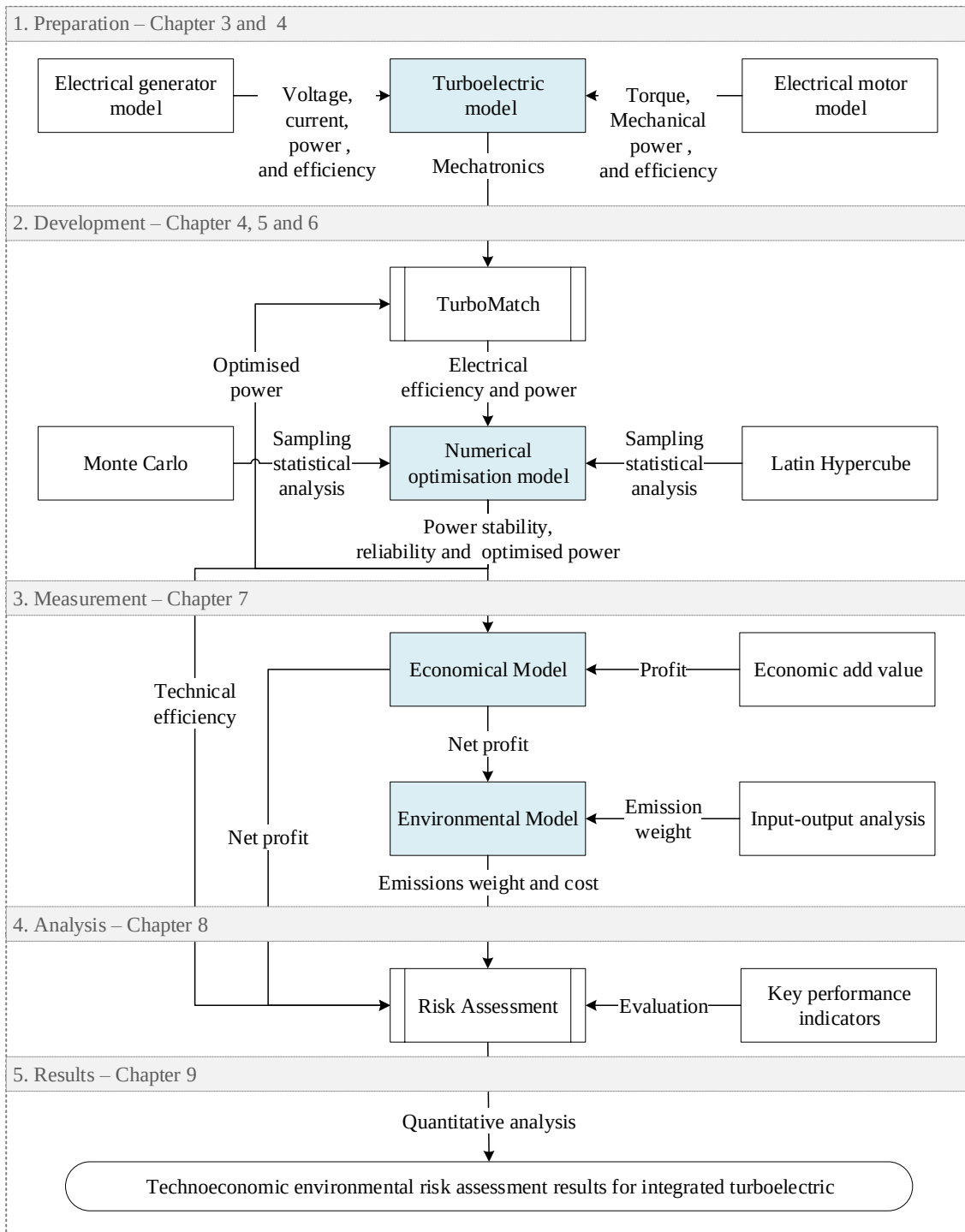


Figure 1.6-1: Thesis structure methodology

Table 1.6-1: Thesis links and contents

Mechatronics Numerical Modelling for Integrated Turbo-Electric Techno-Economic Environmental Risk Assessment			
Chapter	Description	Objective	Knowledge gap
1	Research introduction	-	-
2	Literature review	2	-
3	Research methodology	1 and 3	2
4	Modelling studies	1 and 4	2
5	Simulation development	4	1
6	Research Validation	4	2
7	Economical and environment studies	5 and 6	3
8	Key performance indicators	7	4
9	Research conclusion	7	1

1.6.1 Chapter 1

This introduction chapter establishes the project scope of research and defines the limits of knowledge in turbo-electric for the desired aim, goal, and objectives. It gives a perspective view of the aviation future in technology enhancement, economic, and environmental challenges. Moreover, the thesis structure has been highlighted by summarising chapters' valuable contents and study contributions.

1.6.2 Chapter 2

A systematic review and analysis of using turboelectric power in civilian aircraft have been studied in this chapter. This overview accommodated the fundamental of gas turbine engines required for turboelectric mechanical power. Then comparing the turboelectric future hybrid engine approaches, those include electric generators and motors. The comparison extended to cover the different concepts of power source hybrid with turboelectric types. After that, some proposed example models and numerical modelling research of turboelectric discussed to investigate the limitation on the project scope. By doing that, existing works related to found scope analysed with significance the promising future trends in it.

1.6.3 Chapter 3

This chapter demonstrates the research methodology used in the project. It defines the integration model for electric components and modelling of different electrified disruption power concepts.

1.6.4 Chapter 4

This chapter expounds the numerical modelling development through studying the conduct of electrical elements between gas turbine and electrification of power. It

describes numerical notations for multi approaches of futuristic propulsion and applies unified modelling language (UML) methods in it. Thereafter, the electrical network architecture modelled and digitalised with prime electrical power components. Finite-state automata discussed and applied to the turboelectric system to initialise the simulation environment. From the outcomes, modelling behaviour and analysis contributed to the notation of the turboelectric numerical modelling stage.

1.6.5 Chapter 5

In this chapter, two integrated development environment tools for turboelectric distribution power delivered described and verified. The first tool is an upgraded brick for TurboMatch software by implementing the electric generator and motor while the second as an extension software for optimising the electrical grid to enhance the electric efficiency.

1.6.6 Chapter 6

This chapter estimates the impact and approximate accuracy of turboelectric integration developed using uncertainty and error margins application. Accordingly, it contains quantitative risk analysis Monte Carlo and Latin Hypercube to study the probability of different outcomes. Besides, standard deviation and cumulative distribution function applied in the outcomes to estimate the range of data divergence.

1.6.7 Chapter 7

Focusing on the economic and environmental assessments, this chapter outline the economical methods include net present value, internal rate of return, payback period and economic add value. These methods applied on NASA N3-X as a case study along with including the environmental assessment.

1.6.8 Chapter 8

This chapter finds the key performance indicators for the enhancement of TeDP systems. It accumulated by investigating the results and performance indicators for the system and analysis of the outcomes. This covers a quantities measurement to verify the key results and performance indicators.

1.6.9 Chapter 9

As a last chapter in the thesis, it summarises and concludes the research work with the gained results that concise the bridged knowledge gap. Moreover, it includes a recommendation for future work.

CHAPTER 2

THE UTILISATION OF TURBOELECTRIC POWER IN CIVILIAN AIRCRAFT: A REVIEW

ABSTRACT

Emissions produced by the aviation industry are currently a severe environmental threat. To counter this, aviation agencies and governments have stated future goals and plans to apply restrictions within the next decade. Hybrid aircraft technology is being considered for meeting the goals mentioned earlier. The importance of these technologies lies in their advancements in terms of aircraft life cycles and environmental benignity. These advancements have rendered hybrid systems promising for the aviation industry, considering that the growth of air traffic is projected to double in the next decade. Herein, turboelectric distributed propulsion (TeDP) is discussed in terms of power distribution and power sources. The fundamentals of turbofan and turboshaft engines are presented along with their electricity-generation mechanism. Hybrid technologies have made future hybrid fans and motor-fan engines promising alternative power generators. TeDP is discussed from a design viewpoint, with a detailed discussion of different types of hybrid electric and turboelectric systems. Examples of proposed TeDP aircraft models and numerical modelling tools used to simulate the performance of TeDP models are reviewed. Finally, innovative turboelectric systems in which electric power savers and mechanical gear changers have been discarded for weight optimisation are presented along with other prospective models, engines, approaches, and architectures. The results show the knowledge gaps in the field of numerical modelling for TeDP.

2.1 Introduction

Since the advent of aviation, significant advances have been made in aircraft technology. One primary example of such remarkable advancements took place during the Second World War, where tubes and wings were developed for the aviation industry. Over the past decade, the need for more efficient, economical, and environmentally friendly aircraft led to a series of studies on improving aircraft technology. These studies proposed several power sources and technologies to harvest higher power density. From the

introduction of 12 horsepower engines, technology has advanced to what the National Aeronautics and Space Administration (NASA) intends to achieve in the near future – 54,400 hp in their N3-X aircraft [34]. Turboelectricity is the key to generating this massive amount of power, and it has been demonstrated that electric significantly improves aircraft efficiency.

From a historical perspective, the introduction of electric power systems in aircraft has faced significant challenges despite the advantages of these systems. Beginning from their use in the 1940s and 1950s, electric power systems, such as twin 28V direct current (DC) power generator systems, have been shown to boost aircraft power. This system was fitted with batteries and inverters to power alternating current (AC) aircraft instruments up to 115V. Valinat introduced electric landing gear in the 1950s, which required four 115V AC generators in parallel to provide more control and protection [35]. Increasing the use of electric power systems in aircraft has been shown to be favourable, delivering AC values higher than 230V for the recent passenger aircraft, A350 XWB [36].

Alternative power generators in aircraft engines support the integration of gas turbines and electric power. This alternative integration of mechanical and electrical power is considered an intelligent propulsion source of energy. Furthermore, it would replace legacy gas turbine propulsion systems. The argument for optimum power and energy efficiency makes such a source necessary. Moreover, the full electric distribution of power has significant drawbacks such the limitation in energy conservation technologies, enormous wasted volume space for carrying electrical feed, and long charging time. Just-in-time implementation of electric power systems, which provide the power density needed for the journey, is essential in aircraft. Power can be generated when required, or it can be supplied from a power storage unit. Both these methods have their advantages and drawbacks in terms of weight, emissions, costs, and power efficiency.

Several review articles have been published regarding turboelectric distributed propulsion (TeDP). The first article introducing turboelectric power was published by Lichtenberg [37] in 1971, who published a comparative study on the thermal efficiency of diesel and turboelectricity for use in railways. In 1983, Keszei et al. [38] presented measurement techniques using electronic instruments and discussed the advantages of the proposed design. In 2012, Armstrong [39] studied the configuration of and improvements in the N3-X aircraft developed by NASA. Nalianda and Singh [40] provided a general overview

of the opportunities, benefits, and challenges of TeDP. Finally, Brelje and Martins [41] discussed the electrical fundamentals and concepts of electric fixed-wing aircraft models.

Currently, there is little information available on the status of turboelectric power in aircraft, and hence, it is necessary to review fundamentals of the TeDP technology and its possible future applications; this is especially necessary to educate novices with no background on aviation and thermal power. The focus of this review is to discuss the proposed TeDP models and concepts for future advancements. This review also covers aero-engines, numerical simulations, and existing TeDP technologies. Our focus on the science of TeDP implemented in the category of more electric aircraft (MEAs) and not on the individual types of aircraft, or proposed projects provides a broad, novel overview. This work will be the basis for research on TeDP in the fields of electrical and mechanical expansions.

In the first section of this review, the types of engines that can be used in distributed propulsion systems and the differences between two legacy power engines, Turbofan and Turboshift, are discussed. Later, some proposed engines that are still in the research and development stage are discussed. The reason behind using these type two engines because of the ability to generate electrical power from the theme with the highest efficiency in gas fuelling. Furthermore, these types are the most reliable and developed in the civilian.

2.2 Fundamentals of Turbofan power and propulsion engines

The power generated in the wings and tail of an aircraft is distributed by a number of turbofan engines located in the wings (one or two engines on both sides) based on aircraft design. There are several types of turbofan engines, depending on the number of shafts in the engine (one, two, or three shafts). These engines are designed to merge the thrust from two sources, starting with the inlet and ending with the propelling nozzle [42,43]. Thrust is generated in the turbofan engine according to the following principle [44]:

1. Air enters the engine from the inlet to the fan.
2. A portion of the flowing air mass is compressed in the compressor, and another portion is compressed in the fan nozzle.
3. High-pressure compressed air enters the combustion chamber, which increases air temperature by fuel combustion.
4. The generated high-temperature and high-pressure air enters the turbine and then the propelling nozzle to generate thrust required to propel the aircraft.

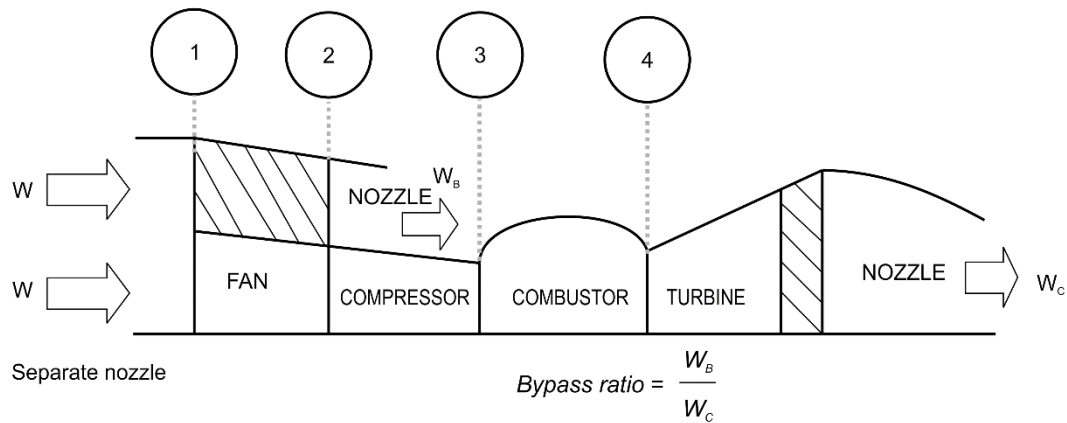
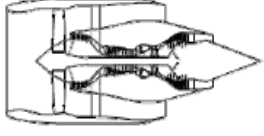
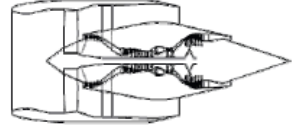


Figure 2.2-1: Schematic of the stages involved in thrust generation in the CFM56 turbofan engine with bypass. The bypass ratio asymmetric by W_B/W_C , where W is the total air mass flow entering the engine, W_B is the fan nozzle-separated air mass flow, and W_C is the compressed air mass in the compressor [44].

Figure 2.2-1 shows a schematic of the stages involved in thrust generation in the CFM56 engine, which is a typical turbofan engine. This engine is characterised by a forward-facing fan that makes air move by entering the core engine or passing through the bypass duct, from which the bypass ratio can be determined. The bypass offers the following advantages – (1) a low engine noise and (2) a high thrust at low aircraft speeds. Table 2.2-1 compares the technical specifications of the conventional CFM56 turbofan engine and the proposed concept of advanced turbofan engines. Thrust and specific fuel consumption results in the table were calculated using the Cranfield University in-house tool (TurboMatch).

Table 2.2-1: Comparison of the technical specifications of conventional and proposed advanced turbofan engines [45]

Schematic of the engine			
Name of the engine	CFM56	gFan	gFan+
Type	Conventional gas turbine	Gas turbine	Advanced gas turbine
Airframe	SUGAR Free	Refined SUGAR	SUGAR high
Fan diameter/ Bypass ratio	61"/5	70"/9	77"/13
Thrust (SLS/+27)	120.1 kN	84.0714 kN	84.0714 kN
Specific fuel consumption at cruise flight	9.92642 g/kN/s (Base)	7.8414718 g/kN/s (−21%)	7.1470224 g/kN/s (−28%)
Weight of the propulsion system	2,385 kg (Base)	2,907.98 kg	3,218.69 kg
Emissions (relative to CAEP/6)	79.2 % (Base)	−58%	−72%

2.2.1 Single-spool and multiple-spool turbofan engines

Flexibility, efficiency, and performance are the three factors that determine the number of shafts or spools in gas-turbine engines. A spool is a rod that delivers power (speed) to all the attached components. If there are multiple spools, power is divided into multiple rods, which implies more control for different components of the engine rather than one power or speed for all the components. The multiple-spool design makes the gearbox unnecessary and increases the number of stages in gas-turbine engines. For example, in a two-spool engine, the compressor consists of two stages – a low-pressure compressor (LPC) and a high-pressure compressor (HPC); they are arranged in sequence and connected to different spools [9–11]. The same concept is used for the turbine section, which consists of a high-pressure turbine (HPT) and a low-pressure turbine (LPT) arranged in sequence. In a three-spool engine, there are three stages in the turbine section, viz. (1) HPT, (2) intermediate-pressure turbine (IPT), and (3) LPT. However, the compressor still consists of only two stages (intermediate-pressure compressor (IPC) and HPC), where the fan shares the same LPT work instead of the LPC. A comparison

between multiple spools is presented in Table 2.2-2. Figure 2.2-2 shows an example of a two-spool turbofan engine.

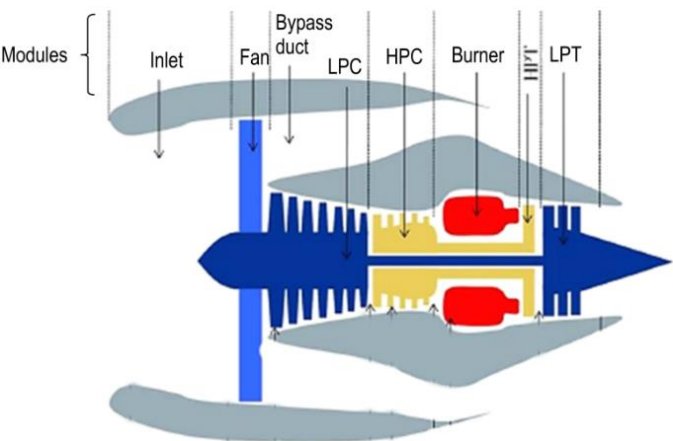


Figure 2.2-2: Schematic of a two-spool turbofan engine. The first spool is highlighted in yellow, and the second spool is highlighted in dark blue [46].

Table 2.2-2: Comparison between one-spool, two-spool, and three-spool turbofan engines

Number of shafts/spools	Stages in the turbofan engine
One	Inlet → Fan → Pressure compressor (PC) → Combustion chamber (CC) → Pressure turbine (PT) → Nozzle
Two	Inlet → Fan → LPC → HPC → CC → HPT → LPT → Nozzle
Three	Inlet → Fan→ IPC → HPC → CC → HPT → IPT → LPT → Nozzle

The concept of turbofan engines is crucial not only for current baseline aircraft but also for future aircraft. Future aircraft with increased electric power will use turbofan engines to generate thrust, electricity, or both. Most TeDP models suggest using turbofan engines owing to their efficiency and flexibility.

2.3 Foundation of power from turboshaft engines

Removing the bypass duct from a turbofan engine reduces thrust, but it increases engine power while reducing engine weight. Moreover, from a technical standpoint, the fan stage does not appear as a station point while estimating the performance of the turboshaft engine. Similarly, using multiple shafts will increase the power of turboshaft engines.

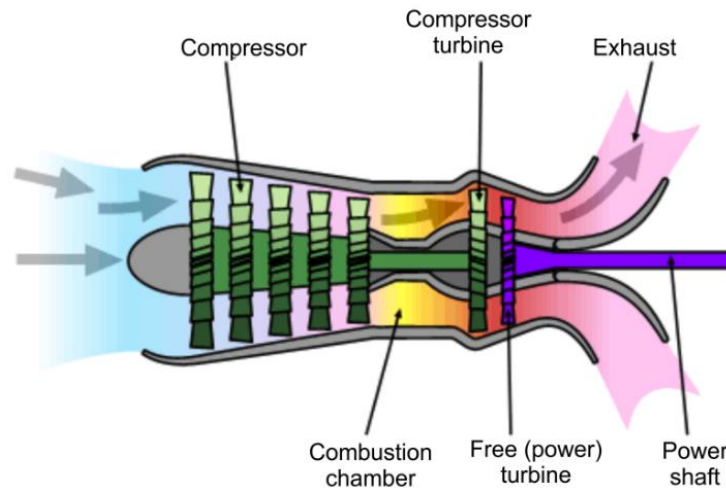


Figure 2.3-1: Schematic of air-mass flow in a turboshaft engine.

In Figure 2.3-1, which illustrates the air-mass flow in a turboshaft engine, it can be seen that air flows through the inlet and then into a compressor. Such highly compressed air then enters the combustion chamber, where it is burned along with fuel. The power generated is transferred to the power shaft, which drives the turbine.

2.4 Future engine designs for increased electric power supply

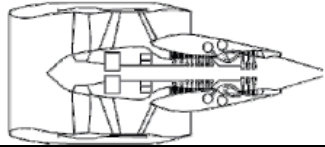
Several aircraft engines with high electric power have been proposed for use in the next decade such as NASA's N3-X (introduced in 2008 [47]), Boeing SUGAR (built-in 2014 [48]), and ESAero ECO-150 (developed in 2015 [49]). The two main objectives of such aircraft are to include a power generator as a hybrid engine or rotating motors as motor-fan engines. The relationship between propulsion and power sources should accomplish one or both of the following goals – convert mechanical power into electrical power (for power generators) or convert electrical power to mechanical power. In addition, power storage should also be included (where necessary), depending on the proposed design for TeDP. This section is focused on several reliable engines, which are expected to be the next-generation engines in the aviation market. Futuristic engines are being mainly designed and developed by the cooperation of four organisations, namely NASA, General Electric, CFM International, and Georgia Institute of Technology. The realistic engine designs developed at these institutions are expected to shift the usage from baseline engines to hybrid power source engines by 2020. There are two main types of engine models currently undergoing research and development: the generator hybrid fan and motor fan engines.

2.4.1 Generator hybrid fan engines

The state-of-the-art hybrid engines are geared towards MEAs. As the name implies, hybrid engines consist of baseline engines and conventional gas turbine engines with an electric generator. This concept was introduced in several types of designs. Based on the relationship between power and weight, reducing the weight of materials needed for the carriage will save more power and thus improve fuel efficiency. However, it is challenging to source suitable materials to manufacture lightweight, yet efficient components. As a result of these futuristic technologies, weight was not included in the research calculation since the significant advance in composite material to reduce the weight as possible. Mentioning the weight would be only as a target for projected power. To overcome this limitation, the just-in-time power generator was introduced for TeDP without any power storage, resulting in a flexible and controllable power source.

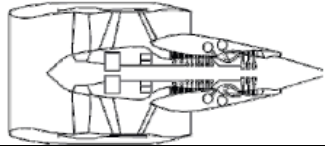
- A. One of the factors that make just-in-time power generators promising is that they integrate the design of several existing engines [50,51]. Table 2.4-1 provides details of a hybrid fan engine proposed by NASA and named genFan as the amalgamation of generators and fans.

Table 2.4-1: The concept Hybrid genFan engine [50]

Schematic of the engine	
Name of the engine	genFan
Type	Hybrid gas turbine
Airframe	STARC-ABL
Fan diameter/Bypass ratio	52"/~7
Thrust (SLS/+27)	101.33 kN
Specific fuel consumption at cruise flight	Not available
Weight of the propulsion system	1877.87 kg class
Emissions (relative to CAEP/6)	To be determined

- B. Fuel-cell hybrid engines can be used to increase engine efficiency; these engines work on the principle of a proton exchange membrane (PEM)-based fuel-cell stack [51]. The 'fFan' is a fuel cell gas turbine hybrid device with a single-spool gas generator. The power generated can be delivered to the attached motor fan, batteries, or other electric propulsion units. This type of engine was developed by Boeing; see Table 2.4-2 for more details.

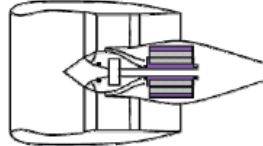
Table 2.4-2: The concept Hybrid fFan engine [52]

Schematic of the engine	
Name of the engine	fFan
Type	Gas turbine-fuel cell hybrid
Airframe	SUGAR Volt
Fan diameter/Bypass ratio	89"/~10
Thrust (SLS/+27)	Not available
Specific fuel consumption at cruise flight	-15% to -25% class
Weight of the propulsion system	6803.89–9071.85 kg class
Emissions (relative to CAEP/6)	To be determined

2.4.2 Motor-fan engines

- A. The ‘eFan’ is an all-electric motor propulsion engine consisting of an electric motor; depending on the aircraft model, it can be attached to a high bypass fan, which can be connected to a gearbox [52]. The engine runs using an external electrical power source, which can be batteries or other alternative electric units, to generate the power required for the mission. Table 2.4-3 shows the specifications of the all-electric motor propulsion engine, ‘eFan.’

Table 2.4-3: The concept All-electric motor-fan engine [52]

Schematic of the engine	
Name of the engine	eFan
Type	All-electric
Airframe	SUGAR Volt
Fan diameter/Bypass ratio	90"/19
Thrust (SLS/+27)	113.429 kN
Specific fuel consumption at cruise flight	-100% (Based on CFM56)
Weight of the propulsion system	3175.15 kg class
Emissions (relative to CAEP/6)	-100% (Based on CFM56)

- B. The ‘hFan’ hybrid fan engine is an advanced version of the conventional CFM56 gas turbine engine, which has a larger fan diameter (by 28") and a higher take-off thrust (by 2,600 lbs) compared to the hFan engine. The lower thrust of the hFan engine can be attributed to a higher percentage of power-sharing between the

generator and the turbine. Table 2.4-4 presents the integration of a Boeing hFan engine in a SUGAR Volt airframe. The ‘hFan’ is a gas turbine-electric hybrid engine that can work in three different modes, as shown in Figure 2.4-1:

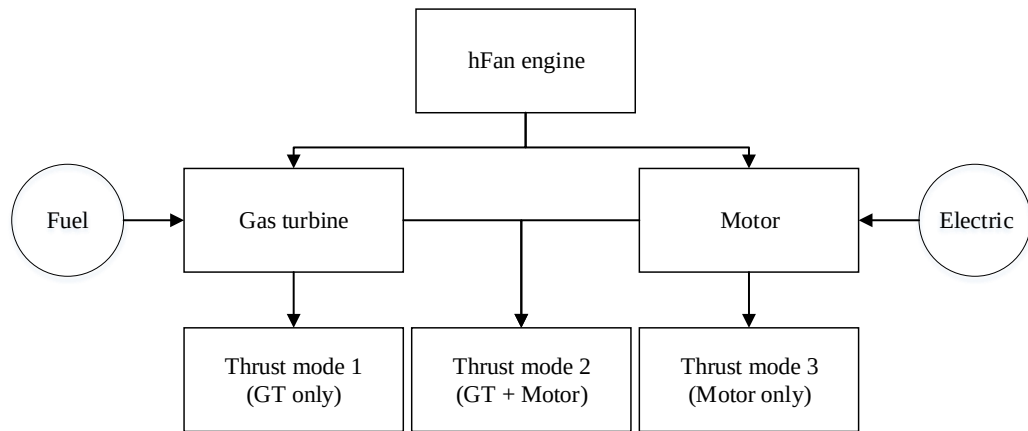
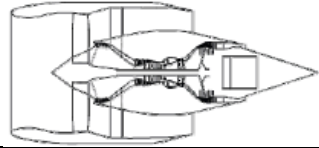


Figure 2.4-1: Thrust modes of the hFan engine.

These modes can be described briefly as follows:

1. Mode 1 (complete gas turbine mode): In this mode, the output power is produced in a manner similar to that followed in a baseline turbofan engine. This means that thrust generated for the aircraft is derived solely from fuel combustion.
2. Mode 2 (hybrid mode): In this mode, both Mode 1 and Mode 2 work together and thus, both fuel and electricity are used as power sources.
3. Mode 3 (all-electric mode): In this mode, the engine works as a motor-fan engine and external electric power is required to drive the motor.

Table 2.4-4: The concept of Hybrid motor-fan engine [52].

Schematic of the engine	
Name of engine	hFan
Type	Gas turbine-electric hybrid
Airframe	SUGAR Volt
Fan diameter/Bypass ratio	89"/18
Thrust (SLS/+27)	113.874 kN
Specific fuel consumption at cruise flight	–28% (gas turbine mode); –100% (all-electric mode)
Weight of the propulsion system	4751.38 kg
Emissions (relative to CAEP/6)	Better than –72%

2.5 Comparison criteria for distributed electric propulsion

Different MEA networks provide new concepts and basis for modelling distributed propulsion. These networks primarily consist of four significant parts that differ in their propulsion methodology. The major components used in different propulsion systems are shown in Figure 2.5-1.

			
Gas turbine	Electric generator	Energy storage (e.g. battery)	Electric motor

Figure 2.5-1: Components of distributed electric propulsion [53].

These components are used for all-electric, more electric, and hybrid distributed propulsion systems. Propulsion systems differ in the following aspects – (1) the amount of carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions, (2) output power generation (which is dependent on mission requirements), and (3) class of the aircraft (which can be megawatts or kilowatts).

2.5.1 All-electric distributed propulsion

All-electric distributed propulsion can be regarded as a green propulsion system because it results in zero CO_2 and NO_x emissions.

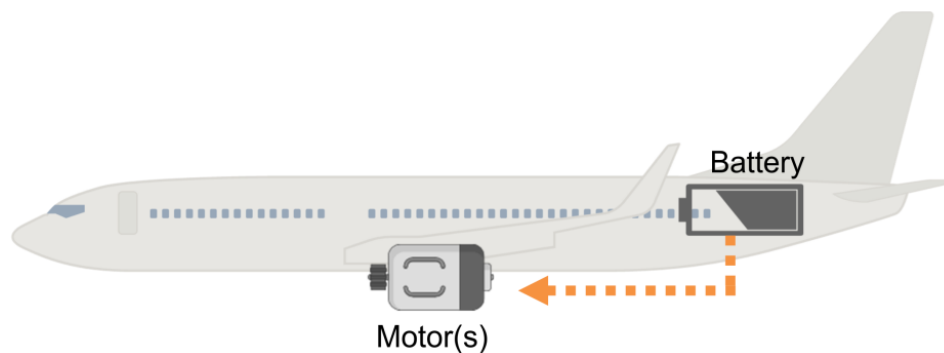


Figure 2.5-2 : All-electric distributed propulsion

Figure 2.5-2 shows a schematic of the all-electric distributed propulsion system. The power source (such as the battery in the figure) is connected to the motor to rotate the engine fan. The source should be recharged on the ground prior to each mission, and the number of motors is generally dependent on the type of aircraft. Therefore, the

relationship between the number of motors and power source is a many-to-many relationship [54], which means that many motors can be attached to many power sources.

2.5.2 More electric/hybrid electric distributed propulsion

In the current field of research, the term ‘hybrid’ implies that there is more than one type of power source. As the name implies, the term ‘more electric’ provides baseline aircraft with more electrical energy to increase thrust. There are two types of hybrid systems – full and partial hybrid systems. In full hybrid systems, thrust is generated by one or more engines or a combination of engines. Partial hybrid systems have multiple engines or a combination of engines to generate thrust. Each type of hybrid system (full or partial) can be further classified as parallel and series hybrid systems, which will be described in the following subsections.

2.5.2.1 Parallel hybrid distributed propulsion

In parallel hybrid distributed propulsion (Figure 2.5-3), the power source (such as the battery in Figure 2.5-2) is connected to the electric motor to rotate the engine fan. However, the electric motor works in parallel with the turbofan as the second source of thrust. Thus, the motor and turbofan serve as a booster for the baseline engine [54]. Moreover, the cardinality of the relationship between the batteries and motors can be extended to a many-to-many relationship, depending on the turbofan engine of the aircraft. The types of relationships, which illustrate exchange between model elements, are presented in Table 2.5-1, considering the number of powerful concepts that can be implemented [53]. X and Y in this table represent element components, while the description denotes the number of elements used relative to the other element.

Table 2.5-1: Analysis of relationships between the two elements [53].

Relationship	Description	X	Y
one-to-one	$X(1) \longleftrightarrow Y(1)$	1	1
many-to-one	$X(*) \longleftrightarrow Y(1)$	$2 \geq$	1
one-to-many	$X(1) \longleftrightarrow Y(*)$	1	$2 \geq$
many-to-many	$X(*) \longleftrightarrow Y(*)$	$2 \geq$	$2 \geq$

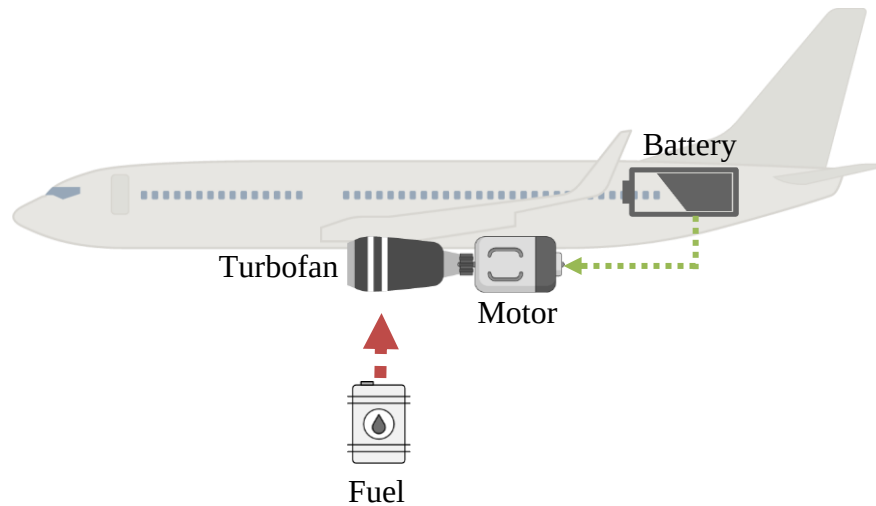


Figure 2.5-3: Parallel hybrid distributed propulsion

2.5.2.2 Series hybrid distributed propulsion

Apart from providing hybrid distributed propulsion, the series hybrid system divides the propulsion thrust into a series relationship between the motors and the turboshaft engine. Motors in a series of hybrid distributed propulsion work as a separate aircraft engine. In addition, there is an electric generator that acts as an electrical power source to run the motor or charge the battery in the series connection. Consequently, when electrical power is needed, a part of the work generated in the turbofan will be consumed. The full hybrid engine uses a turboshaft, and most of the power generated is consumed in the motors [54]. Figure 2.5-4 shows the concept of series hybrid distributed propulsion and power generation from motor engines.

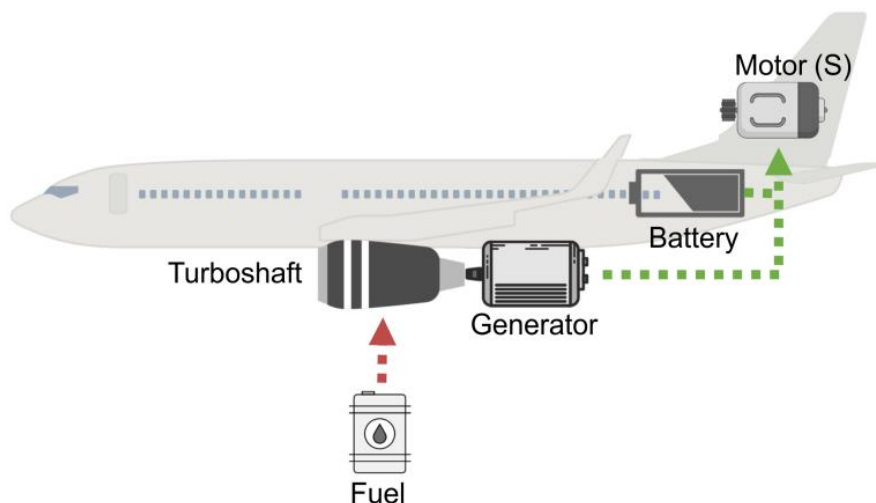


Figure 2.5-4: Series hybrid distributed propulsion

2.5.2.3 Series/parallel partial hybrid distributed propulsion

As described previously, multiple engines are used to generate thrust in partial hybrid distributed propulsion, and these engines work simultaneously in parallel. Other series-connected sources may also be used to generate thrust. Figure 2.5-5 shows the concept of series/parallel hybrid distributed propulsion. The decision to use parallel or series hybrid distributed propulsion (indicated by the blue circle in Figure 2.5-5) depends on whether the battery supplies power to the motors and generator simultaneously or separately [48,53,54]. However, if the battery is not used as the power source, it is used to charge the generator, which then supplies power to motors. Even though the number of motors, generators, and batteries is generally dependent on aircraft design and model, the concept of partial hybrid distributed propulsion (series or parallel) is similar.

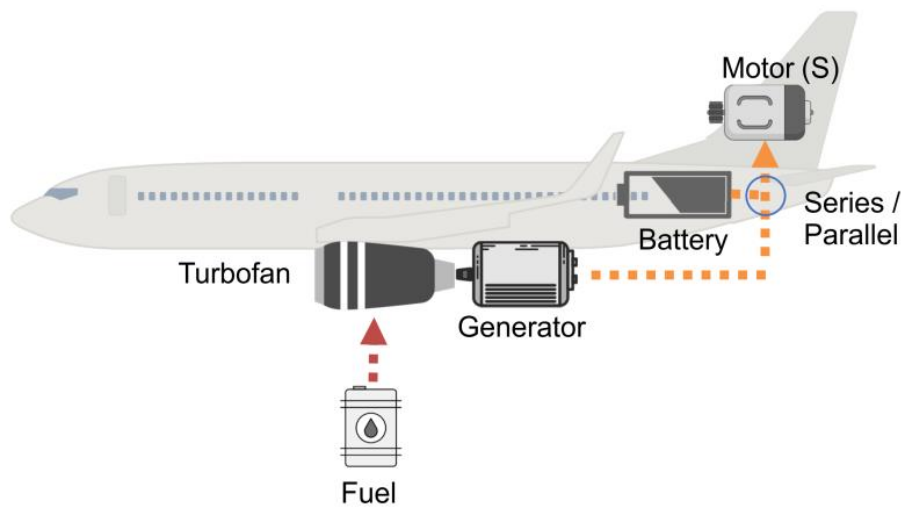


Figure 2.5-5: Series/parallel partial hybrid distributed propulsion

2.5.3 Quantitative analysis for hybrid distributed propulsion

Based on the previous description of different types of futuristic distributed propulsion, a quantitative comparison has been conducted, on the basis of the advantages and drawbacks of each type. The comparison evaluated three parameters, namely, efficiency, emission, and cost. The propulsion systems were evaluated using the criteria rated percentage as follows.

I. Efficiency [55,56]

a. Analysis method

All electric	: $\eta_{\text{Battery}} \times \eta_{\text{motor}}$
Parallel hybrid	: $\eta_{\text{Gas turbine}} \times \eta_{\text{Battery}} \times \eta_{\text{motor}}$
Series hybrid	: $\eta_{\text{Gas turbine}} \times \eta_{\text{Generator}} \times \eta_{\text{Battery}} \times \eta_{\text{motor}}$
Series/parallel partial hybrid	: $\eta_{\text{Gas turbine}} \times \eta_{\text{Generator}} \times \eta_{\text{Battery}} \times \eta_{\text{motor}}$

b. Assumptions

$$\eta_{\text{Battery}} = 90\% \quad \eta_{\text{motor}} = 90\% \quad \eta_{\text{Gas turbine}} = 30\% \quad \eta_{\text{Generator}} = 90\%$$

II. Emission analysis [55,56]

a. Analysis method

All electric	: Noise	(Number of emissions 1)
Parallel hybrid	: NO _x and Noise	(Number of emissions 2)
Series hybrid	: NO _x and Noise	(Number of emissions 2)
Series/parallel partial hybrid	: NO _x and Noise	(Number of emissions 2)
Conventional Gas Turbine	: CO, CO ₂ , NO _x and Noise	(Number of emissions 4)

b. Assumptions

All proposed alternative systems fuelled by hydrogen.

III. Cost analysis [57–64]

a. Analysis method

All electric	: Cost _(Battery) + Cost _(motor)
Parallel hybrid	: Cost _(Gas turbine) + Cost _(Battery) + Cost _(motor)
Series hybrid	: Cost _(Gas turbine) + Cost _(Generator) + Cost _(Battery) + Cost _(motor)
Series/parallel partial hybrid	: Cost _(Gas turbine) + Cost _(Generator) + Cost _(Battery) + Cost _(motor)

b. Assumptions

$$\begin{aligned} \text{Cost}_{(\text{Battery})}^* &= \$ 367\text{M} & \text{Cost}_{(\text{motor})} &= \$ 600\text{K} \\ \text{Cost}_{(\text{Generator})} &= \$ 600\text{K} & \text{Cost}_{(\text{Gas turbine})} &= \$ 4\text{M} \end{aligned}$$

* Battery lifetime assumed as 30 years for an average of 3,500 hours with a speed of 500 miles per hour. (30×3500×500 = 52,500,000 Miles)

The final analysis results reveal that the series hybrid has the most disadvantages, whereas the all-electric model obtained the most advantages. In the specific analysis, the series and parallel hybrids achieve the highest power generated for the propulsion system, whereas the all-electric model achieves the best aircraft weight and emission production. However, in terms of technology and cost, the parallel hybrid and all-electric models have almost identical percentages, which are the lowest among the models. Figure 2.5-6 presents these results and the analysis of the different distributed propulsions. From the analysed results, the all-electric system has the highest efficiency with 25% of conventional gas turbine emission and 91% more cost.

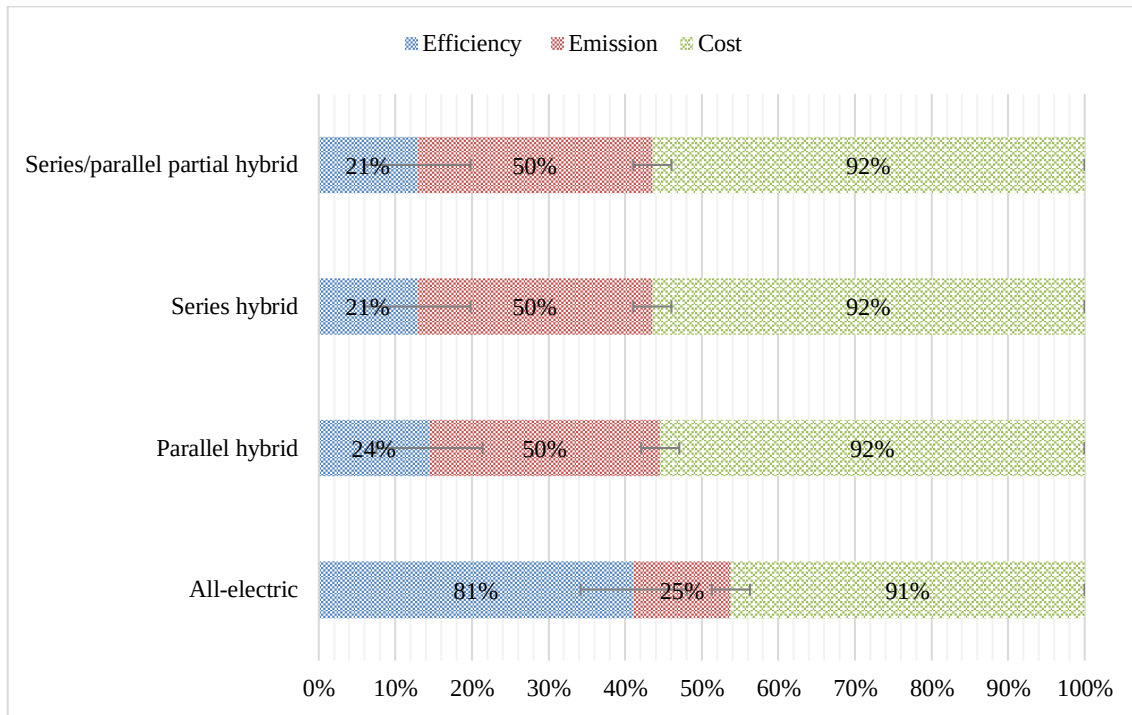


Figure 2.5-6: Comparison results between alternative distributed propulsion to the conventional system

Table 2.5-2 lists the data used for the quantitative analysis of the comparison assessment for the alternative distributed propulsion.

Table 2.5-2: Comparison assessment of alternative distributed propulsion methods

DP type	Efficiency	Emission	Cost
All-electric	81%	25%	91%
Parallel hybrid	24%	50%	92%
Series hybrid	21%	50%	92%
Series/parallel partial hybrid	21%	50%	92%

2.6 Advances in turboelectric conceptual designs

TeDP design is based on the concept of ‘just-in-time’ energy generation. This design reduces energy wastage and increases aircraft reliability, particularly in the event of single-engine failure. In addition, turboelectric distributed propulsion reduces battery weight and overcomes technological limitations to save megawatts of energy [48,54,65,66]. The currently available TeDP design can be used to transport 300 passengers at a maximum speed of 0.78–0.84 Mach [67,68]. Previous TeDP designs had a higher bypass ratio (hybrid wing-body designs) compared to baseline tube and wing aircraft. In general, the primary difference between different generations of TeDP aircraft is the aircraft design and a number of motors, which depends on fan size rather than the

required thrust. Two types of hybrid TeDP, full and partial hybrid TeDP, are discussed in the following sections.

2.6.1 Full turboelectric distributed propulsion

The TeDP or full TeDP design (Figure 2.6-1) includes a turboshaft, and most of the thrust is generated by the motors. In theory, the turboshaft must deliver most of the power to the electric generator, which means that more electric power is distributed to the motors [54]. The relationship between the turboshaft and generator is a one-to-one relationship; meanwhile, the relationship between the electric generator and motors is a one-to-many relationship.

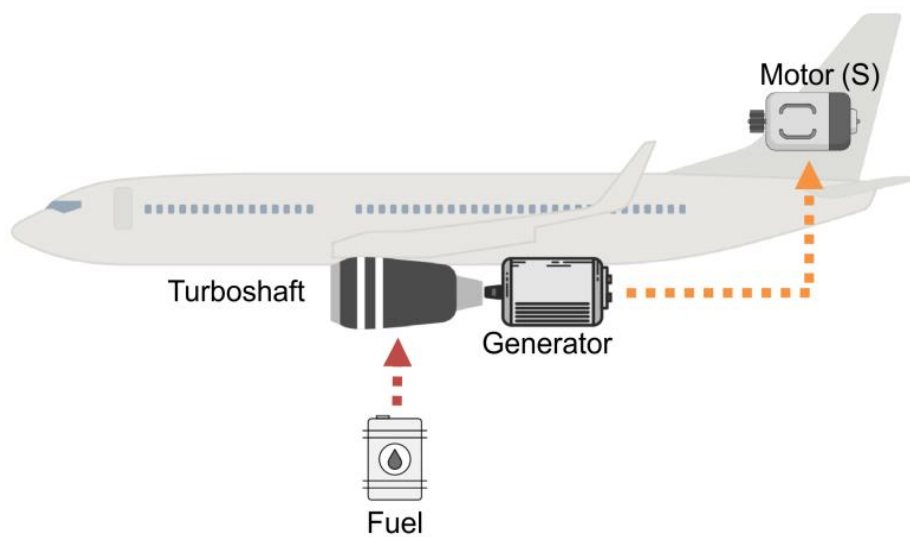


Figure 2.6-1: Full turboelectric distributed propulsion

2.6.2 Partial turboelectric distributed propulsion

Depending on the baseline engines and thrust, in partial TeDP, more thrust or power is generated using electric engines [54]. Figure 2.6-2 shows the concept of partial TeDP. The analytical relationship between full and partial TeDP components is similar, and this relationship is dependent on the TeDP design proposed for the aircraft. The only difference between full and partial TeDP depends on the gas engine used. If the turbofan is attached to the TeDP system, then part of the thrust will be obtained from the gas turbine engine and the remainder from the motor-fan.

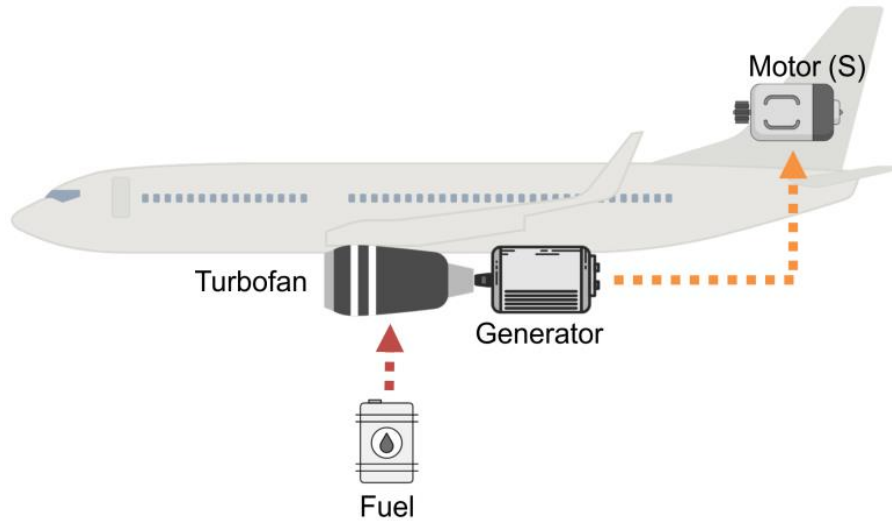


Figure 2.6-2: Partial turboelectric distributed propulsion

2.6.3 Quantitative analysis for TeDP

Based on the data available for each type of TeDP, a quantitative analysis was performed for three parameters, namely, efficiency, emission, and cost. These results indicate the advantages of each type relative to each other. The evaluation method established weights for the parameters depending on the model, components, and expected performance. The system was evaluated using the criteria percentage as follows. Figure 2.6-3 illustrates the results of this analysis.

I. Efficiency [55,56]

a. Analysis method

Full turboelectric	: $\eta_{\text{Gas turbine}} \times \eta_{\text{Generator}} \times \eta_{\text{motor}}$
Partial turboelectric	: $\eta_{\text{Gas turbine}} \times \eta_{\text{Generator}} \times \eta_{\text{motor}}$

b. Assumptions

$$\eta_{\text{motor}} = 90\% \quad \eta_{\text{Gas turbine}} = 30\% \quad \eta_{\text{Generator}} = 90\%$$

II. Emission analysis [55,56]

a. Analysis method

Full turboelectric	: NO_x and Noise	(Number of emissions 2)
Partial turboelectric	: NO_x and Noise	(Number of emissions 2)

b. Assumptions

All proposed alternative turboelectric systems fuelled by hydrogen.

III. Cost analysis [57–64]

a. Analysis method

Full turboelectric	: $\text{Cost}_{(\text{Gas turbine})} + \text{Cost}_{(\text{Generator})} + \text{Cost}_{(\text{motor})}$
Partial turboelectric	: $\text{Cost}_{(\text{Gas turbine})} + \text{Cost}_{(\text{Generator})} + \text{Cost}_{(\text{motor})}$

b. Assumptions

$\text{Cost}_{(\text{Gas turbine})} = \$ 4\text{M}$

$\text{Cost}_{(\text{motor})} = \$ 600\text{K}$

$\text{Cost}_{(\text{Generator})} = \$ 600\text{K}$

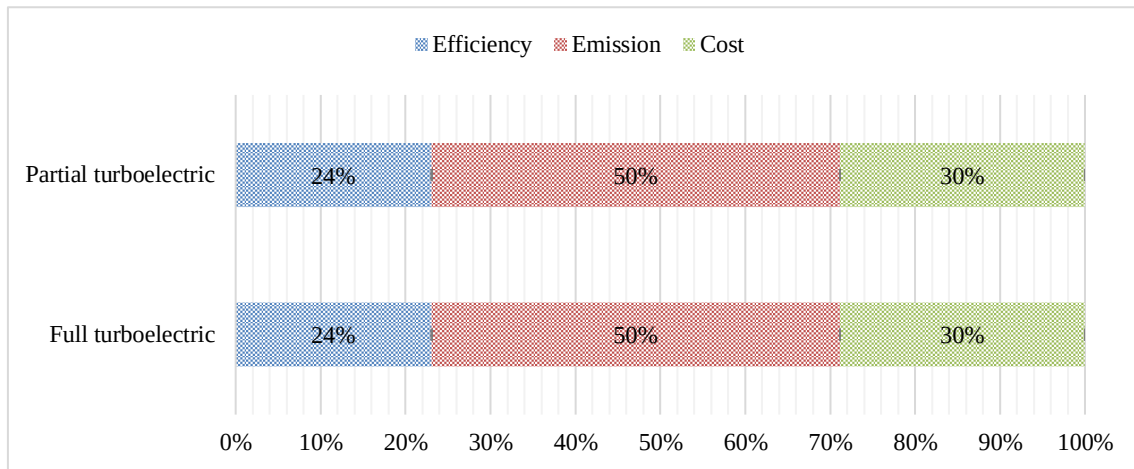


Figure 2.6-3: Comparison results between Turboelectric distributed propulsion

Moreover, Table 2.6-1 lists the data used to assist the different types of TeDP. The evaluation was performed based on the overview comparison results while accounting for a standard margin of error. The result of this analysis shows that the two types of turboelectric expected to reduce the emission to half of the conventional gas turbine with a 30% increase in cost.

Table 2.6-1: Comparison assessment of alternative turboelectric distributed propulsion methods

DP type	Efficiency	Emission	Cost
Full turboelectric	24%	50%	30%
Partial turboelectric	24%	50%	30%

2.7 Examples of proposed turboelectric distributed propulsion aircraft models

When discussing TeDP designs, it is essential to include proposed aircraft designs with advanced concepts to show how each TeDP component fits in the aircraft to deliver an alternative solution. TeDP design depends on the class of the aircraft and produces the necessary kilowatt or megawatt power for the motor fans.

2.7.1 Single-aisle turboelectric aircraft model

Among the most reliable models, the one that is closest to reality was introduced by NASA and developed by Boeing. The main feature of this model is that the aircraft tube

and wing design are retained while some modifications are made to the body; these provide an alternative solution for the motor-fan design.

2.7.1.1 STARC-ABL

NASA's Langley Research Centre (LRC) has developed a single-aisle turboelectric aircraft model with aft boundary layer propulsion (STARC-ABL). This aircraft can carry more than 150 passengers for 3,500 nautical miles [48,50,51,53,54,65–69]. The aircraft design introduces TeDP with twin underwing turbofans and a rear fuselage boundary layer for electric motor fans. This design is the most suitable for single-aisle class commercial transport. This design aims to reduce fuel consumption and emissions as compared to the current baseline aircraft model. Figure 2.7-1 shows the STARC-ABL model and the connection network between TeDP components.

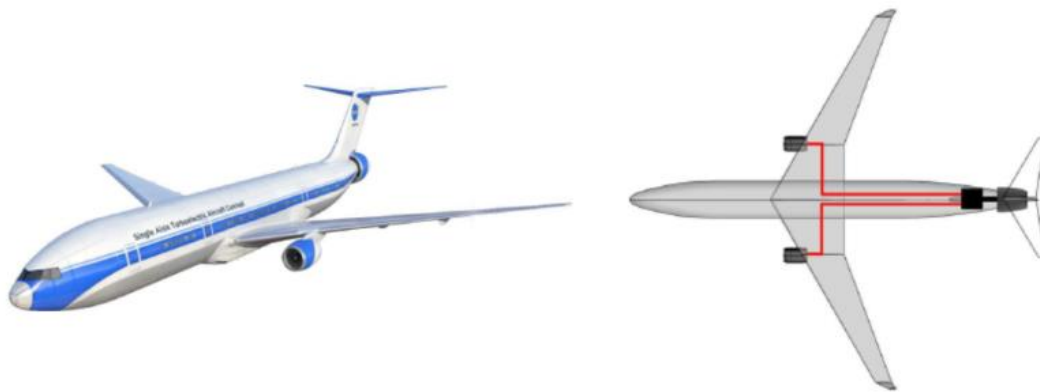


Figure 2.7-1: NASA's STARC-ABL aircraft design. The model scale is 1:48.

Electricity is generated by two underwing turbofans. Rotational power from the turbofan shaft rotates the electric generator, which extracts electric current. Fuselage propulsion in the aircraft tail absorbs electric power from underwing electrical generators and transmits it to the rear electric motor fan. This fan can operate continuously at 3,500 hp and a pressure ratio of 1.25. The pressure ratio is calculated by dividing total pressure in the nozzle section by the total pressure in the inlet fan section [70].

2.7.1.2 E-thrust concept

The concept of e-thrust (illustrated in Figure 2.7-2) is based on distributed electrical aerospace propulsion; it was developed jointly by Airbus Group Innovations, Rolls Royce, and Cranfield University [71]. This concept is based on a hybrid distributed electric propulsion; it is a 1:6 relationship model, where one power engine runs six smaller motor-fan engines to generate the required thrust.



Figure 2.7-2: E-thrust concept [71].

2.7.2 Hybrid wing-body aircraft model with turboelectric distributed propulsion

The hybrid wing-body (HWB) aircraft model is an advanced design, which differs from the tube wing design powered by TeDP. This advanced design enhances the efficiency of propulsion and reduces emissions, especially acoustic emissions owing to a significant drop in the fan pressure ratio.

2.7.3 N3-X aircraft model with turboelectric distributed propulsion

NASA has adopted the TeDP technology to meet its goals by 2050 and develop novel solutions to the challenges faced in the development of the N3-X aircraft. The relationship between TeDP components is 2:16, i.e., two gas turbine engines work to produce electric power for 16 electric motor fans [65]. Each gas turbine engine has two electric generators, each of which serves four spread motors. In the event of engine failure, all 16 motor fans work together to produce asymmetric thrust using the four allocated motors. Each motor is powered by a different electric generator. Two electric generators located at the sides of the wingtip produce the required power and thrust is distributed at the middle rear of the body-wing shape. Table 2.7-1 summarises the relationship between TEDP components and Figure 2.7-3 shows the HWB concept of the N3-X aircraft [65–73].

Table 2.7-1: Relationship between the TeDP components of the N3-X aircraft [72] (M = motor).

N3-X aircraft															
Gas turbine engine								Gas turbine engine							
Generator				Generator				Generator				Generator			
M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M



Figure 2.7-3: The N3-X aircraft concept [73]

2.7.4 Cambridge-MIT-Institute SAX-40

This concept aircraft was presented by a collaborative project conducted by Cambridge and MIT; its novelty was the low noise produced. SAX-40 could carry 215 passengers while producing an estimated 63 dBA acoustic noise. The difference between SAX-40 and N3-X with respect to the propulsion is that the gas turbine engine and motor fans reside on the tail of the aircraft. The idea of this concept is to have one gas turbine surrounding by two motor fans inside one collapse intake and nozzle. In total, it contains three gas turbine engines and six motor fans. Figure 2.7-4 depicts the concept of aircraft. Additionally, Table 2.7-2 illustrates the relationship between propulsion components [74–76].

Table 2.7-2: Relationship between SAX-40 aircraft propulsion components (M = motor).

SAX-40 aircraft					
Gas turbine engine Generator		Gas turbine engine Generator		Gas turbine engine Generator	
M	M	M	M	M	M



Figure 2.7-4: Concept of SAX-40 aircraft [74].

2.8 Numerical modelling of future aircraft performance

Numerical simulations have been conducted on two types of engineering models, viz. physical and mathematical. The physical model presents natural phenomena, while the mathematical model represents the formalism of physical behaviour [77]. Due to time and

cost constraints, numerical modelling tools are required to facilitate the development of future distributed propulsion, overcome technical challenges in aircraft models, and analyse the proposed optimal solutions. For example, numerical modelling was conducted to estimate the force and impulse of Boeing B737-800 aircraft [78]. Another study provided an open-source numerical modelling tool to estimate aircraft kinematic performance [79]. Numerical simulations have also been performed to analyse aircraft crash on a large tank [80].

There are some challenges in implementing numerical simulations for the proposed models. Future aircraft requires the integration of an increasing base of electric knowledge with legacy simulations. Electrical parts and networks influence the performance of hybrid aircraft because they play a role in aircraft propulsion. In addition, the size, weight, heat, and resistance of electrical parts affect the overall efficiency to a greater extent when compared to the calculated power.

Numerical methods used to model TeDP and MEA require a stable, robust, and flexible gas turbine engine simulator. A multidisciplinary simulator commonly used to analyse the performance of gas turbine engines is TurboMatch. It was developed in the 1970s at the Cranfield Institute of Technology (which is now known as Cranfield University) to perform thermodynamic simulations of gas turbine engines [81]. This modelling tool was later updated to simulate the performance of different types of powerful gas turbine engines. TurboMatch was written in Fortran IV to simulate the performance of various engine designs. The results are presented in the form of characteristic maps of gas turbine components, which facilitates engine performance analysis.

An evaluation of the methods presented in numerical modelling for future aircraft reveals the limitations of an integrated developing environment for assisting tools.

2.9 Existing studies on TeDP modelling

The number of published studies on TeDP numerical modelling is lower than the number of reports on aircraft design and physical experimentation. In general, studies on TeDP numerical modelling can be classified as follows:

1. Simulator

Benjamin B. Choi from NASA's Glenn Research Centre (NGRC) introduced a method to simulate the TeDP powertrain to determine the relationship between torque and speed curves [82]. His work includes an experimental study to emulate the power distributed through TeDP. The model (closed-loop electric motor control drive system) was simulated on MATLAB/Simulink to obtain propulsive fan maps. A propulsion electric grid simulator (PEGS) is an analytical TeDP model that shows the dynamic characteristics required to control the electric motor drive. This model is still under development, and many electrical components need to be added. Moreover, the performance of the TeDP model has not been evaluated, and therefore, validation is needed to determine the reliability of the model.

A novel TeDP model was developed in 2016 at Cranfield University. This model was simulated using an academic tool called the 'TeDP_SIMULATOR,' which is not a standalone tool. This tool uses an outsourcing tool to simulate turbo generator performance, and another tool was used to simulate the propulsor [83]. There is no synchronisation between these tools, and hence, the TeDP model could simulate only one type of shaft- drive gas turbine engine.

Yazar developed a design model for TeDP using MATLAB/Simulink to study the integration of turboshaft in the turboelectric system [84]. This study has been compared with real data result to assist the uncertainty of simulation reliability. The author encourages future development extension for power system design and management. In contrast, an in-house aircraft sizing tool at Georgia Institute of Technology has been used to assess the thermal implementation of TeDP for the megawatt-class aircraft [85]. This study focused on design turboshaft engines and not enhance the performance turboelectric as one system.

2. Electric architecture

The architecture of an electrical network is just as important as the thermodynamics of propulsor components. Electric architecture is related to the overall aircraft efficiency because the electrical model plays a significant role in determining the weight, size, heat distribution, generated power, and performance of the aircraft. Electric architecture describes the power generated in gas turbines and the resulting

electric thrust available for aircraft propulsion [86–88]. Thus far, researchers have mostly focused on the electric architecture of the N3-X aircraft and its model alternatives. The knowledge base developed based on these models illustrates the limitations and challenges of the superconducting concept.

3. Failure

Currently, there is limited information available on the failure of TeDP components. The available reports considered the failure of the electric network, superconducting cables, materials, redundancy management, and design methods. For example, Nolan discussed the effects of superconducting cables on TeDP aircraft performance [89]. Another study investigated the challenges and benefits that turboelectric systems can present for crewless aircraft [90].

4. Design

a. Boundary layer ingestion

Several studies investigated boundary layer ingestion (BLI) for distributed propulsion to improve future aircraft performance. BLI reduces fuel consumption by reducing propulsive power consumption [91]. Figure 2.9-1 shows the BLI concept; it produces less wake and jet kinetic energy while maintaining the same net force [92].



Figure 2.9-1: Boundary layer ingestion concept [92].

It is predicted that in the future, aircraft efficiency increases with a decrease in fuel consumption. NASA expected to achieve fuel savings of 7%–8% for the N3-X aircraft by implementing the BLI concept, despite the considerable number of electric components. The fundamental principle of BLI is to reduce wasted kinetic energy by splitting thrust between the propulsor units [93,94]. Research on an algebraic simulation has been conducted to optimise the BLI for turboelectric aircraft based on the sizing and performance [95]. This study presented a more detailed analysis of the conventional configuration.

Therefore, a RANS CFD optimisation simulation done using the OpenMDAO framework is shown in Figure 2.9-2 for the BLI fan [96]. This study recommended having a lower fan pressure ratio (FPR) and analyse a full aircraft optimisation on the thermal and aerodynamic side.

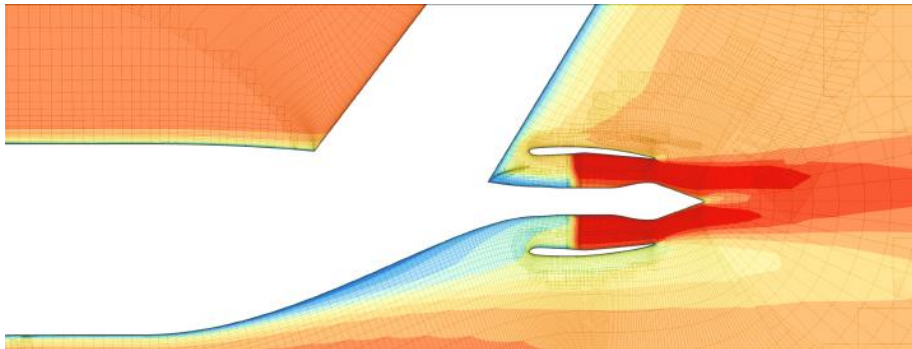


Figure 2.9-2: NASA'S STARC BLI RANS CFD [96].

Another modelling research aimed to reach 89.95% of the total electric efficiency for a single-aisle TeDP by investigating the development of a power splitter for the fans and simulating turbomachinery degradation [97].

b. Hybrid wing body (HWB)

After NASA introduced the TeDP model for the N3-X aircraft, several researchers attempted to study the N3-X model to develop novel solutions [98]. The challenges in the implementation of this new concept design include finding a way to reshape 300-passenger-class aircraft with more imaginative airframes. Furthermore, the arrangement of numerous motors and generators needs to be distributed within the frame.

c. Methods

A few methods have been reported to model TeDP; these methods vary in terms of the components included or the outcomes needed from the model. Each researcher has his/her method of TeDP modelling, depending on the area of investigation [72]. For example, Liu et al. [83] developed a method to calculate the power required for electrical propulsor units. Moreover, another methodology was developed by the same author to reduce fuel consumption and noise emission [84]. Other published methods for TeDP include a method for speed control that rewarded a 4% reduction in system weight and

propellant consumption [85] and a method for evaluating TeDP architectures [90].

2.10 Promising research areas and future trends

From the literature review, TeDP is a promising area of research compared with other alternative futuristic propulsion methods with several research directions. Each part of TeDP could be enhanced, simulate and optimised in stand-alone research. Moreover, the relation between two or more components affects the total efficiency. However, achieving high efficiency of the total system is still under consideration as it is affected by various parameters. The author's point of view for identifying proposing research areas and directions, including future trends determined in four "M"s: modelling, manufacture, mechatronics and merchandise.

1. Modelling

This area of research and development promising to overcome the current challenging of aviation drawbacks with intelligent solutions. It should solve technical threats in economic and risk safe. The future trends of TeDP in scientific modelling encompasses architecture and simulation of the system.

As examples support this overview from published work, Felder examines the effect of BLI using the algorithm of modelling and simulation tools that published on NASA technical reports. The results from work show further quality and details of design and modelling is desirable with the integration of both systems, electrical and mechanical [99]. Another model, Karen studied the fault behaviour for superconductors inside TeDP using the algorithm of modelling and simulation. The results show to have a wide range of sensitive studies to cover the fault profile [100].

A. Architecture

The notion of the TeDP concept and system implementation is exposed, but the actual design and architecture of each part of the system still not representative. The area for structure a detailed hybrid gas turbine engines, electric generators, electric motors and

even the airframe of the aircraft quite limited and needed. This includes futuristic fuel requirements such as fuel tank and batteries.

B. Simulation

The development of computer software increases rapidly in the technology of complicated simulations in sure of the time. Early researches in this area recommend implementing authentic and professional tools to study TeDP and optimise it. These include a significant level of optimisation preparatory with deterministic then stochastic and finally artificial intelligent. The thermal reaction between TeDP system elements could also be studied using CFD methods and applications.

2. *Manufacture*

After the stage of modelling and implementation, the next area of promising future is manufacturing, especially with the fourth industry evolution. Until this time, there is no TeDP system been manufactures for commercial use. Only some emulator prototypes applied to estimate the expectation of TeDP outcomes. The limitation of this area consists of manufacturing materials and operations.

A collaboration of NASA, Rolls-Royce, Georgia Institute of Technology, and the University of Strathclyde in TeDP architecture, voltage and components discussed the importance of manufacturing reflectivity on the research [101].

A. Material

Nanomaterial can be used in TeDP as the high proprieties in thermal heat conductivity it can handle. This area of research is the leak of data that consider efficiency enhancement of experimental limitations.

B. Operation

Building TeDP systems need a strategic plan and operation management to come over all manufacturing challenges. Study the right methods to apply in manufacturing TeDP systems will lead to reduce waste and improve productivity.

3. *Mechatronics*

The integration of mechanical and electrical components in the TeDP system results in the need for mechatronics science. The promising scope of the research includes computational mechanics, stability and control [102]. From the authors view the primary trends in the future for TeDP are control electronics and electromechanics.

A. Control electronics

The area of control electronic is critical in TeDP while it detects and isolates faults. This consists of current, voltage and power mode for each component in the grid. Also, it studies the system control strategy for the build-up resistance and inductance to meet the optimised target in power efficiency.

B. Electromechanics

Usage of mechanical power to get electricity (generator) or electrical power to rotate with mechanical force (motor) considered as electromechanics. The research in this area aims to reduce the losses in converting between two environments of powers as the least possible. The futuristic trends in TeDP within this area presented in the literature to focus on the electromechanical design system capable of meeting the required torque and energy in the time needed.

4. *Merchandise*

Converting the proposed technology to commercial use needs to be investigated to distinguish visibility from the potential market. The study should focus on the reliability of TeDP operation time with financial

analysis. This promising area leads by two sectors industry and supply chain of the aircraft market.

Published research by Cambridge University through Birch N. reviewed the market drives for 2020 for TeDP and the impact on the economic [103]. As a support to this chapter author's view, the outcomes show the challenges that exist in the current industry of aerospace are interesting and innovate to investigate.

A. Industry

With the growth in the aviation market and improve the industry sector, especially for the evolution of industry 4.0, there is a vision to reach for civil aviation. Stockholders of the industry need to convince about the value TeDP will add to the sector. That is why an enormous future research area of converting legacy industry systems to TeDP.

B. Supply chain

To ensure the ability to adopt TeDP within the industry; the availability of materials and parts of the system is an area to elaborate. Moreover, the supply of spare parts and experts for the new integration has the capability for the supply chain management.

2.11 Analysis of possibilities

This section presents the bounded of TeDP based on data availability. A more in-depth analysis of possibilities is needed to conduct future development and spot physical limits. Found from the overview, there are several probable enhancements and challenges to analyse the components in TeDP. These development possibilities are:

- *Aircraft airframe*

As the novel configuration of airframe needed from the concept of turboelectric, the distribution of propulsion will be divided between the motor fans and turbofans in one case or all directed to motor fans for turboshaft engines. This will mean that the current structure of aircraft needs to redesign for motor fans integrate [104–106]. Moreover, the challenge of consuming

gravity balance, space and weight should be considered in the development [105]. One of the projected designs was BLI with the risk of one prime mover and noise emission [107]. Still, there is no real design tested or built for TeDP as known for the author's knowledge. Furthermore, the high cost needed to research, design, investigate and validate a novel model.

- *Gas turbine engines*

The implementation of electric generators inside the gas turbine engine is a thrilling confrontation for the thermal and performance of both systems. Because of the high level of heat in the turbine, which will affect in negative for the electric generator performance. HTS generators also have physical limitations which will reduce the efficiency of electricity produced [65,108]. Besides, from modelling and designing point, there is a limitation of restructuring the generator concept to fit in the shape of the turbine [109]. The number of generators could implement also considered as a development challenge where it may result in a gas turbine efficiency drop.

- *Electrical motors*

There are three main development possibilities in electrical motors that essentials in applying the motors within the propulsion system. These three are cost, affordability, and technology. For example, the high cost effecting in NASA N3-X comes from a large number of motors used [110]. The lack of technology development, especially for aircraft motors, lead to the unaffordability of it and result in high cost.

- *Electrical superconductors*

This technology is related to the three previously discussed development possibilities as the embedded design of aircraft with superconducting and connected to motors and generators [65,111]. Superconducting buss has a challenges application of weighing, size, design and manufacturing material [112]. There are some research and production examples produced but still not for aero application use.

- *Numerical modelling*

The absence of TeDP numerical modelling is a critical motivation to accelerate the possibilities. Offering an authentic tool specifically for academic and research to assess the TeDP will clarify the challenges and optimise the development of TeDP [113,114].

2.12 Conclusion

The utilisation of electric power in aircraft is revolutionising the aerospace industry. However, the increasing use of electric systems present significant challenges in the development of aircraft models as well as in studies performed to achieve the desired outcomes. Research is being undertaken to bridge this gap, and several alternative power sources have been proposed for future aviation problems as shown in Table 2.12-1.

Table 2.12-1: Proposed alternative power sources for future aviation problems

Type	Full hybrid	Partial hybrid	Parallel	Series	Full TeDP	Partial TeDP
Number of main thrust sources	[1]	(1,∞)	[1,∞)	[1,∞)	[1]	(1,∞)
Number of batteries	[1,∞)	[1,∞)	[1,∞)	[1,∞)	Θ	Θ
Number of fuel sources running simultaneously	[1,∞)	[1,∞)	[2,∞)	[1]	[1]	[1]
Margin number of power sources	[1]	(1,∞)	[2,∞)	[1]	[1]	[1]
Total number of power sources	[1,∞)	[1,∞)	[1,∞)	[1,∞)	[1]	(1,∞)

This review considered the solutions and concepts, beginning from the history of electric aviation to the present and proposed technologies with an aim to collate the knowledge of different electric aviation approaches to facilitate the development of advanced TeDP architecture. Figure 2.12-1 shows a summary of this review; it presents the different aero propulsion power sources considered and their distribution, including the differences between models related to TeDP.

Most of the research endeavours in this area have focused on increasing the efficiency of current aircraft configurations. These studies have yielded a number of methods to integrate hybrid systems into distributed propulsion on a small scale with limited enhancements. Another apparent research trend is the focus on opportunities and challenges associated with all-electric motors for future implementation in the aviation sector while considering technological limitations.

Future possibilities for the civilian aircraft sector will be dominated by all-electric and turboelectric motors. Recent validation studies have been conducted to compare the three types of future alternative methods for aircraft propulsion, namely hybrid, electric, and turbo-electric that oscillate the TeDP approach [115,116]. The opinions on the probable future of the turboelectric power in civilian aircraft promising in the direction of TeDP for Megawatt class as a significant carries segment around 300 passengers and above. It could be more convenient to use for smaller segments if more research directed to enhance the science challenges in design, weight, and material. The critical element affecting the integration of TeDP into the aviation sector is the fuel for generating power. For example, if hydrogen is used as fuel for TeDP, power can be generated with almost zero emissions using a battery-less system (less weight) and just-in-time power generation.

To integrate TeDP into this sector, numerical modelling tools must be developed to analyse aircraft performance and optimise the proposed distributed propulsion models. These tools should be geared towards users working in research and development and should incorporate implementation methods to optimise the configuration of future aircraft.

In the following chapter 3, the authors of this study intend to propose a novel method that provides an integration framework environment as a TurboMatch extension to facilitate the analysis of different TeDP systems.

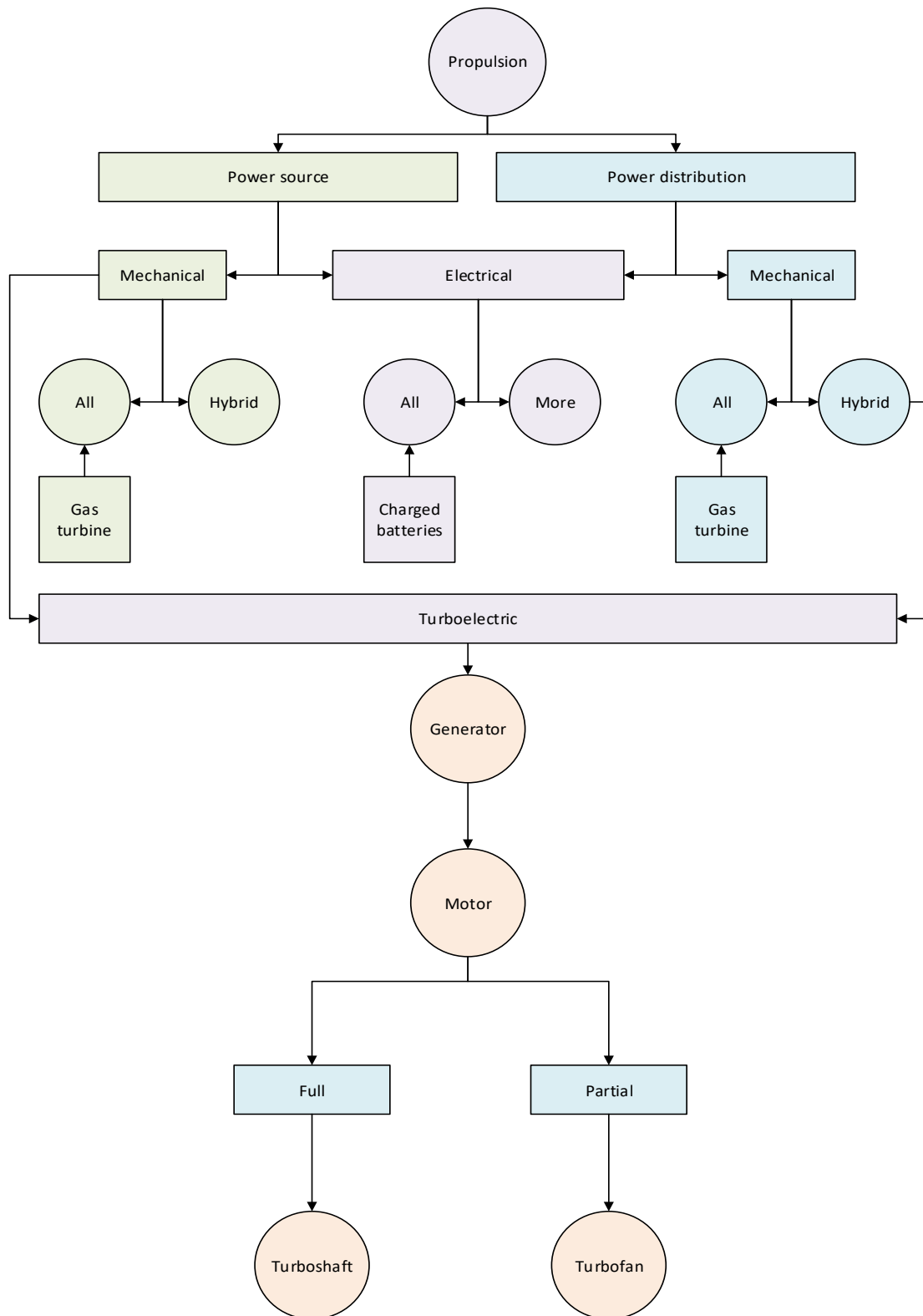


Figure 2.12-1: Summary of turboelectric aero propulsion systems [53].

CHAPTER 3

RESEARCH METHODOLOGY: A METHOD TO ASSESS INTEGRATED TURBOELECTRIC DISTRIBUTED POWER WITHIN TECHNO-ECONOMIC AND ENVIRONMENTAL ASPECTS

ABSTRACT

The chapter introduces a novel method to integrate the current research numerical modelling tools for turboelectric performance assessment along with TERA methodology. As discussed in the previous chapter 2, shortage of reliable method to evaluate turboelectric through the numeric tool intended as a result of providing such elucidation for the promising system. In the first section of this chapter, an overview of the research methodology had been described. Then the second part defined the structure of the consistent performance numerical tool used in gas turbine evaluation (TurboMatch). This defining includes the fundamental mathematical models of the electrical parts upgraded. The third section illustrates different futuristic propulsion system models built as case studies for the method validation. After that, in the fourth section, a presentation of the calculated results from the developed models expound and then been discussed in the fifth section for the current and future challenges. Finally, suggested potential solutions been accommodated for the last section. The chapter delivered a method for upgrading the legacy gas turbine engine performance tools with the futuristic propulsion systems by intending the respected of economic and environmental conditions. This established methods expected to provide a candid developing environment for exceptional integration of turboelectric challenges to arise with the novel system.

3.1 Introduction

A method to conduct research is the way that will be taken to reach the final goal and result. The method itself could be a novelty if the result is realised as intended. From that perspective, this chapter will present an overview of the methodology for this project.

The latest version of numerical modelling tool TurboMatch 2.1 and more electric propulsion systems information best available conceptual approaches are used. The method overview for integrating turboelectric and developed system models descriptions are discussed in the following sections. In addition, six case study models introduced for all-electric, hybrid and turboelectric distributed power systems and their results are presented in the sections below as they arise. This method is predicting techno-economic environmental risk assessment for integrated turboelectric using existing NASA's research development literature until real production data available.

3.2 Overview of the Research Methodology

The methodology framework for the research project is divided into five separate stages to cover the research objectives. Each stage is connected to the previous stage and is built on it. Figure 3.2-1 explains these stages and illustrates the model relationships in each stage. The five stages are as follows:

1) Preparation and calibration

This initial stage contains a prime model of turboelectric contains two sub-models electric generator and motor. The aim of this stage is to understand the extensive of a turboelectric aircraft concept and then to model a case studies with the available data for this project. The model of electric generator will take the power shaft from the gas turbine engine to estimate the eclectic power based on the generator specification. The output will be voltage, current, electric power and power transformation efficiency. The motor model, on the other hand, is adverse to generator model by estimating the mechanical power, torque and efficiency for the given motor specification. These two sub-models with the electrical grid specification, which could include the converter or rectifier, deliver the turboelectric model. The outcome from the preparation stage will be the mechatronics data to be as an input for the next stage.

2) Development

After the first stage is established, mechatronic numerical modelling is used to develop the computing part of the project by converting the turboelectric model into programmable code. This stage divides into two parts: the simulation tool TurboMatch and numerical optimisation model for the electrical grid.

The developed turboelectric model from the previous stage upgrades the legacy TurboMatch software in this stage by introducing generator and motor. Then the outcomes of electrical power and efficiency used to next model to increase the electrical efficiency. The optimisation model consists of methods to analysis Monte Carlo and Latin Hypercube. After the optimisation process, electrical power stability and reliability for the case study model would be cumulated as output from the model. This part developed on extension tool (GridMatch) for TurboMatch as the power median and carrier changed. There is a return loop between the two as optimisation of the electrical part could reduce the required power and result in an increase the total mechatronics efficiency.

3) Measurement

This stage contains two models, economic and environmental, which cover the other two studies in TERA method. The economic model has finance methods to calculate and estimates the projected profit using economic add value. This could be done through the merge of the techno-economic data from turboelectric case studies that require collection for economic analysis. After that, the environmental model related to the economic model in converting and collecting the data of the emission by using the input-output analysis method to find the weight and level of emission.

4) Analysis

To assess the risk of turboelectric distributed power in the modelled components, techno-economic and environmental aspects need to be composed for the optimum in the three segments. Moreover, find alternative integration for turboelectric by applying the key performance indicators analysis been included in the risk assessment. Validation of the given outcome could take part in this stage before proposing the integration.

5) Results

This stage delivers the research outcomes that cover the TERA methodology and the aim of the project. The outcomes presented in the type of quantitated analysis with future trends of development.

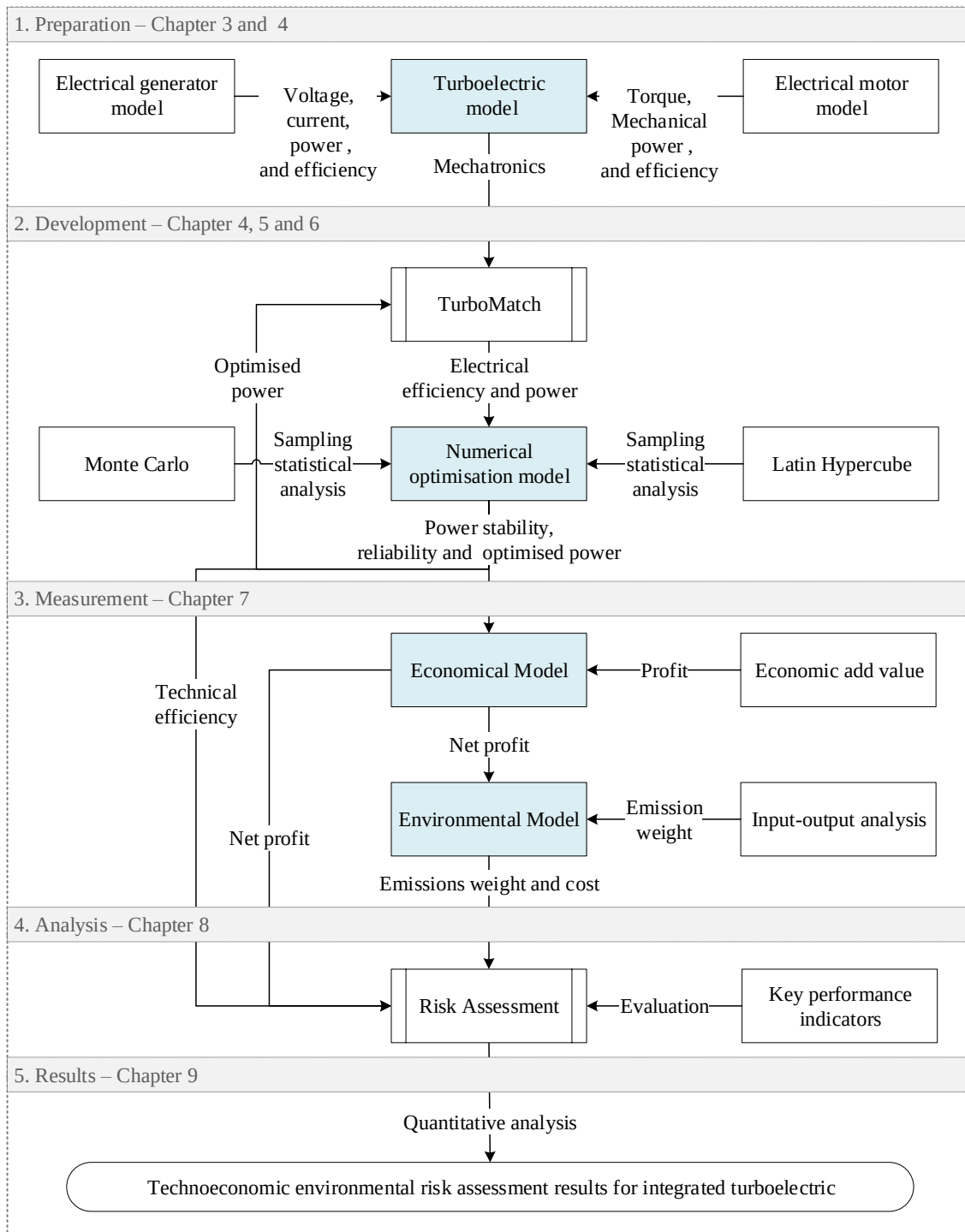


Figure 3.2-1: Research methodology flow chart.

To illustrate the contributed models add to TeDP research, in Figure 3.2-1 the blue rectangular shows the core knowledge implementations. Each model has its own elements that could be a method, micro model, analysis or process to produce an input for the model. These models were chained together as each one related to the other outcomes.

3.3 Defining the ‘More Electric’ Aircraft Model

The modelling for MEA within the preparation and calibration stage is divided into two sections: TurboMatch and mechatronics. The first section covers the modelling environment, while the second covers initialising and sizing the mechatronic model power studies conducted within the numerical modelling for the next stage.

3.3.1 More electric to all-electric integrated developing environment

Cranfield University developed a set of generic gas-turbine elements in the TurboMatch modelling environment that can be used to assess the significant type of all-electric to ‘more electric’ (increased electric) distributed propulsion.

The advanced version of TurboMatch models, which was constructed by NASA and Georgia Tech, and the authentic published methods ensure the flexibility, usability, and verifiability [48]. The potential algorithm for such a model follows the software engineering principles and the TurboMatch modelling structure. The implemented list of modelling elements includes primary station vectors and the main electric components needed for the electric calculation. TurboMatch has the elements to model the turbofan and turboshaft in the MEA case studies for the designed housing and the mechanical construction of the mechatronic part, while the electric model components are discussed within this chapter.

The TurboMatch software architecture method could be an analogy to wall construction. The building process needs three components: bricks, mortar (cement between the bricks), and render (rendering the outside of bricks). When applied, the individual elements in gas-turbine or electric models represent the bricks. Station vector items connect the different bricks together as mortar and represent the fundamental units in the calculation process. Finally, the render defining the brick data is needed for covering bricks (as inputs) but is still not part of the station vector [81]. Figure 3.3-1 illustrates these components in the black bricks for the model element, blue for the brick data, and white mortar for the station vector.

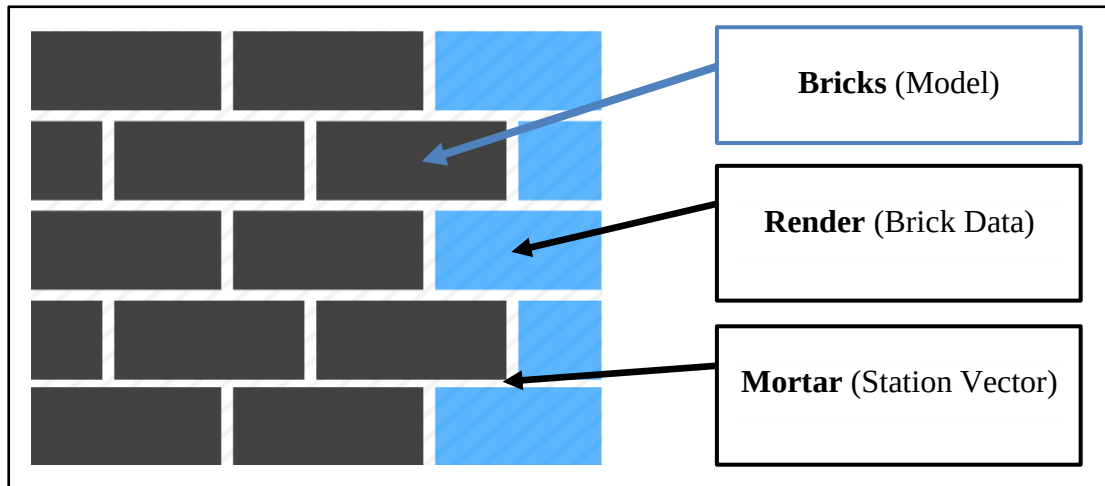


Figure 3.3-1: TurboMatch software architecture.

The individual electric-element bricks in MEA modelling that will be described in this chapter need to have new components for the mortar (station vector) to model the electric parts. Electric station vectors are in Table 3.3-1 with their suggested symbols for the next development stage.

Table 3.3-1: Electric station vectors.

Electric Station Vectors	
VOLT	Voltage, Electric Potential, Electric Pressure, or Electric Tension
EI	Electric Current
EFR	Electric Frequency
PHS	Polyphaser

These are the basic electric station vectors that will allow connecting the electric elements and sizing them for the performance calculation.

3.3.2 Fundamentals of the electric model

A suite of electric elements grants electric propulsion systems of both types (full and hybrid) to be modelled with TurboMatch. The construction of these elements is made with a simple base model to be extended in the future development of TurboMatch if needed. Still, there is flexibility to connect these models to the network with any number of power sources required. The superconducting technology is also included in the model construction to have the chance to customise the model for superconducting and

conventional conducting. The limitations on the simple base model consist of significant amount of power loss than the complex model. Also, simple model would not consider the design specification, dimension, size and weight of the components.

3.3.3 Electric motor modelling

As mentioned in the primary electric model, to have flexibility and simplicity, the electric motor was modelled to allow long- and intermediate-term modelling with the capability of both superconducting and non-superconducting motors. Even in the electric network, the backing of cryogenic propulsion systems is combined in this model.

The electric motor model influences the following parameters in the numerical calculation:

- V_i = Back electromotive force (back emf) is the power spine of the motor.
- V_r = Volt-amperes reactive or reactive power (KVAR) is the power needed to produce the magnetising flux.
- V_a = Watts or actual, active, or real power (KW) is the power that makes the useful work.
- V_t = A parent power (KVA) is the summation of both KW and KVAR.

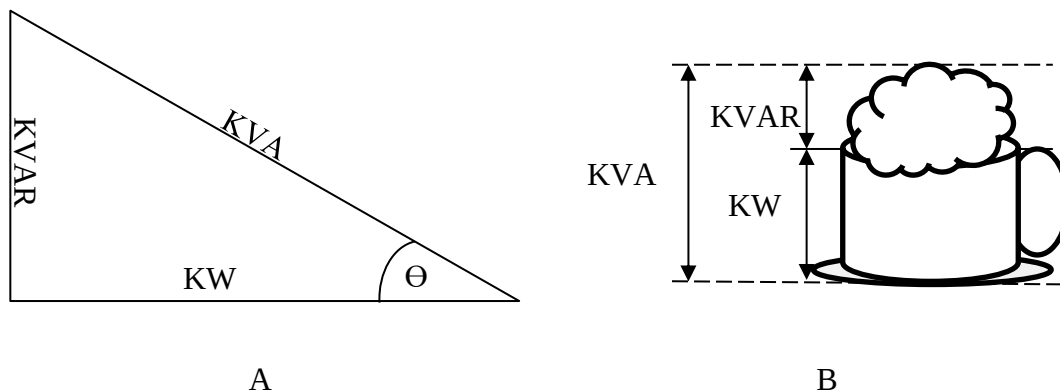


Figure 3.3-2: Electric power factor triangle and explanation.

Figure 3.3-2 shows the relationship between the KVAR, KW, and KVA. In the same figure, B shows an analogy of the power with the coffee cup. The real liquid coffee represents the real power, which is KW, and the foam, which is a part of the coffee but

not real coffee, represents KVAR. These two powers, KW and KVAR, together give KVA, which is the whole or the coffee in the example. Moving to A, this relation can be expressed in the Pythagorean Theorem, called the power triangle.

$$KVA = \sqrt{KW^2 + KVAR^2}, \quad (3-1)$$

where the two motor constants are as follows:

- K_e = Back electromotive constant,
- K_t = Torque constant.

To find the induced voltage in the motor V_i , K_e is multiplied with the rational speed of armature or the angular velocity (ω):

$$\omega = \frac{\text{frequency}}{\text{pairs of poles per phase}} \cdot \frac{60}{2\pi}, \quad (3-2)$$

$$V_i = K_e \cdot \omega. \quad (3-3)$$

By finding the value of the back emf power, the value of the actual power V_a can be found by adding V_i to Ohms law:

$$V_a = V_i + I \cdot R, \quad (0-4)$$

Where I refers to the current and R refers to the resistance. Moreover, the reactive power V_r can be formulated by multiplying the current I with inductance L :

$$V_r = I \cdot L. \quad (3-5)$$

Again, the apparent voltage V_t that represent KVA will be defined as follows:

$$V_t = \text{sqrt}(V_a^2 + V_r^2). \quad (3-6)$$

To find the angle θ between V_t and V_a , use the follows:

$$\theta = \arctan\left(\frac{V_r}{V_a}\right). \quad (3-7)$$

After deriving the results from the previous equations, the motor outcome power factor, motor work, torque, and efficiency can be calculated with these formulas:

- Since K_t and K_e should have almost the same value, the assumption for this model is to substitute K_e with K_t , and the following unit applies.

$$Torque = Kt \cdot I \quad (3-8)$$

$$Power Factor = \cos \theta \quad (3-9)$$

$$\bullet \text{ Output Motor Work} = Vt \cdot I \cdot PF \cdot \sqrt{\text{number of phase}} \quad (3-10)$$

$$\bullet \text{ Efficiency } (\eta) = \frac{\text{output motor work}}{\text{input motor work}} \cdot 100\% \quad (3-11)$$

The electrical model (EMOTOR) in the TurboMatch program will be presented in Table 3.3-2.

Table 3.3-2: Electrical motor (EMOTOR) model.

Brick		Electrical Motor (EMOTOR)
Brick Data		
1	MKE	Motor constant
2	MR	Motor resistance
3	ML	Motor inductance
4	NPM	Number of Pole pairs in the motor
5	HTSM	High-temperature superconducting motor
Motor Vector (Not SV Outputs)		
1	MTOR	Motor torque
2	MPWFC	Motor power factor
3	MWORK	Motor work
4	MEFFI	Motor efficiency

3.3.4 Electric generator modelling

The electric generator model will have the formulation and assumption that the electric model had, only changing the sign to negative in these two equations.

The real power is:

$$Va = Vi - I \cdot R. \quad (3-12)$$

Moreover, the reactive power is:

$$Vr = -I \cdot L. \quad (3-13)$$

The TurboMatch electric generator model is presented in the following table 3.3-3.

Table 3.3-3: Electric generator (EGNRTR) model.

Brick		Electrical Generator (EGNRTR)
Brick Data		
1	GKE	Generator constant
2	GR	Generator resistance
3	GL	Generator inductance
4	NPG	Number of pole pairs in the generator
5	HTSG	High-temperature superconducting generator
Generator Vector (Not SV Outputs)		
1	GTOR	Generator torque
2	GPOW	Generator power
3	GEFFI	Generator efficiency

3.3.5 Cooperative electric-elements modelling

To connect the motor and generator to the electric element, the efficiency of the cooperative electric elements was considered to have an accurate result for the simulation. Cooperative electric elements include several types of power converters (inverter, rectifier, and transformer), a temporary power source storage (battery), and a heat management system.

3.3.5.1 Electrical converter

The model brick for the electric converters is to find their efficiency to determine the change in the power network and power loss. Three electrical elements in this model allow the movement of power. First, the power inverter converts direct to alternating current (DC to AC) and frequently has a high overall efficiency, which is calculated as:

$$\text{Inverter efficiency } (I\eta) = \frac{\text{Power (AC)}}{\text{Power (DC)}}. \quad (3-14)$$

The second element is the rectifier device that works to invert the process of the inverter by converting the alternative to direct current (AC to DC), and the efficiency equation is:

$$\text{Rectifier efficiency } (R\eta) = \frac{\text{Power (DC)}}{\text{Power (AC)}}. \quad (3-15)$$

Finally, the transformer works with the same current (AC to AC) or (DC to DC) to transfer the adjusted electric energy, depending on the electric circuit requirement. The efficiency can be calculated for both types as follows:

$$\text{Transformer efficiency } (T\eta) = \frac{\text{Power (output)}}{\text{Power (input)}}. \quad (3-16)$$

For integrating them in TurboMatch, Table 3.3-4 shows the brick data for this model.

Table 3.3-4: Electrical converter (CCONVR) TurboMatch model.

Brick		Current Converter (CCONVR)
Brick Data		
1	DAC	DC to AC inverter efficiency
2	ADC	AC to DC rectifier efficiency
3	DDC	DC to DC transformer efficiency
4	AAC	AC to AC transformer efficiency

3.3.5.2 Battery

Since the battery is vital in MEA or AEA, as it affects the weight, operation time, cost, and availability of the advanced battery technology, it is essential to have the optimal battery selection. The defined model sizing parameters will measure the ordinary battery geometry in terms of voltage, amperes per hour, and the capacity. The suggested outcome is to calculate the wattage the battery can perform per hour and the time to discharge so that any form of the battery can be fit into the evaluation. The energy saved in the battery is measured by watt-hours and is assumed to approximately equal the pack voltage multiplied by amperes per hour as follows:

$$\text{Watt} - \text{hours} = \text{Battrey Voltage} \times \text{Amp} - \text{hour Capacity}. \quad (3-17)$$

The energy density is defined by the relationship between the watt-hours and the mass is defined as the weight effects on aircraft performance. In addition, the energy density gives the ability to compare different types of battery cells using the following equation:

$$\text{Energy Density} = \frac{\text{Watt-hours}}{\text{Mass}}. \quad (3-18)$$

The battery brick data and vector suggested for the TurboMatch model are presented in Table 3.3-5.

Table 3.3-5: Battery (BATTERY) model.

Brick		Battery (BATTERY)
Brick Data		
1	BATVOL	Battery Voltage
2	BATCAP	Battery Capacity
3	BATMAS	Battery Mass
Battery Vector (Not SV Outputs)		
1	WATHOR	Watts per Hour
2	DISTIM	Discharging Time (used for series time simulation)
3	ERGDEN	Energy Density

3.3.5.3 Electrical heat management system

One of the essential components of a fault management strategy in future aircraft modelling is the electrical management system through cryogenics or a cryocooler. To reject the overflowing heat generated from the electric part and maintain the requested performance, a cryocooler is used. The coefficient of the cryocooler performance used to examine the sizing ability depending on the heat expected to be generated due to a full load of electric work using the following equation:

$$COP = \frac{T(Cold)}{T(Hot) - T(Cold)}. \quad (0-19)$$

Table 3.3-6 shows the data brick for the cryocooler model, including the highest cooling temperature reached, the overflow heat temperature, and the power consumption that the cooling process requires for the asset system.

Table 3.3-6: Cryocooler (CRYCOL) model.

Brick		Cryocooler (CRYCOL)
Brick Data		
1	TMPHOT	Hot temperature needs to cool
2	TMPCLD	Cold temperature
3	COLPOW	Cooling power
Cryocooler Vector (Not SV Outputs)		
1	CLRTMP	Temperature after cooling
2	CRYCOP	Coefficient of performance

3.3.6 Electrical network power

The power network in the MEA or AEA has mostly considered a DC distributed network if neglecting the generator and the motor connection to the network. The technology available for networking provides two cable solutions: superconducting or conventional. The superconducting cables will lose their design capability by exceeding the current max temperature limit, while the conventional solution depends on the resistance that increases with the cable length. That loss provides the voltage drop given by Ohms law:

$$\Delta V = I \cdot R. \quad (0-20)$$

Several cables are needed in each connection, depending on the electric polyphase, and an electric bus is created. The assumption of ignoring the effect between cables was taken in this model, and the brick model for the electric cables is represented in Table 3.3-7.

Table 3.3-7: Electric cables (ECABLE) model.

Brick		Electrical Cables (ECABLE)
Brick Data		
1	NR	Cable resistance
2	NΔV	Cable voltage drop
3	SCC	Superconducting cable
4	ADC	Type of carried current cable (AC/DC)
5	NCB	Number of cable buses

3.4 Outlining the Modelling Case Study

The MEA model was built to study different kinds of proposed future distributed propulsions. This section provides the project case studies for simulation based on the MEA model. The case study contains all-electric, hybrid, and TeDP configurations.

3.4.1 All electric

Greener models in future aviation depend only on the electric power source. This model as is shown in Figure 3.4-1, consisting of two parts: the cooperative electric element and the conceptual design of the Cranfield Motor-Fan 1 (CMF-1) engine. This model consists of three types of networking grid which are they Cryoflex tube carrying the more cooling liquid (blue line), high-temperature superconductor cable to supply the electric components with the power (orange line) and motor power supply high-temperature superconductor bus (yellow line). As a limitation of this model, the reverse tube of Cryoflex can be upgraded to heat the cabin.

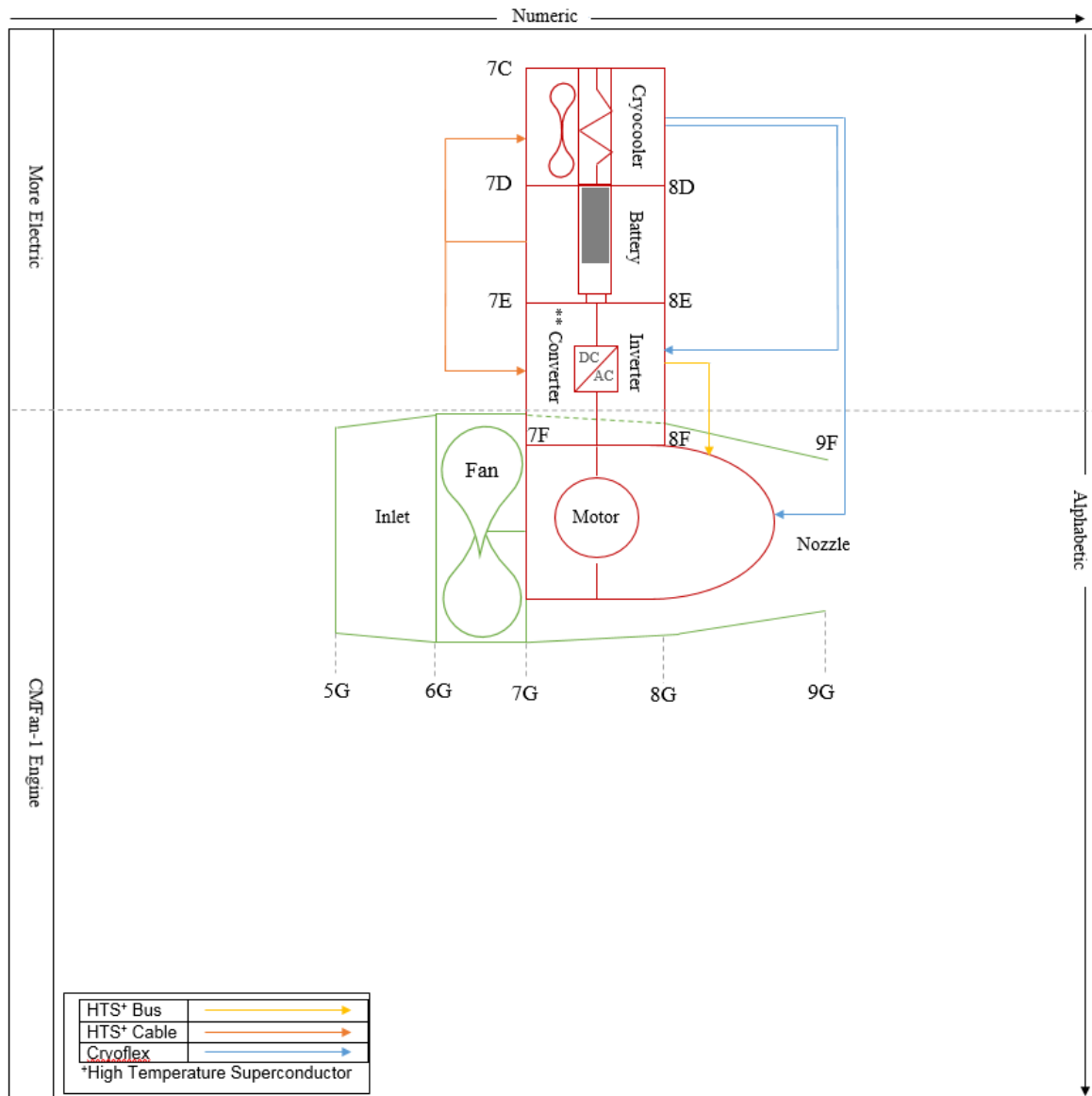


Figure 3.4-1: All-electric case study model.

3.4.2 Hybrid

A significant part of future aviation development belongs to hybrid studies. Having the furthestmost type in the case study allows the comparative estimation between them and the TeDP because the TeDP can be a part of the alternative hybrid model. The available proposed concept of a hybrid case study within this section contains three types of hybrid MEA: parallel, series, and partial.

3.4.2.1 Parallel

This model consists of two parts: the Cranfield Generator Fan 1 (CGF-1), a turbofan with an electric generator engine, as a conceptual study model and the cooperative electric

elements as shown in Figure 3.4-2. This case study model demonstrates the parallel concept with a parallel power source, generating the thrust within the same engine.

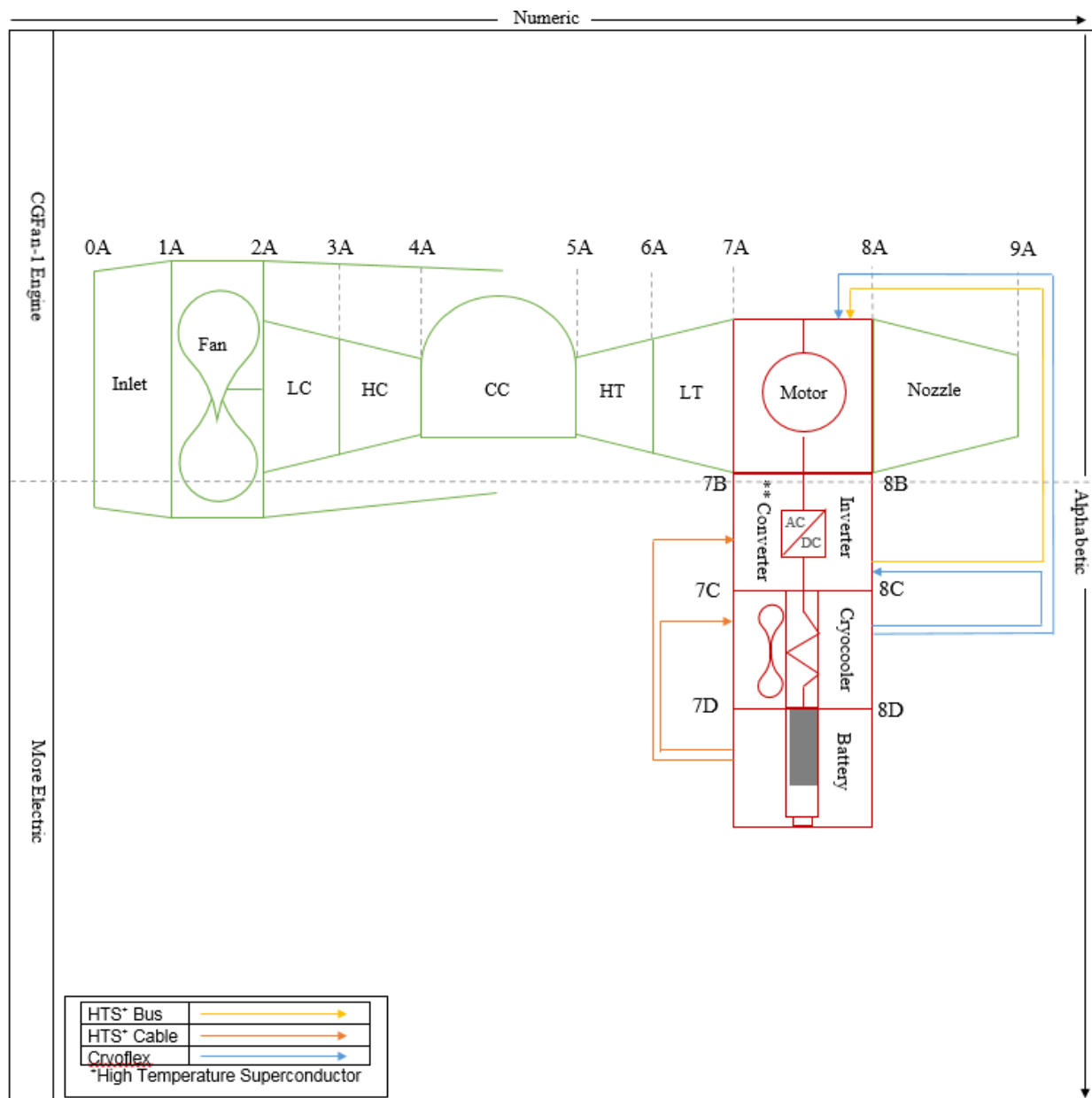


Figure 3.4-2: Parallel hybrid case study model.

3.4.2.2 Series

This concept is characterised with two power sources to generate the thrust with separate engines. They could perform simultaneously or by depending on the other, as the mission requires. The case study for this concept is modelled with two engines and cooperative electric components. The two engine concepts are the Cranfield Generator Turboshaft 1 (CGShaft-1) and the CMF-1. Figure 3.4-3 illustrates the model with the proposed electric network.

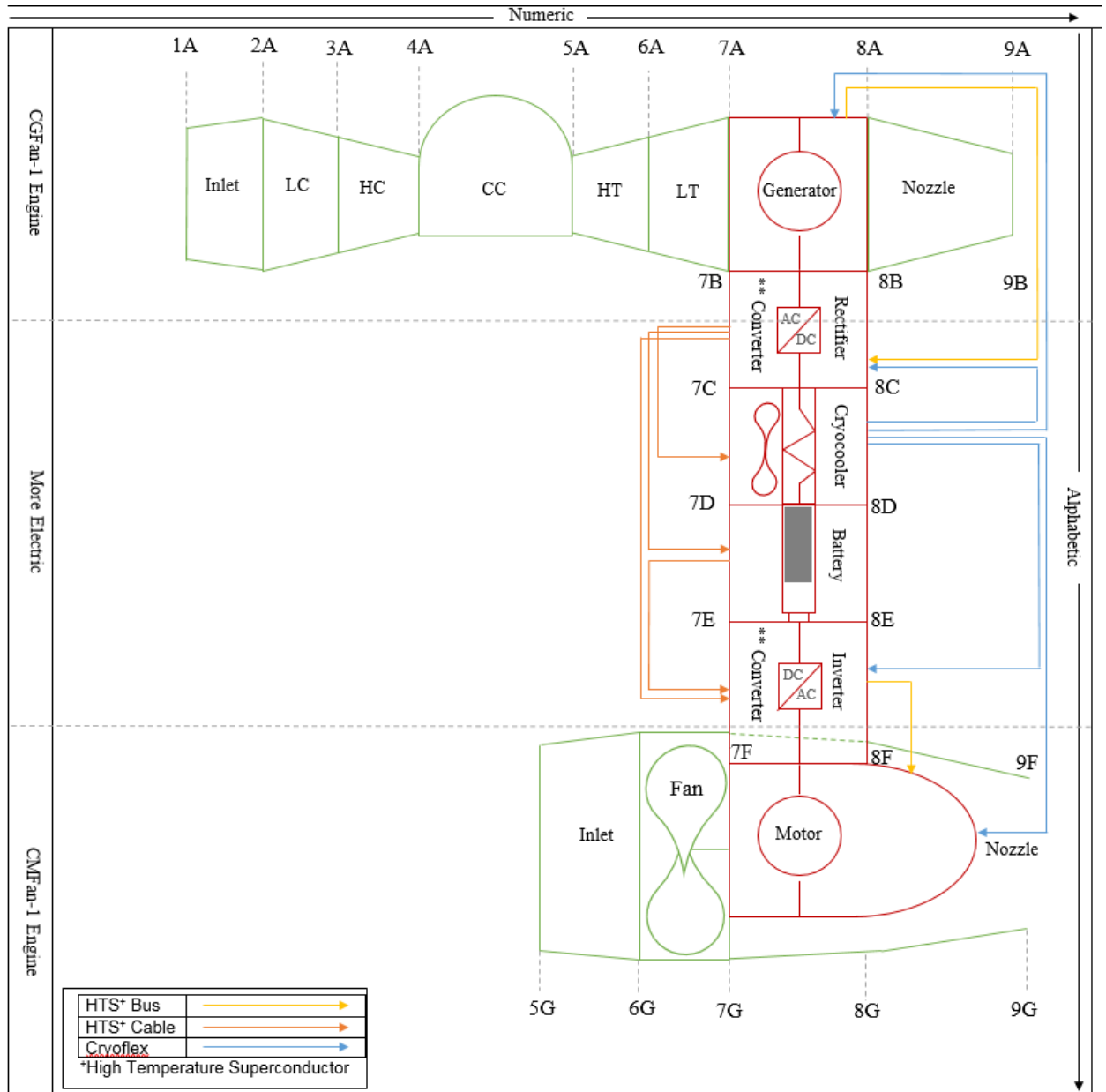


Figure 3.4-3: Series hybrid case study model.

3.4.2.3 Partial

Partial hybrid is the concept of having a portion of the power generated from the turbofan to generate electric power. That amount of energy generated from the CGFan-1 engine can be used from CMTan-1 to generate the required thrust through the cooperative electric elements. Using the two networking methods (AND – OR) produces a series or parallel partial hybrid. Figure 3.4-4 shows the parallel hybrid case study model.

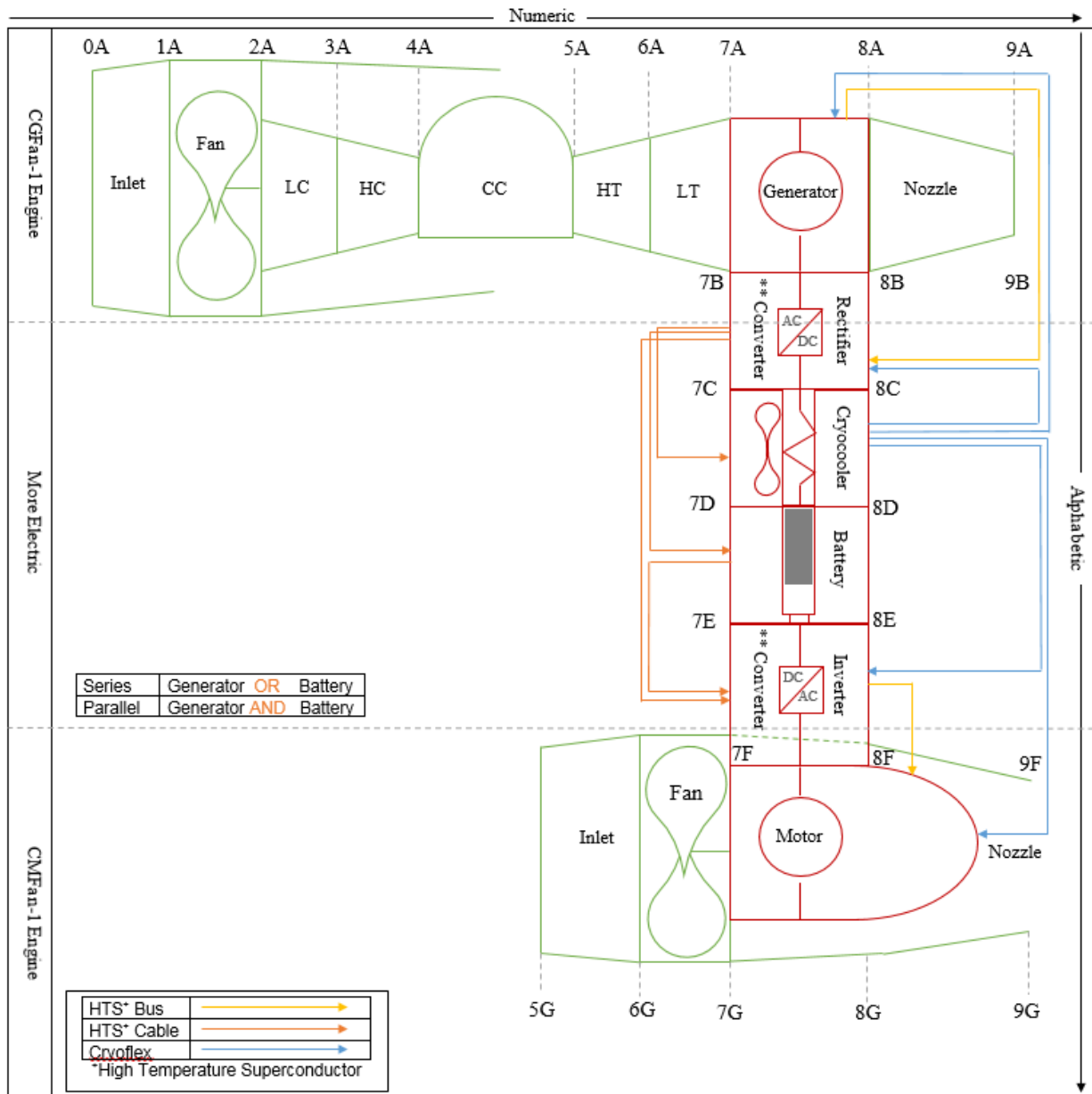


Figure 3.4-4: Partial hybrid case study model.

3.4.3 TeDP

The advantage of the TeDP concept model is that it has a lighter weight within the same class of electric power plugging. No batteries mean less power to deliver, while the energy density could have a higher relation to the mass. That provides two alternatives for TeDP with different types of engines.

3.4.3.1 Full

This case model is presented in Figure 3.4-5. The corporative electric element required for TeDP connects both the CGShaft-1 and CMFan-1.

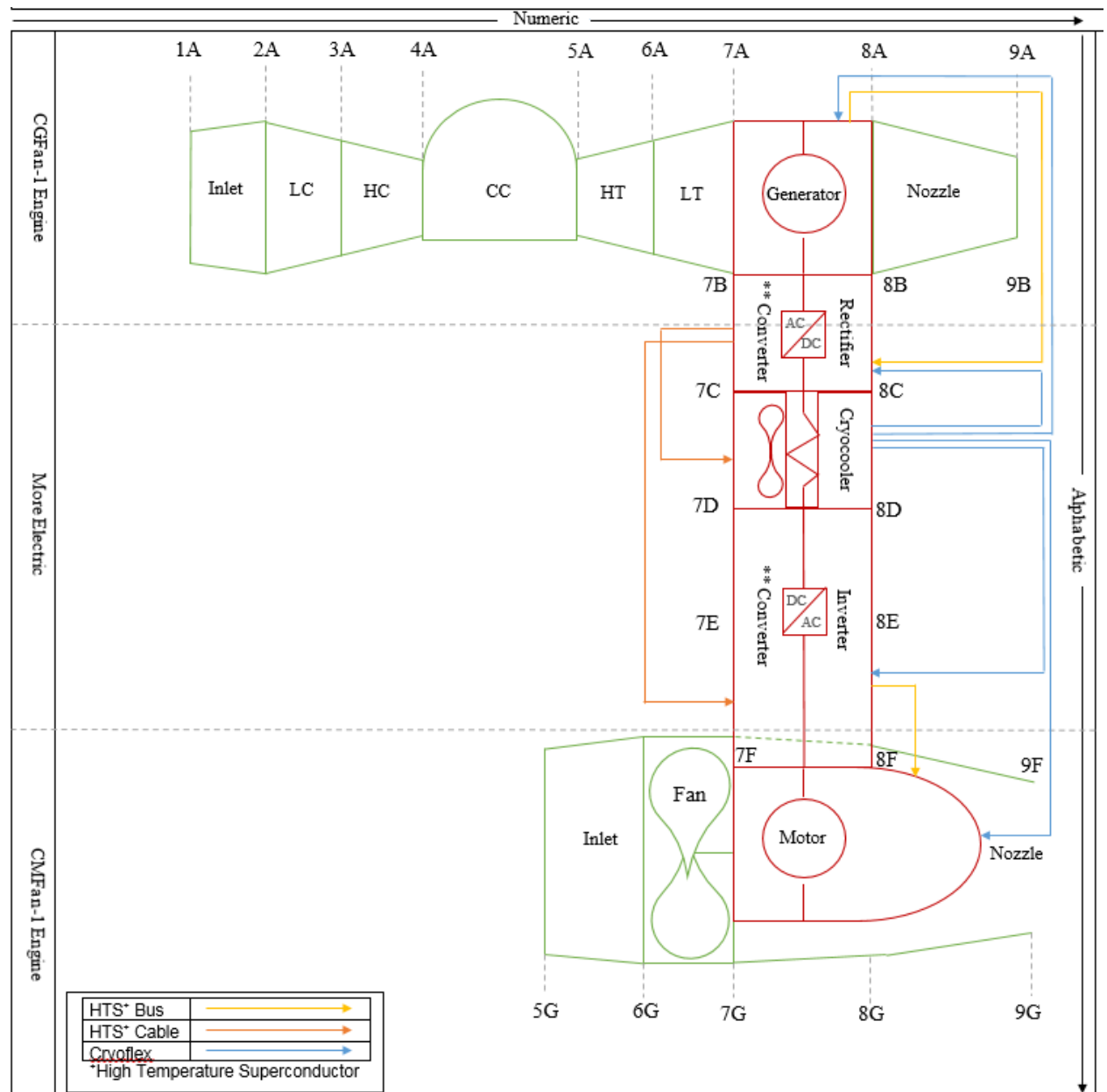


Figure 3.4-5: TeDP case study model.

3.4.3.2 Partial

Different engines from full TeDP produce partial TeDP as part of the CGFan-1 power derived from CMFan-1. Figure 3.4-6 shows the case study model for the partial TeDP model.

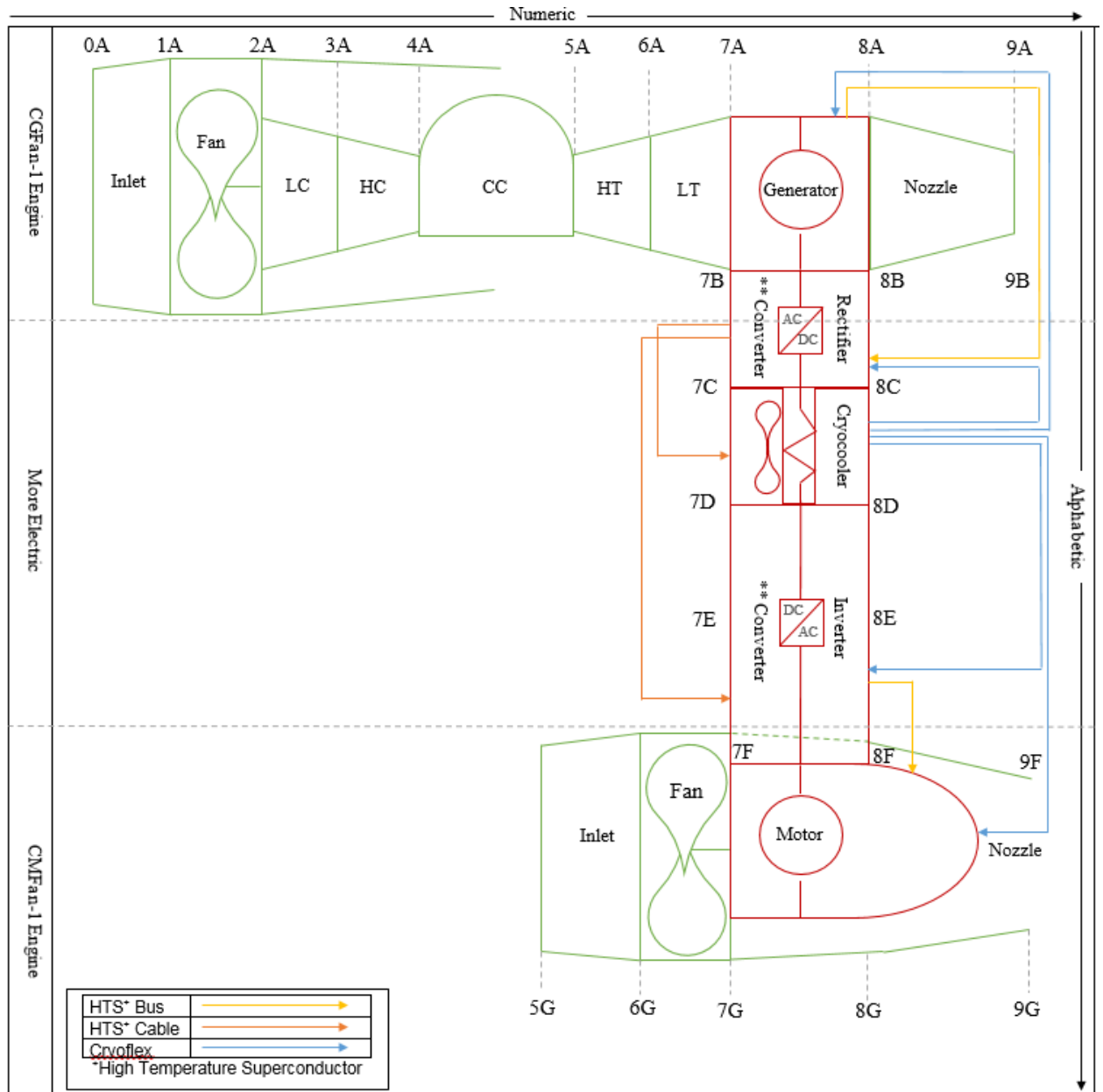


Figure 3.4-6: Partial TeDP case study model.

3.5 Case Study Models Results

System components specification and performance estimation are predicted using data from the gas turbine TurboMatch tool. The electrical characteristics adopted from published researched done to develop turboelectric components and accumulated within the proposed model. As the six models share the same baseline components, table 3.5-1 illustrates the result from the built methodology for the initial part and cover the objects given for the research.

Table 3.5-1: Modelled system components results and assumptions reflect on the case studies [31,117–122]. (* represent the presumed data from the references)

system components	Station	Component	Pressure Ratio / Total Pressure / Total Temperature / Specific Power / Specific Weight			Efficiency
CGFan-1 Engine	X-axis (A)			kPa	K	%
	0	Ambient	1	101.32	288.00	100
	1	Inlet	0.99	101.00	288.00	99.6
	2	Fan	1.45	146.45	322.35	93.9
	3	LC	1.45	212.35	361.35	92.0
	4	HC	27.9	5924.63	994.86	90.6
	5	CC	0.95	5628.39	1633.00	95.0
	6	HT	0.92	4559.10	1555.55	92.5
	7	LT	0.94	510.52	938.88	94.1
	8	Generator	8.0 hp/lb (1.44MW)	-	938.88	96.0 *
	9	Nozzle	0.93	479.00	929.00	93.8
More Electric	Y-axis (7)			kPa	K	%
	C	Rectifier	1.43 MW	-	-	99.8 *
		Converter	1.42 MW	-	-	98.8 *
	D	Cryocooler	5.00 lb/hp-input	-	2 kW @ 50	30 of Carnot *
	E	Battery	1.19 MW	-	-	99.0 *
	F	Inverter	10.0 hp/lb (3500hp)	-	-	98.0 *
		Converter	2.60 MW	-	-	99.8 *
Electrical Network	XY-axis			kPa	K	%
	8D	Thermal management System (TMS)	0.68 kW/kg	-	~ 42.2 (20-65)	30 of Carnot *
	7(B-F)	Circuit Protection	33.0 kg/MW	-	-	99.5 *
	7(A-G)	Circuit (Cables, and Buss)	3.9 kg/m (750 V,1926 Amp)	-	-	99.6 *
CMFan-1 Engine	X-axis (G)			kPa	K	%
	5	Ambient	1	101.32	288.00	100
	6	Inlet	0.99	101.00	288.00	99.6
	7	Tail Cone Fan (TCF)	1.25	126.25	307.81	95.7
	8	Motor	8.0 hp/lb(3500hp ~ 2.61 MW)	-	307.81	96.0 *
	9	Nozzle	0.95	119.93	290.0	95.0

3.6 Discussion of Current and Future Challenges

There are several challenges face the turboelectric integration. These challenges presented, as there is a lack of real data and development of electrical components, especially for destitution propulsion systems. Moreover, the conceptual studies lie in a small area of testing and implementation that need to face the real size of the engines. Cost of research, development and manufacturing extensively eliminate the visibility of real-world experimental for components system. Current challenges, therefore, narrow in the simulation and emulation accuracy development and optimisation.

Future challenges should be less than the current ones but as turboelectric will enter the servicers within the next ten years development and resolution of simulation limitations would valid. In addition, reducing the weight, size, and cost should be considered within the challenges.

3.7 Potential Solutions

As a solution for current challenges, using intelligent of era technology and automated optimisation can help in turboelectric integration. The promising technology needs to be tested in real-world with scale down methodology to validate the technology outcomes. Then the reliability of developed systems could be reflected in specific methods.

3.8 Chapter Summary

This chapter has introduced the research methodology of the research with an explanation of the different stages. This project method delivered five stages given in preparation, development, measurement, analysis and results. Through this chapter, six case study models developed and reviewed. The focus is to develop a method that could assess the integrated turboelectric systems within the techno-economic environmental studies. Further developed for technical assessment through implementations stages discussed in the follows chapters. Moreover, the economic and environmental methods and studies were discussed in chapter 7.

CHAPTER 4

MODELLING NOTATION OF MORE ELECTRIC TO TURBO-ELECTRIC PROPULSION

ABSTRACT

Currently, numerical modelling is becoming increasingly important as an essential stage in research development, particularly for futuristic projects. Although numerical modelling is advantageous for modelling a project in terms of cost and efficiency, further research needs to be conducted to analyse its effects in terms of all other aspects of project modelling. Thus, there advanced numerical notations are required to study the majority of the aspects surrounding the research that could affect the model behaviour. As a continuation from chapter 3, this chapter aims to investigate the gap of modelling notation and behaviour of turboelectric distributed propulsion (TeDP) elements; it focuses on these advanced modelling notations and analyses their behaviour from more electric propulsion in aircraft concepts to turboelectric propulsion. The study includes scientific modelling methods used in computer engineering for modelling and initialisation of a system.

Moreover, it includes unified modelling language (UML) with a state machine, structure and sequence. Subsequently, the electric generator and motor in the electric grid were modelled in a novel method. Finally, finite state automata with both types of deterministic and non-deterministic methods were applied to the model. The results of this study demonstrate that TeDP behaviour related to more electric is enhanced with electric generator type, model, and size.

4.1 Introduction

Numerical modelling architectures for aero propulsion were introduced in the '70s as a method to enable performance estimation and design resolution. Numerical modelling software systems for these architectures are advanced in terms of the structure and behaviour of the modelling components, including the connection relationship. In addition, the reliability and performance of the system can be attributed to non-functional properties. The modelling notations for software systems can be categorized into two

types of design documentation. First, informal modelling notation, which comprises simple boxes and lines, representing natural and modelling languages (e.g., UML). Second, formal modelling notation representing both specification and description languages. The informal modelling notation can be used for modelling components and their connections, whereas the formal modelling notation is used for behaviour studies in addition to non-functional property analyses [123]. The use of these two types of modelling notations enables the modification and creation of different novel, systematic, and prototypical scenarios. Furthermore, all possible processes can be conducted within the system flow, including the trap stages. The importance of these notions lies not only in their applicability but also in their promotion of further development, in addition to the development of rapid numerical systems.

Modelling research for turboelectric systems are being developed using simulation tools for power systems and management studies. An alternator model for turboelectric propulsion was designed using the MATLAB/Simulink environment [82]. This model focuses on a Turboshaft engine in connection with an electric generator and two motors [84]. Another propulsion system model was designed for single-aisle turboelectric concept aircraft with boundary layer ingestion (STARC-ABL) using the same tool MATLAB/Simulink but with a Turbofan engine [97]. In addition, a signomial (algebraic function) model was developed for electric and mechanical propulsion system components, and turboelectric was one of the case studies. The research main focus is on the model of material property and operation conditions [124]. The signomial program model was used to assess the performance of STARC-ABL [95].

Furthermore, an interconnected aerodynamics model was proposed for turboelectric aircraft. This model is based on the integration between propulsion dynamics and vehicle dynamics [125]. Meanwhile, the fault behaviour of superconducting turboelectric distributed propulsion networks was presented as a model with two stages of failure modes and effect analysis [100]. Additionally, the cabling technology for turboelectric propulsion system grids was modelled to obtain the optimal combination of power distribution [126]. A turbogenerator comprises a turbofan developed using TurboMatch (Cranfield University engine performance tool). The superconducting generator is modelled to achieve the goals of the NASA N+3 subsonic commercial aeroplane [127].

There are different types of methods for modelling systems, as well as studying, building, and analysing system components. As an alternative approach, this chapter proposes a

novel method for turboelectric modelling studies, architecture, and behaviour analysis. The proposed method, UML, models each component in terms of component, structure, and sequence that makes network architectures. Then, using the two types of finite-state automata concepts, i.e., deterministic and nondeterministic, the computational problems are solved. Finally, the analysis and discussion of the behaviour of the modelling components and stages are presented.

4.2 Defining the Multi-Approach Futuristic Propulsion

Modelling turboelectric systems requires an understanding of the multi-approach concepts of more electric systems until the turboelectric disruption propulsion system is achieved. In this manner, the relation between mechanical and electrical power is divided based on model availability. As an example, the configuration of more electric modelling ensures that the modelled components resemble a turboelectric system. Therefore, the TurboMatch, which is a gas turbine engine performance simulation tool, needs to be upgraded with two models, namely, an electrical generator (EGNRTR) model and a motor (EMOTOR) model. With the addition of these two models, almost any electric propulsion configuration attached to the engine can be assessed. However, if one or both of them are not within the engine, then they are assessed through the electrical grid. For this purpose, the extended version of the TurboMatch is used, which analyses the electrical power flow, including the electrical buss (EBUSS) model, current converter (CCONVR) model, cryocooler (CRYCOL) model, and battery (BATTERY) model. This extension as a node optimization tool enables the investigation and enhancement of the stability of the electrical power flow. Figure 4.2-1 illustrates a flowchart depicting the multi-approach futuristic propulsion and the method relationship between the modelling components. Moreover, the blue blocks in the figure show the core implementations to the numerical modelling add to the assessment process.

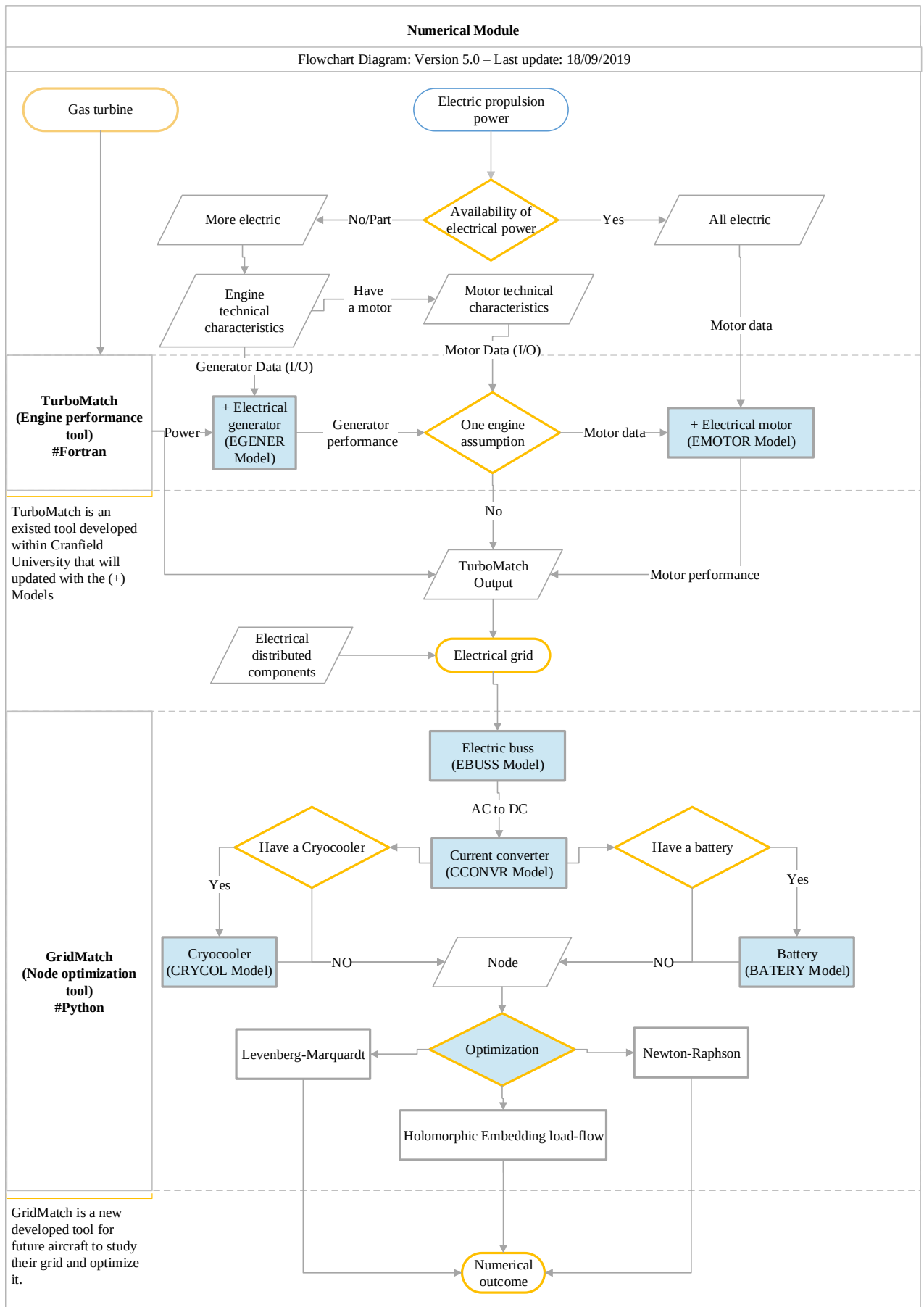


Figure 4.2-1: Multi-approach future propulsion flowchart

- TurboMatch® Upgrade

An upgrade, in general, is to add new aspects to an old object. TurboMatch is upgraded with two new models, namely, an electric generator and a motor. These two models are modelled using the FORTRAN language and structured using the same method used for TurboMatch. The model fact for each of them in terms of inputs and outputs is modelled on the basis of the outcome of legacy TurboMatch software and according to the project objectives.

- *Electrical Generator* (EGNRTR model)

This model can be divided into three stages: inputs, processes, and outputs. The inputs are mechanical power, torque, high temperature superconducting (HTS) heat, and generator resistance, generator constant, and temperature. The first two inputs are taken from TurboMatch, and the others are taken as user inputs from the manufacturing design specification data. These input data result in the following outputs following the in-process stage: revolution per minute (rpm), electric power, HTS efficiency, generated voltage, and generator current and efficiency. An additional stage is introduced if further assessment is needed, such as the use of multi generators, considering period, and efficiency enhancement, wherein the output is connected with the input to study different conditions. Moreover, this stage introduced for the optimisation process and uncertainty assessments. Figure 4.2-2 depicts the generator model with the three main stages and one additional stage.

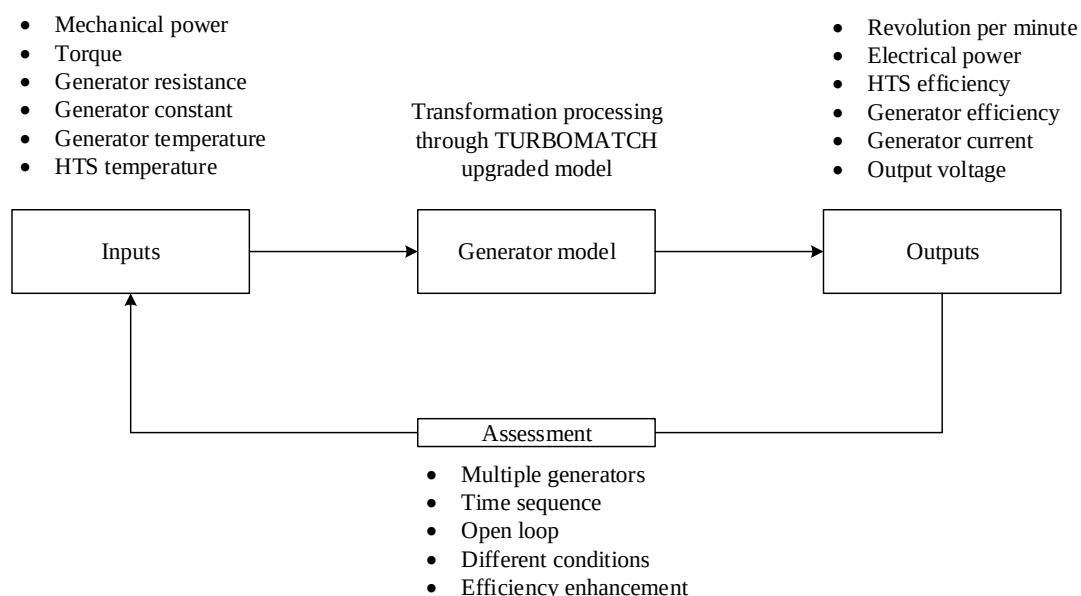


Figure 4.2-2: Electrical generator input/output

The process stage, which has the generator model, consists of a number of mathematical and physical relations. The required electrical power is converted from mechanical power through the calculation of generator model parameters. Figure 4.2-3 illustrates the considerable parameters in the model.

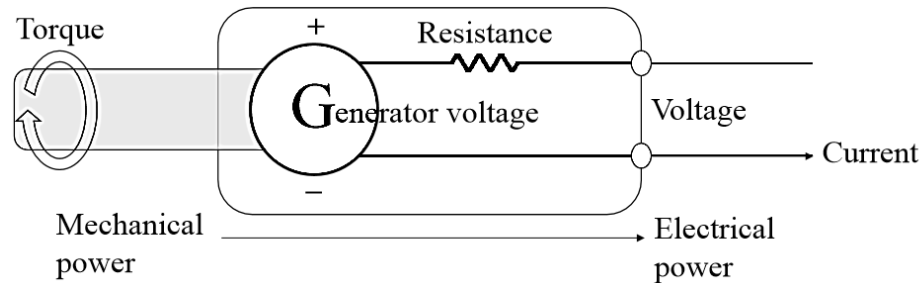


Figure 4.2-3: Electric generator parameters

To describe the generator model calculation, seven steps were formulated, listed in sequence order as follows:

- Step 1: Calculate the rotation rate from the TurboMatch data, comprising shaft power and torque.
- Step 2: Calculate the speed constant.
- Step 3: Calculate the torque constant.
- Step 4: Determine the generator voltage.
- Step 5: Measure the output current.
- Step 6: Determine the HTS affection on power loss.
- Step 7: Determine the HTS affection on generator efficiency.

Figure 4.2-4 illustrates the steps mentioned above and the connectivity between them. Also, it determined the material losses could get from the reactive power generated and the conductivity level of the material used.

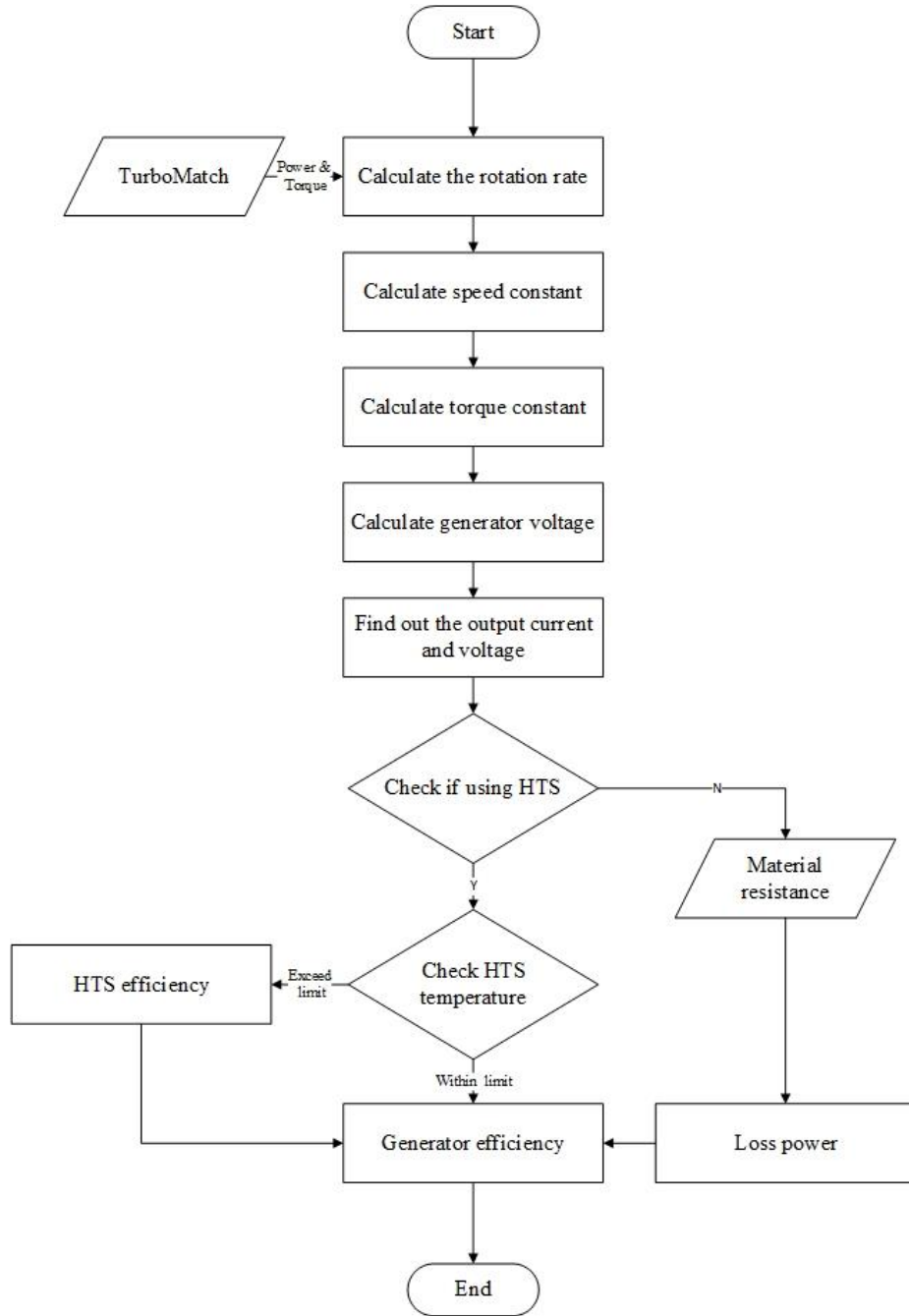


Figure 4.2-4: specific and description language for the generator model

The following are the equations used to determine the generator model steps and calculation. The sequence of these equations is simultaneously calculated with specific descriptions for the generator model.

$$Rotation\ rate = \frac{Power\ Shaft}{Tourque} \quad (4-1)$$

$$Revolutions\ per\ minute = \frac{Rotation\ rate}{\pi/30} \quad (4-2)$$

$$\begin{aligned} \text{Speed constant (Radian)} & \quad (4-3) \\ &= \frac{\text{Speed constant (Revolutions per minute)}}{\pi/30} \end{aligned}$$

$$\text{Torque constant (Radian)} = \text{Speed constant (Radian)} \quad (4-4)$$

$$\text{Generator voltage} = \frac{\text{Rotation rate}}{\text{Speed constant (Radian)}} \quad (4-5)$$

$$\text{Current} = \text{Torque} \times \text{Torque constant (Radian)} \quad (4-6)$$

$$\text{Voltage} = \text{Generator voltage} + \text{Resistance} \times \text{Current} \quad (4-7)$$

$$\begin{aligned} \text{High temperature superconductor efficiency} & \quad (4-8) \\ &= \frac{\text{Total current temperature} - \text{Temperature limit}}{\text{Temperature limit}} \end{aligned}$$

$$\text{Electric power} = \text{Voltage} \times \text{Current} \quad (4-9)$$

$$\text{If high temperature super conductor} > 0 \quad (4-10)$$

Generator efficiency

$$\begin{aligned} &= \frac{\text{Electric power}}{\text{Power Shaft}} \\ &- \text{High temperature superconductor efficiency} \times 100 \end{aligned}$$

$$\text{Else} \quad (4-11)$$

$$\text{Generator efficiency} = \frac{\text{Electric power}}{\text{Power Shaft}}$$

$$\text{Loss Determination} \quad (4-12)$$

$$\text{Loss power} = \text{Shaft power} - \text{Electric power}$$

$$\text{Loss Power} = \text{Windage Fraction} + \text{Materials Resistance} \quad (4-13)$$

$$\text{If high temperature super conductor} \leq 0, \quad (4-14)$$

$$\text{materials resistance} = 0$$

$$\text{Loss Power} = \text{Windage Fraction}$$

- *Electrical Motor (EMOTOR Model)*

Here, the same strategy is used as that used in modelling the generator. The model can be divided into three stages: inputs, motor model processes, and outputs. Revolutions per minute, input voltage, HTS temperature, and motor resistance, current, constant, and temperature are all considered as model inputs. The motor process model is described next in the motor model specification and description language (SDL). The output stage includes mechanical and electrical power, output torque, HTS, and motor efficiency. An extra stage called assessment is applied to multi motors, considering time and efficiency enhancement. Figure 4.2-5 depicts these stages.

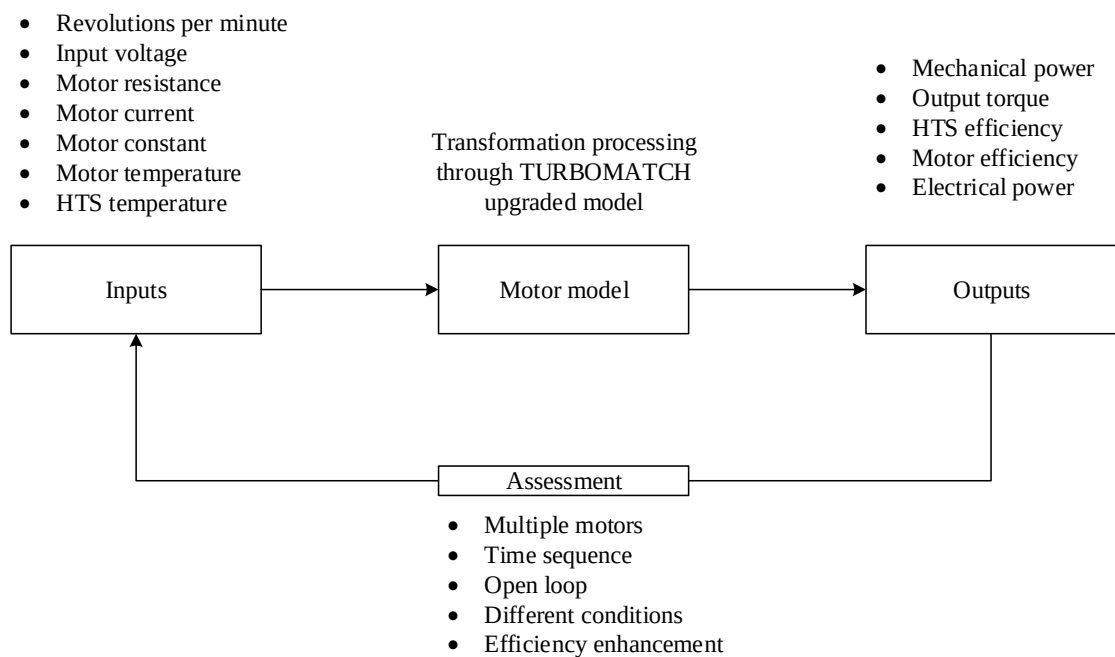


Figure 4.2-5: Electrical motor input/output

To illustrate the motor parameters, Figure 6 demonstrates the conversion of electrical power to mechanical power. The electrical power first enters the motor as an electric current and voltage. Depending on the motor type and material used, the resistance will affect the calculation process. Then, the motor voltage, which is the core of the magnetic power, is used to rotate the shaft attached. From the output torque, the adaptation in the mechanical power can be estimated. Moreover, the description and specification of the motor model process stage are depicted in Figure 4.2-6.

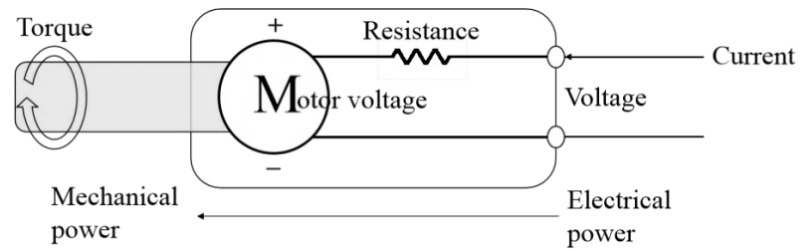


Figure 4.2-6: Electric motor parameters

Description and specification of the motor model process stage present in Figure 4.2-7.

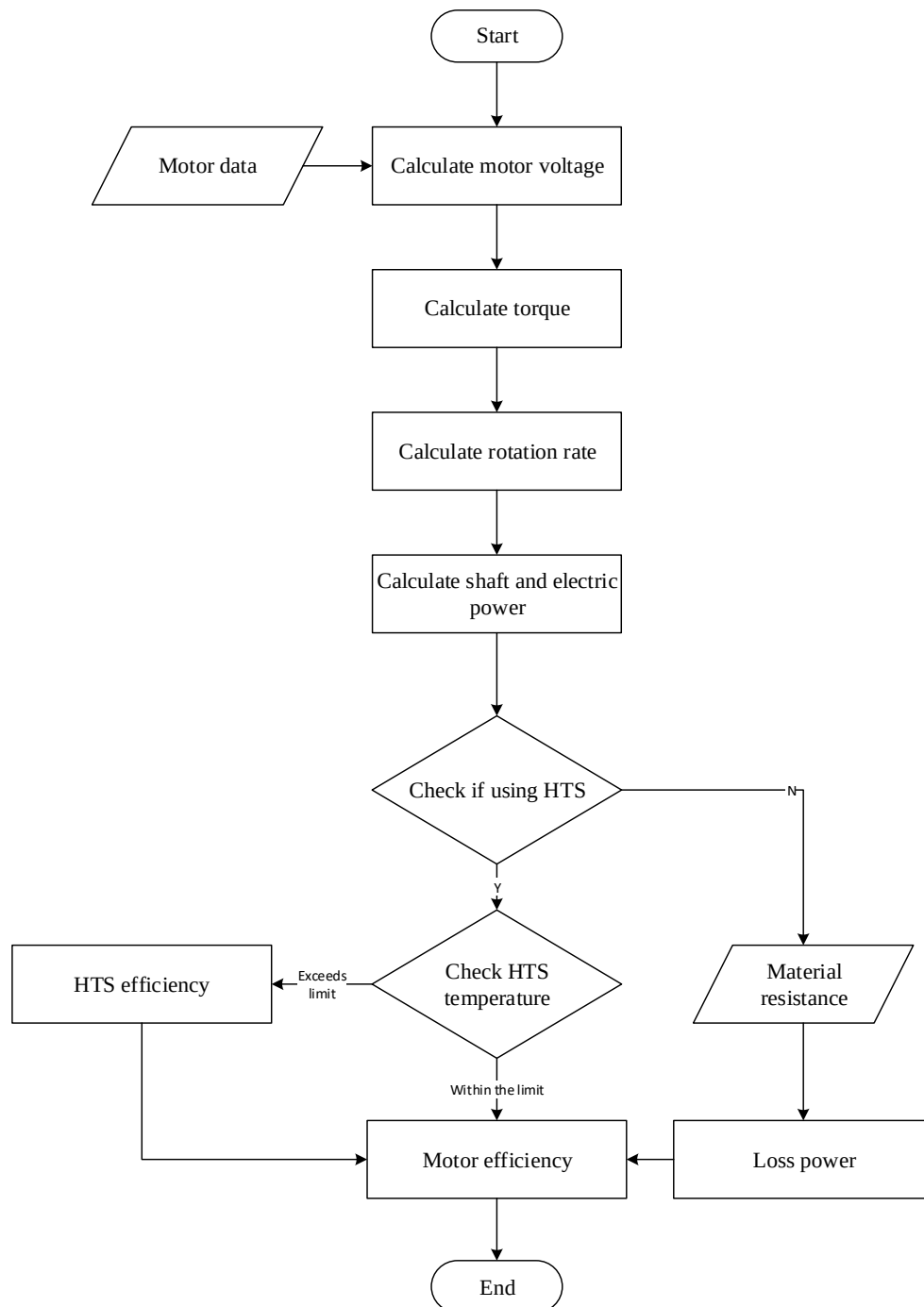


Figure 4.2-7: Motor specification and description language

The follows equations used in the motor model:

$$\text{Motor voltage} = \text{Voltage} - \text{Resistance} \times \text{Current} \quad (4-15)$$

$$\text{Speed constant (Radian)} = \text{Torque constant (Radian)} \quad (4-16)$$

$$\text{Torque} = \frac{\text{Current}}{\text{Torque constant (Radian)}} \quad (4-17)$$

$$\text{Rotation rate} = \text{Motor voltage} \times \text{Speed constant (Radian)} \quad (4-18)$$

$$\begin{aligned} \text{Speed constant (Revolutions per minute)} \\ = \text{Speed constant (Radian)} \times \pi/30 \end{aligned} \quad (4-19)$$

$$\text{Rotation rate} = \text{Revolutions per minute} \times \pi/30 \quad (4-20)$$

$$\text{Power Shaft} = \text{Rotation rate} \times \text{Torque} \quad (4-21)$$

$$\text{Electric power} = \text{Voltage} \times \text{Current} \quad (4-22)$$

$$\text{High temperature superconductor efficiency} \quad (4-23)$$

$$= \frac{\text{Total current temperature} - \text{Temperature limit}}{\text{Temperature limit}}$$

$$\text{If high temperature superconductor} > 0 \quad (4-24)$$

Motor efficiency

$$= \frac{\text{Power Shaft}}{\text{Electric power}}$$

$$- \text{High temperature superconductor efficiency} \times 100$$

$$\text{Else} \quad (4-25)$$

$$\text{Motor efficiency} = \frac{\text{Power Shaft}}{\text{Electric power}} \quad (4-26)$$

$$\text{Loss Determination} \quad (4-27)$$

$$\text{Loss power} = \text{Electric power} - \text{Shaft power}$$

$$\text{Loss Power} = \text{Windage Fraction} + \text{Materials Resistance} \quad (4-28)$$

$$\text{If high temperature super conductor} \leq 0, \quad (4-29)$$

$$materials\ resistance = 0$$

$$Loss\ Power = Windage\ Fraction$$

- TurboMatch® Extension (GridMatch)

Adding more than one aspect as part of the system to make it larger or more capable is considered as an extension. The idea of building a TurboMatch extension arose from the need for having an electrical flow environment and support for its studies. Regarding hybrid components, the legacy TurboMatch simulation environment executes the mechanical functions of analysis and calculation, whereas the extension includes the electrical part to study the grid. This extension contains five different main models to build-up the extension, and each of them can include more micro models. Electrical buss, current converter, cryocooler, battery, and optimization are the structure models for the TurboMatch extension.

A brief explanation of each of these models is provided below:

- Electrical Buss (EBUSS Model)

The same building strategy as that used for building the generator and motor models is applied here. The buss model inputs are the maximum and minimum amounts of reactive power, maximum and minimum voltage, and connected generators, batteries, and loads. The progress stage serves as a station to carry and connect all the possible devices. The outputs are the electrical branches and nodes. Figure 4.2-8 depicts the model stages and their construction.

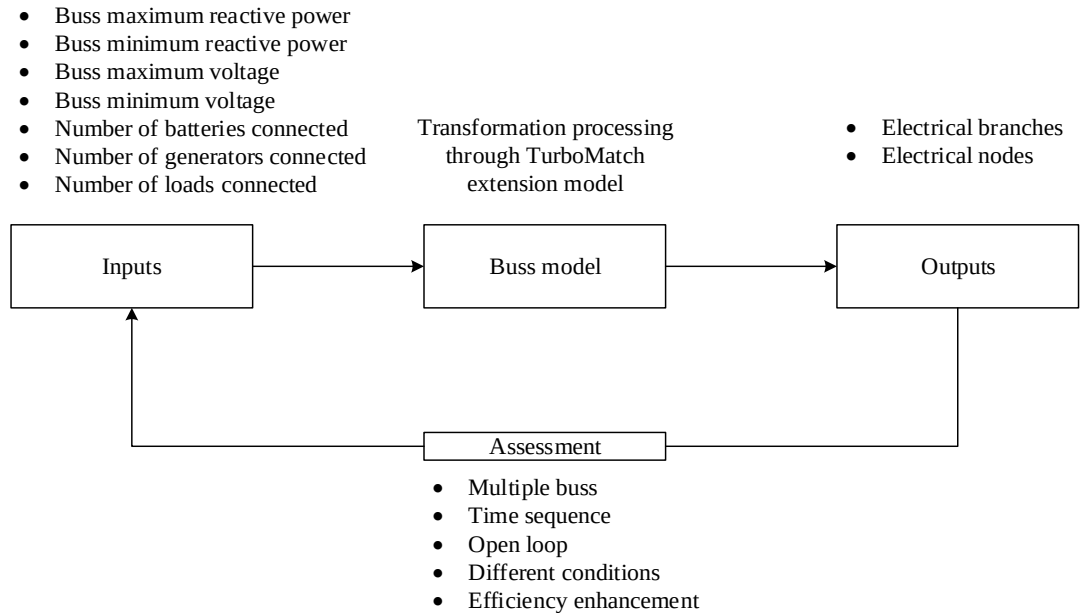


Figure 4.2-8: Electrical buss

○ Current Converter (CCONVR Model)

This model converts direct current to alternating current or alternating current to direct current.

○ Cryocooler (CRYCOL Model)

There are three stages in the cryocooler model responsible for cooling the generator and motor to obtain higher efficiency. The cryocooler power, current, and resistance are the model inputs. The process stage treats cryocooler power as an electric load because of its function of electric power consumption. The only output of the cryocooler is the coefficient of performance. Figure 4.2-9 depicts the cryocooler inputs and outputs.

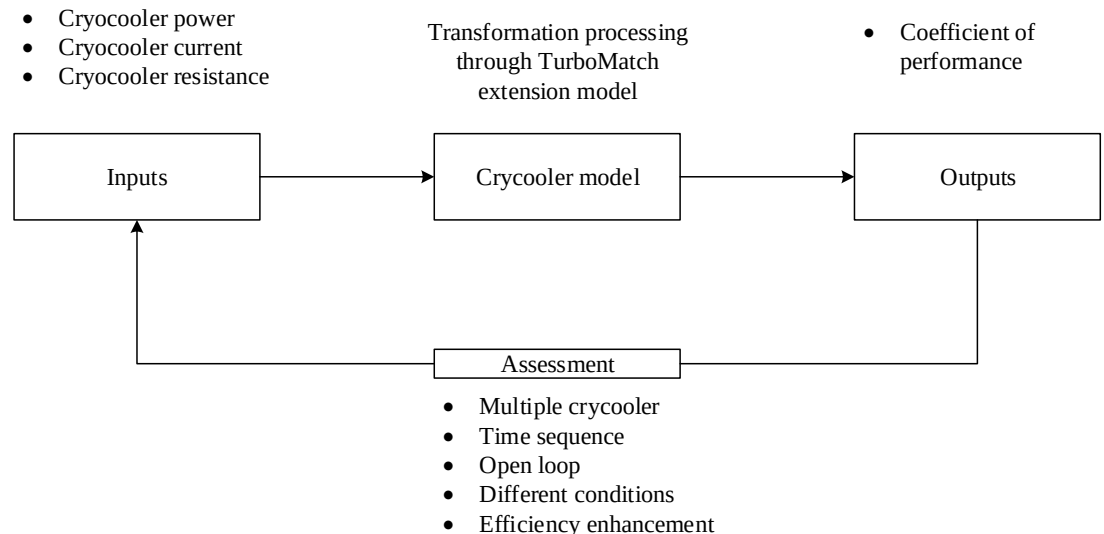


Figure 4.2-9: Cryocooler inputs and outputs.

- Battery (BATTERY Model)

As a power saver, the battery was modelled to boost the electric power for a specified period. The turboelectric proposal does not include batteries due to weight limitations. The model applied in this study was evaluated and compared with different types of hybrid systems.

- Optimisation

The optimisation stage includes quantitative risk analysis and lean efficiency enhancement. Two types of optimisation methods exist: deterministic and stochastic. Each method has its own algorithm to minimise the errors and power waste.

4.3 Unified Modelling Language Approaches

One of the modelling methods for documenting, visualising, and specifying a system is the UML. This method provides the blueprint for the system-specific construction and components. Three types of UML were studied for the modelling approaches: component and state machine, structure, and sequence.

4.3.1 UML Component and State Machine

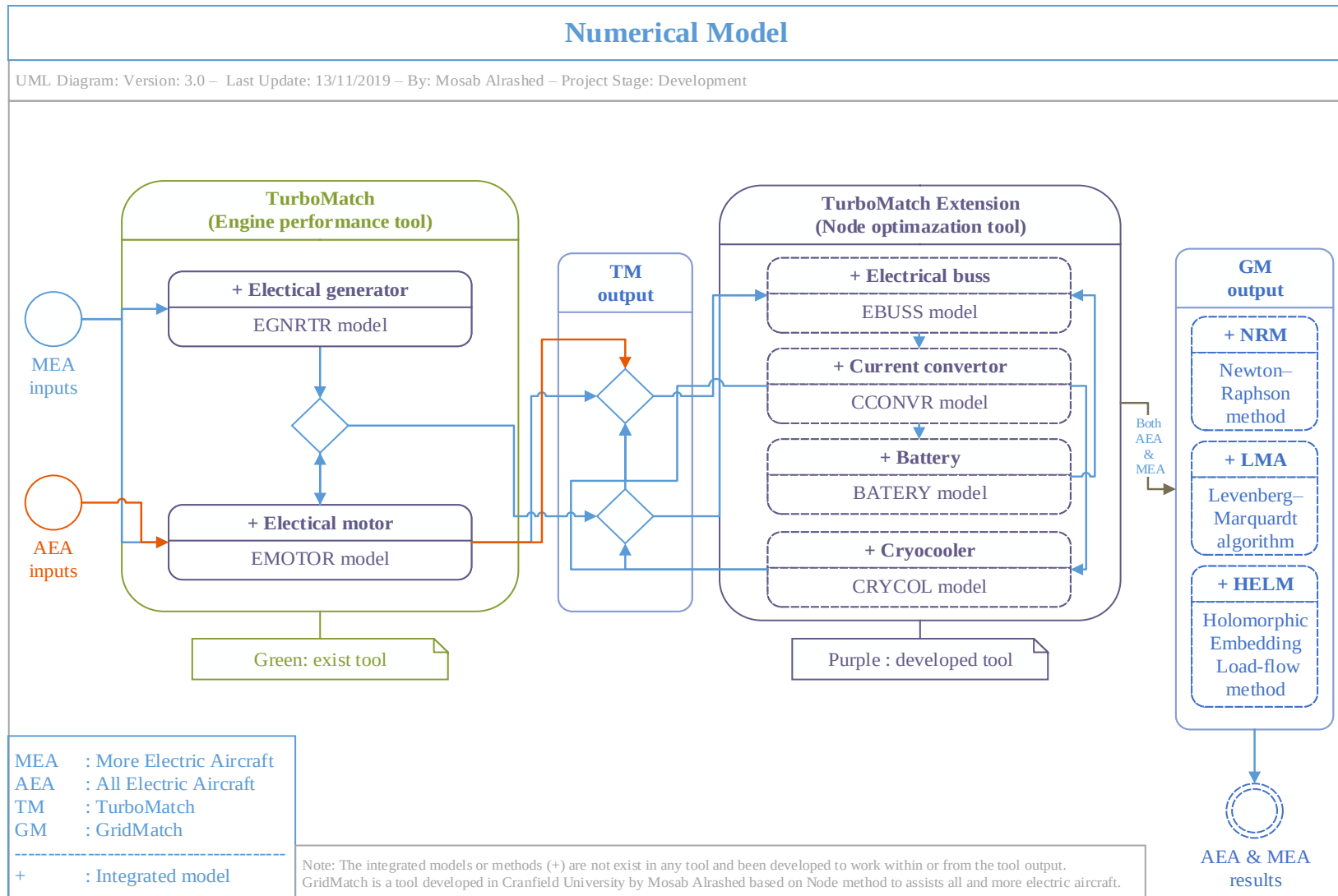


Figure 4.3-1: UML Component and State Machine

The dynamic behaviour is characterised in different occasions by using UML components and the state machine. The UML components are modelled within three processes: identifying the auxiliary ingredients that need to be a part of a system, modelling them as components, and defining the relationship between these components and other auxiliary components or systems.

Figure 4.3-1 depicts two systems: TurboMatch and its extension (GridMatch). By identifying the auxiliary ingredients for the first system (TurboMatch), the electrical generator and motor to be modelled as components for the system are selected, and then the relationship between the expected inputs and the outputs from the system after the integration are determined. Additionally, the second system (TurboMatch extension) has four identified and modelled components, namely, electrical buss, current converter, battery, and cryocooler. The relation between the second system components and the inputs depends on the output from the first system, whereas the output of this system requires some optimization and filtration within the three Newton Raphson, Levenberg Marquart, and holomorphic embedding load flow methods. These optimisation components are not within the auxiliary elements of the system, as they are not a core component, but simply analysis results.

Two scenarios can be applied in the UML state machine depending on whether the input is more electric aviation (MEA) or all-electric aviation (AEA):

- MEA as a start state: This scenario begins with model inputs according to the type of MEA in the transition, leading to the electrical generator model or motor model, but if the case study has both models, then the flow will merge in the branch. Then in TurboMatch (TM) output, two branches are connected to each other, which is performed as an intermediate state between the two systems. In GridMatch (GM), the primary action state is the electrical buss, as the other action states within the system rely on it. The current converter, battery, and cryocooler as the active states move the state flow between them as inputs are provided until GM outputs results.
- AEA as a start state: In this scenario, the electrical motor is considered in the active state in the TurboMatch system with no branches inside. The triggerless transition is moved to the TM output branch, resulting in the same flow as that of MEA in GM.

For both scenarios, after GM outputs are obtained, three active states are included for optimisation. GM software will apply the numerical outcome to the three optimisation methods for filtering the result. The stop state (AEA and MEA result), therefore, will be the end of the machine state assessment, as shown in Figure 10.

4.3.2 UML Structure

Figure 4.3-2 represents the UML structure for the numerical modelling of turboelectric systems. This structure reflects the inheritance between each super and subclasses in the model. The numerical model acts as a parent in the structure for two children, namely, mechanical and electrical power. The inheritance from the mechanical power results in only two children: the generator and motor. The electrical power has the same number of children: buss and the electrical grid. The buss has three children: battery, generator, and loads, whereas the motor and cryocooler are the grandsons from the last child. On the other hand, the rectifier and inverter are the children of the converter, which is the sole child of the branch, which in turn, is the sole child of the electrical grid.

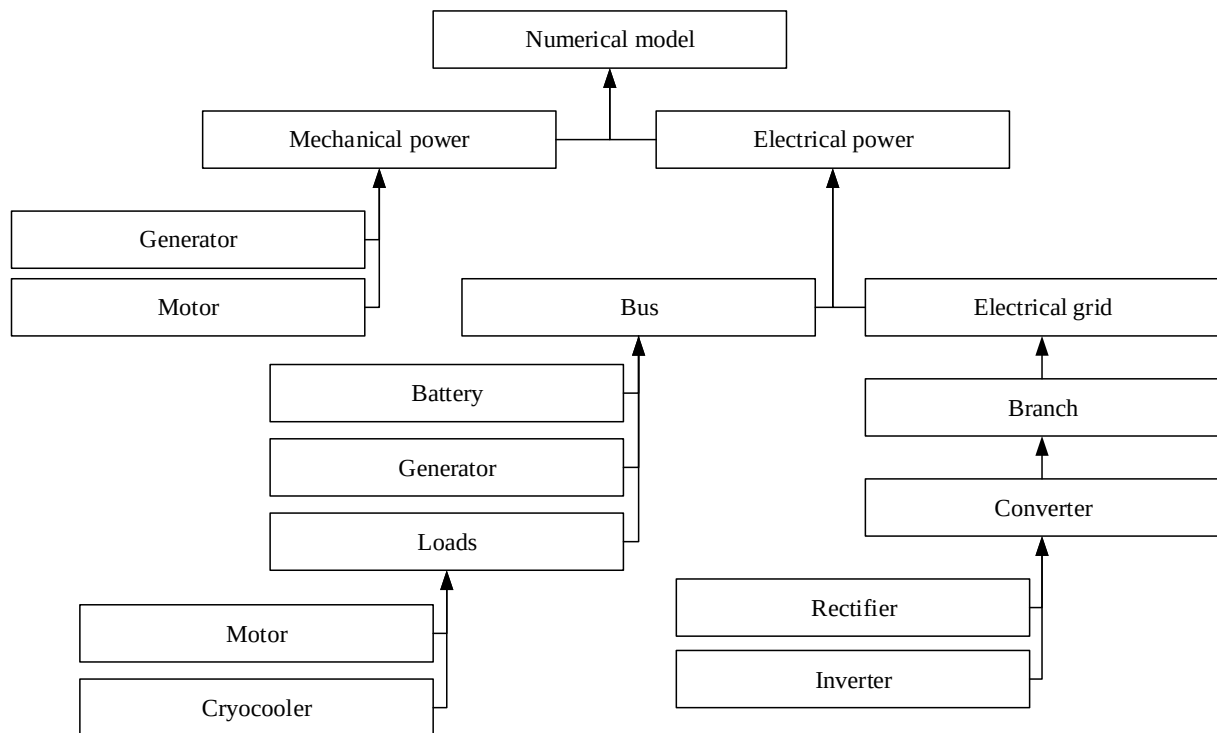


Figure 4.3-2: UML Structure

4.3.3 UML Sequence

The sequence diagram in UML is used to visualise the interaction between the object model systems. Usually, there exists one or more actors and objects to interact with and

study the possible links. Figure 4.3-3 illustrates the expected objects and the actor in a turbo-electric numerical model. A generator, motor, buss, battery, and cryocooler are the five objects, and the researcher or modal user is the actor. In addition, there are two alternative scenario dialogues titled ‘alt’ to represent all the possible scenarios that can occur during the model processing. In the first alt, the two scenarios include a generator, a motor, or both in the system; thus, they are valid.

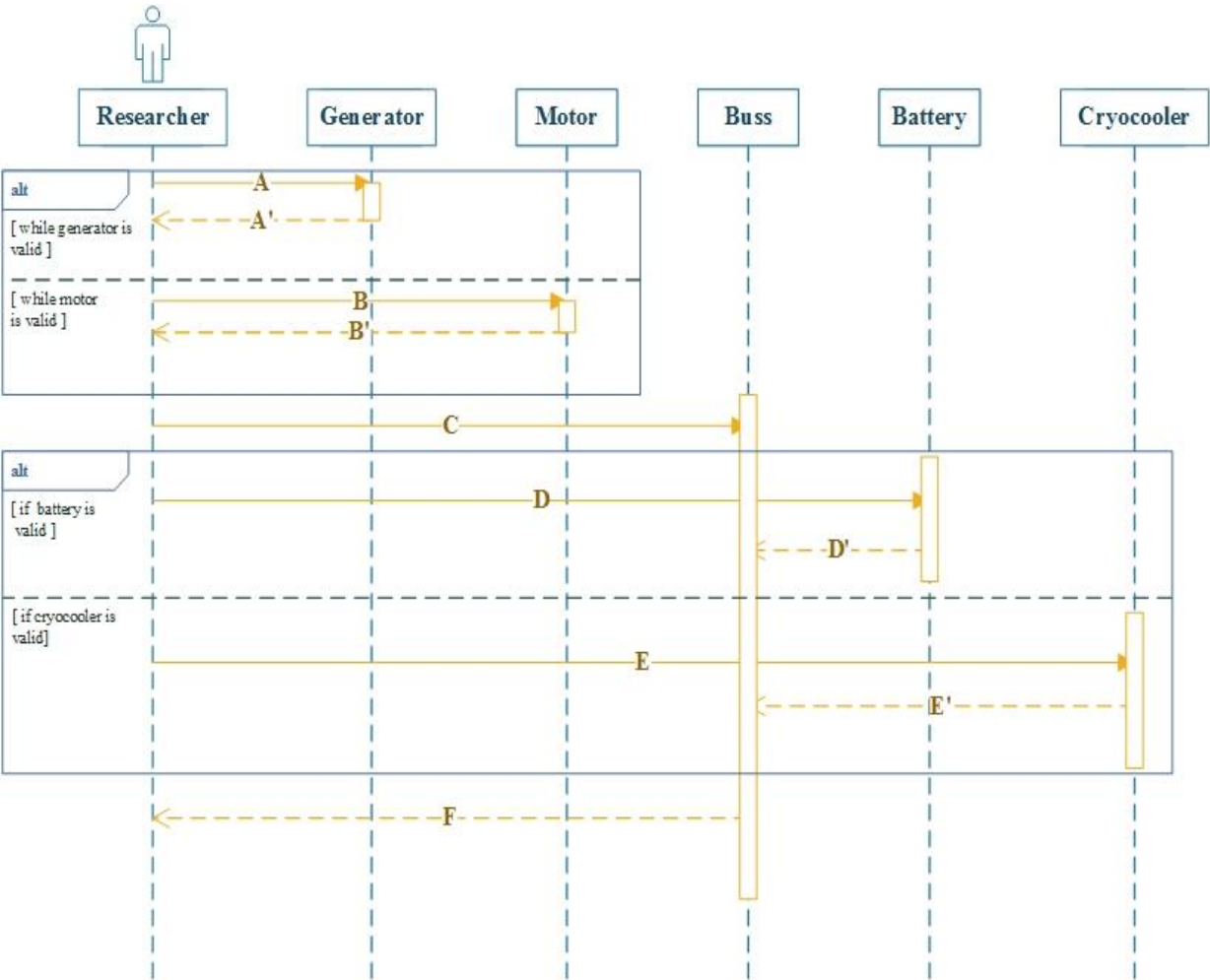


Figure 4.3-3: UML Sequence

The transferred data between each object and the actor are represented as A–F, whereas the dashed alphabet characters represent the return data or the response message, as defined in UML. Table 4.3-1 summarizes these characters and the possible data carried by each of them.

Table 4.3-1: UML sequence data

Input/output	Data
A	Mechanical power / Input torque / Generator resistance / Generator constant / Generator temperature / HTS temperature
	Generator angular velocity / Generator inductance / Generator resistance / Generator current / Generator constant / Number of electric phases / Generator manufactured efficiency
A'	Revolutions per minute / Electrical power / HTS efficiency / Generator efficiency / Output voltage / Generator current
B	Revolutions per minute / Input voltage / Motor resistance / Motor current / Motor constant / Motor temperature / HTS temperature
	Motor angular velocity / Motor inductance / Motor resistance / Motor current / Motor constant / Number of electric phases / Motor manufactured efficiency
B'	Mechanical power / Output torque / Electrical power / HTS efficiency / Motor efficiency
C	A' / B' / Buss maximum reactive power / Buss minimum reactive power / Buss maximum voltage / Buss minimum voltage / Buss nominal voltage / Number of batteries connected / Number of generators connected / Number of loads connected
D	Battery nominal capacity / Battery nominal power / Battery dispatched power / Upper reactive power limit / Lower reactive power limit
D'	D / Battery efficiency
E	Cryocooler power / Cryocooler current / Cryocooler resistance
E'	E
F	Post-process / Electrical node

4.4 Network Architectures

A high-level set of electrical network architectures are designed to obtain the optimal power flow within the required post-process results. At the start of the designed network, the input data is considered first. These data are the values of the electrical parameters generated or intended for propulsion design. Then, these values are applied to Kirchhoff's and Ohm's laws. The three principle laws are

- *Kirchhoff's current law*

G. R. Kirchhoff, a German scientist, proposed a fundamental law, known as Kirchhoff's current law (KCL). This law states that the sum of the currents at an electric node needs to be zero, which is defined formally in [128]:

$$\sum_{n=1}^N i_n = 0 \quad (4-30)$$

- *Kirchhoff's voltage law*

Voltage is the motion of electric charge between two points and can be defined as the total work per unit charge. Furthermore, the voltage was defined as a unit of energy per charge by the Italian physicist Alessandro Volta as part of his contribution with regard to the electric battery:

$$volt = \frac{joule \ (energy)}{coulomb \ (electric \ charge)} \quad (4-31)$$

After several experimental works on voltage, Kirchhoff proposed his second law called Kirchhoff's voltage law (KVL) based on the principle that no loss in energy can occur in an electric circuit. This implies that the sum of all voltage sources must be equal to the sum of load voltages, which results in a total of zero for any closed circuit, as in [128]:

$$\sum_{n=1}^N v_n = 0 \quad (4-32)$$

- *Ohm's law*

Material properties are the main factors that affect the resistance when electric current flows through the conductors or circuit elements. This resistance during the current flow in the circuit elements can be considered as energy loss, which may be converted to the form of heat. According to Ohm's law, which deals with an ideal resistor,

$$V = I R \quad (4-33)$$

As R is the value of resistance with the unit Ohm (Ω), it can be defined as the voltage across an element divided by the current flow through it.

$$\Omega = \frac{V}{A} \quad (4-34)$$

To optimize the power flow in this stage, three methods were included within the module, as described below:

- *Levenberg Marquardt*

In the early 1960s, the Levenberg-Marquardt algorithm (LMA) was introduced to solve the nonlinear least-squares problem. It minimizes the sum of squares errors using a sequence of updates to the parameter values between the measured data points and the fit parameterized function. Moreover, the nonlinear problem implies that the parameters of the fit function are not linear. The algorithm by itself consists of two methods, combination and calculation, depending on the optimal value: the gradient descent method, which updates the parameters in the steepest-descent direction, and the Gauss-Newton method, which assumes that the least-squares function is locally quadratic by determining its minimum. Thus, when the optimal values for the parameters are distant, then the LMA adopts the gradient descent method, whereas when the optimal values for the parameters are close to each other, then the LMA adopts the Gauss-Newton method [129].

- *Newton Raphson*

This method was proposed in 1685 by John Wallis as a root-finding approximation using a straight tangent [130]. Figure 4.4-1 illustrates the function of Newton Raphson for the tangent line.

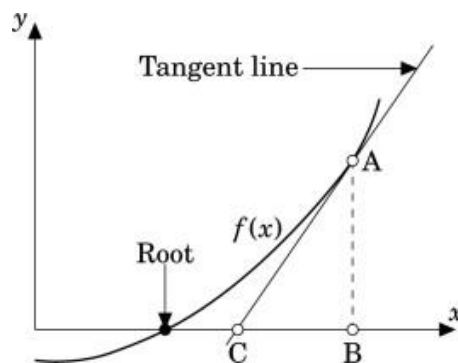


Figure 4.4-1: Newton Raphson method [131].

- *Holomorphic embedding*

In 2012, Antonio Trias proposed the holomorphic embedding load flow method (HELM) as a novel non-iterative and non-initial value algorithm. It uses the techniques of complex and deterministic analysis. In brief, the HELM mechanism comprises the following steps [132]:

1. Find a suitable complex holomorphic embedding with the help of a complex parameter.
2. Calculate the power series using a sequence of linear systems that yield the coefficients progressively.
3. Determine the solution of the complex parameter as the analytical continuation of the power series via Pad e Approximants.

Figure 4.4-2 depicts these methods and illustrates the modelled electric network architecture for the numerical simulation software to solve hybrid and turboelectric implementation.

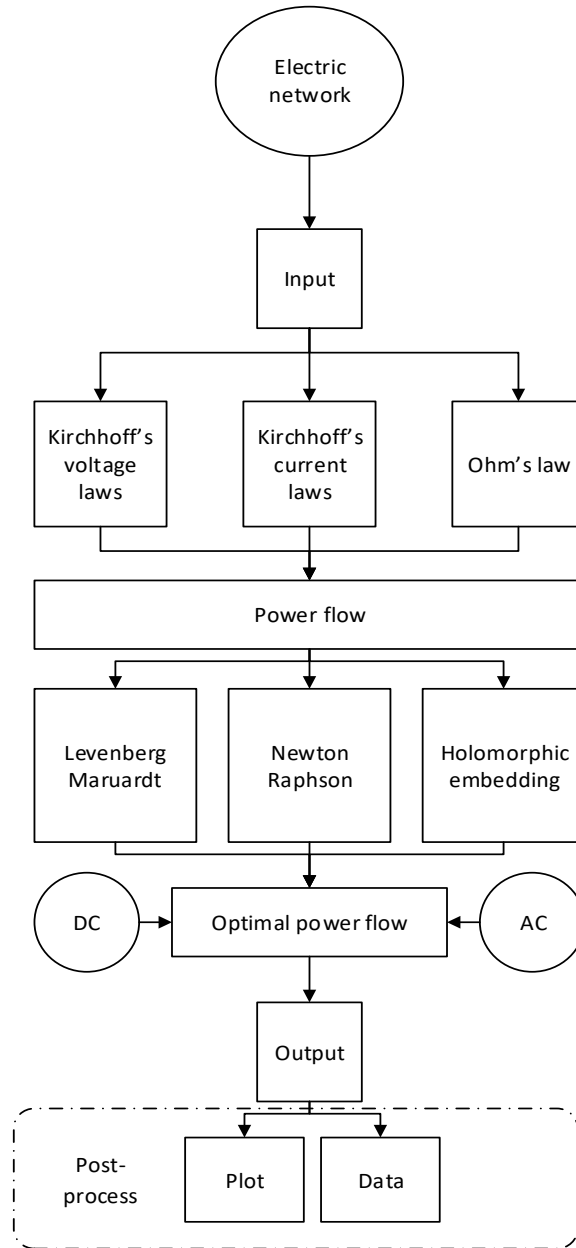


Figure 4.4-2: Electrical network architecture.

4.4.1 Generator

The generator is modelled as a function in a specific buss. For generator x , the function is

$$G(x) = P(x) + jq(x) \quad (4-35)$$

which combines the active and the reactive powers for the generator in the specific buss as follows:

$$Generator\ power\ (bus) = Active\ power\ (bus) + Reactive\ power\ (bus) \quad (4-36)$$

Then, the connection between the generators using a matrix and the buss is expressed as follows:

$$Generator\ bus(x) = matrix(x) \times Generator(x) \quad (4-37)$$

As per the basic generator concept, magnetic power is the hidden power that converts mechanical power into electrical power. Through the rotation of the components, a magnetic field is generated, and the conductor or the coil absorbs these effects to generate electricity. Therefore, depending on the conductor type (material specifications), in the event of high-temperature superconductivity, the efficiency of the conductance varies with temperature limitations. The generator can be of two types: two rotating rings or a rotating split ring, depending on the type of generated current. In the case of the rotating split ring, the output is a direct current, whereas, in the case of two rotating rings, the output is alternating current. Figure 4.4-3 depicts the relation between the generator-modelled prototypes, the inverse of which is the motor prototype.

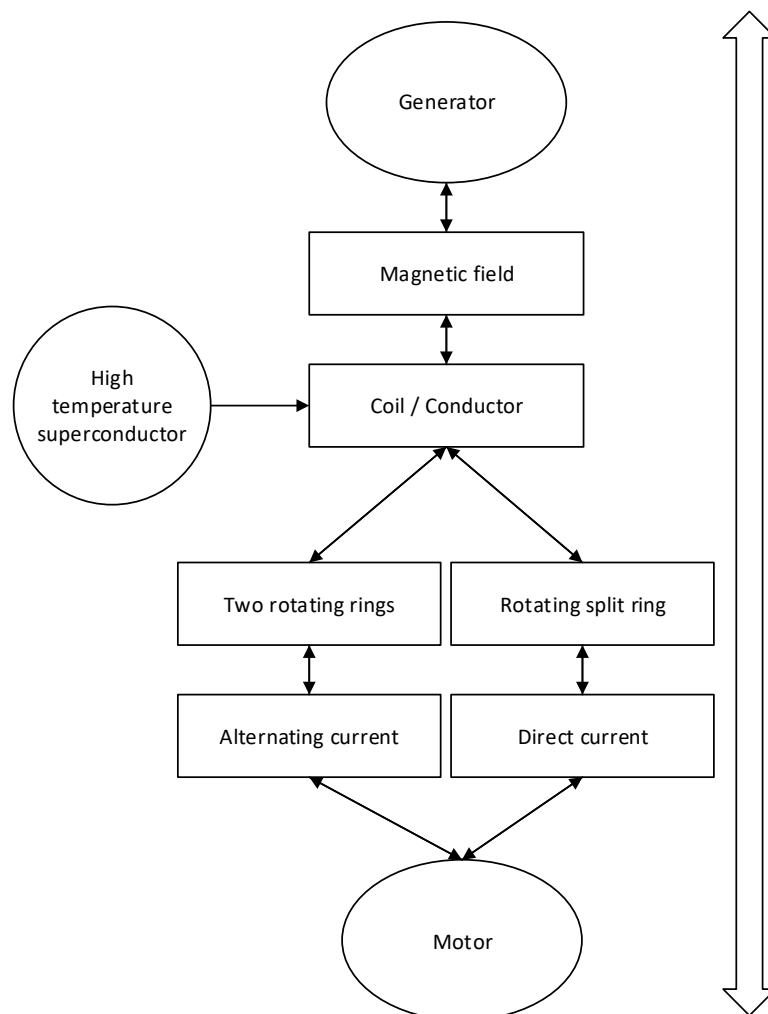


Figure 4.4-3: Generator model prototype

4.4.2 Motor

The motor is modelled as a constant power load with a specified quantity of active and reactive power consumed at a buss. For buss x, the load is

$$M(x) = P(x) + jq(x) \quad (4-38)$$

which combines the active and reactive powers for the motor in the specific buss as follows:

$$\text{Motor power (buss)} = \text{Active power (buss)} + \text{Reactive power (buss)} \quad (4-39)$$

Moreover, as mentioned in Figure 4.4-3, the motor model prototype is the inverse of the generator prototype.

4.4.3 Circuit

The electric circuit is modelled as a standard electric principle to represent nodes and branches. To illustrate the electric circuit structure, Figure 4.4-4 depicts an electric branch, node, loop, and mesh. This circuit can be used in multi-circuits as the scale of the data examined by means of object ordinated capability.

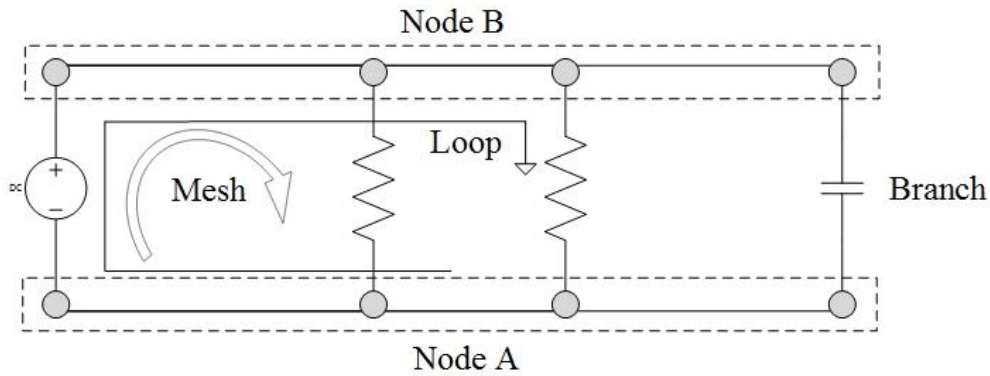


Figure 4.4-4: Electric circuit structure and explanation

4.4.3.1 Node

The node model helps to analyse and calculate the electrical circuit parameters by applying KCL in each node to obtain the simultaneous equations, whereas the mesh model needs to apply KVL to solve the electrical parameters [133].

4.4.3.1.1 Bus

The buss is a part of the node configuration, which represents the wiring connection between the power sources, loads, and electrical converters. It carries the reactive power, voltage, and the resistance of the link depending on the material or the length of the bus.

4.4.3.2 Branch

The branch model is a median between different nodes and has the ability to transfer the power type and size.

4.5 Finite State Automata

One of the mathematical models used in discrete computation as a set state, and the transition between states is called finite-state automata. This method captures the behaviour of the dynamic system aspects from the start to the termination point, including any possibility of a trap. As results expected from finite automata defined in one initial state in a system, labelled states transition and final state [134]. The results are described in the follows sections.

There are two types of finite state machine automata: deterministic finite-state automata and non-deterministic finite automata. The difference between the two is that they have different target states from the same input over one source. More expected and nonelected results are approximated from several inputs [134,135].

4.5.1 Deterministic Finite Automaton

As the modelling approach structured for this study, the deterministic finite automaton (DFA) behaviour for the turboelectric system is divided into two systems. This division provides a more precise illustration of the expected results by analysing the mechanical grid and electrical grid separately.

In DFA, for each labelled transition system, there is only one action for each state. Applying this to the study, the initial state is a gas turbine in the first system, which represents the mechanical grid. If this state has the action of validation, the transition state will be a generator. This implies that if the gas turbine generates electricity and it is valid, then the behaviour of this transition for the power and data is credible. Moreover, if the power still exists, then validation will remain in the same sate. The generator state is also considered as a terminated state because it is the final stage in the system and should reach

an ideal situation. However, in the event of system failure, the transition will be to a gas turbine state, which is the start state of the null state in terms of power and data.

Furthermore, the state will remain still until a change occurs in the gas turbine. For more explanation, if the gas turbine is not running or does not provide the generator with sufficient power to ride the generator, then no electric power is generated, and no data are simulated until a change occurs to the gas turbine. Figure 4.5-1 depicts DFA for the first system of the study.

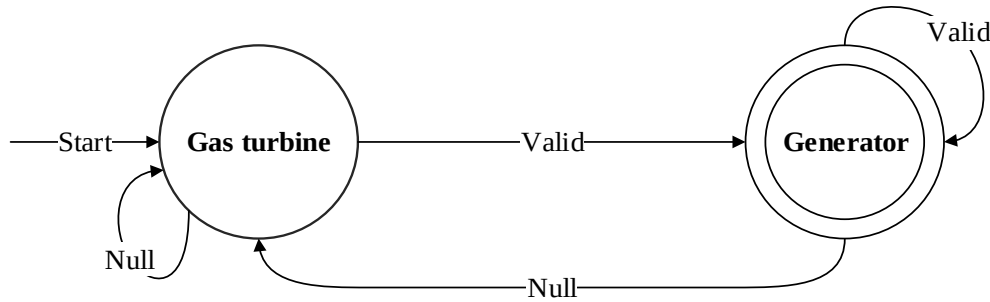


Figure 4.5-1: Gas Turbine and Generator Deterministic Finite Automata

Moreover, Table 4.5-1 presents the state transition of the automaton for the mechanical grid system in turboelectric systems. To apply the condition of DFA, the matrix shows that for a piece of input and source state, there is only one target state that exists.

Table 4.5-1: Deterministic finite automata for the mechanical grid system

State	Valid	Null
Gas Turbine	Generator	Gas Turbine
Generator	Generator	Gas Turbine

Similar theoretical concepts of DFA are adopted in the second system, which represents the electrical grid, but with five states. The initial state for this system is the generator as a gate of electric power and the synchronization stage for the first and second systems. For an ideal scenario of power and data, the transition state will be the buss carrying out this outcome from the initial state. By continuing this scenario, the terminated state will be the motor and remain in this state while the power and data are valid. If an error occurs, the motor exhibits a null behaviour, which may be because the generator is overheated. The next stage is the cryocooler, where power is consumed, and the data generator validates the transition to the buss again.

Nonetheless, if the cooling is still not saturated, then the state will remain stalled in the generator until the nonexistence of the null behaviour. Moving to the buss state, if the null behaviour is observed, then it implies that the power on this state is not sufficient to run the motor. Then, two options are available according to the batteries state. If the battery exists within the propulsion design and has the power to combine the reaming charges, then the motor state will be valid. In the other option of existence, the null behaviour of the batteries encourages the generator to generate more power for the buss state. Figure 4.5-2 illustrates these transitions between states for the electrical grid system.

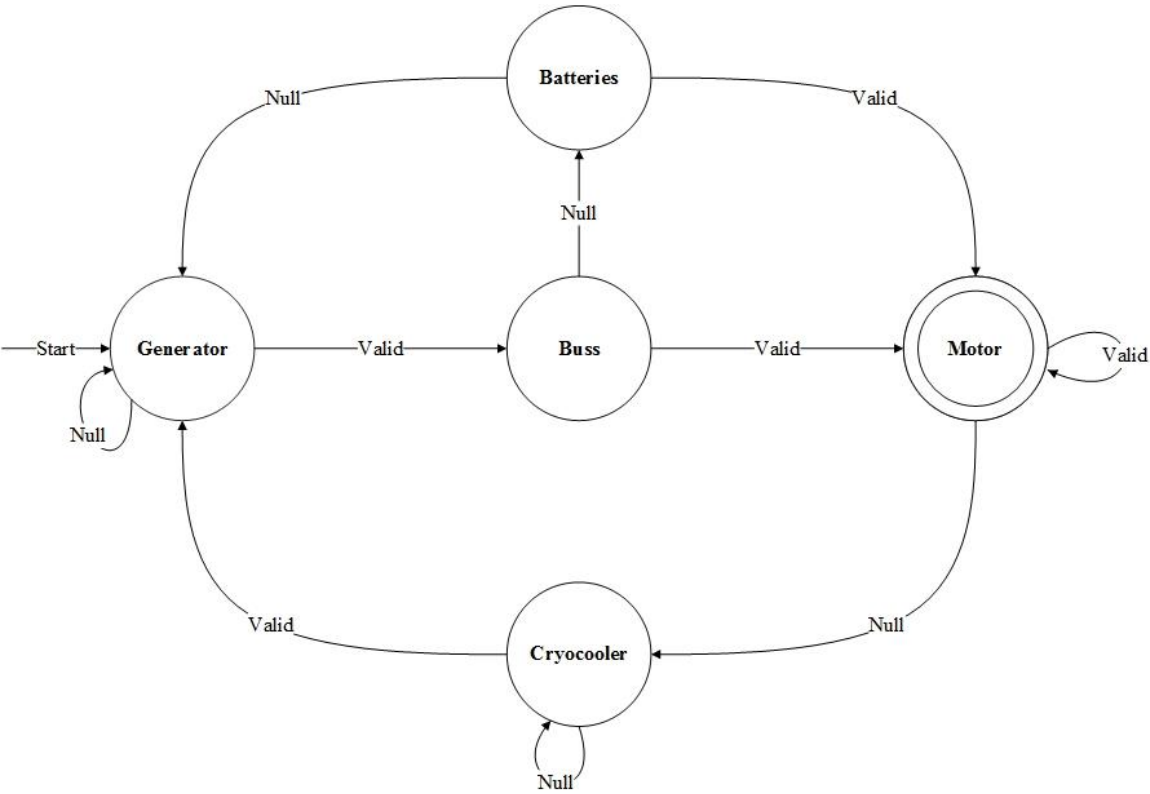


Figure 4.5-2: Deterministic finite automata for the electrical grid system

Table 4.5-2 presents the state transition of the automaton for the electrical grid system in modelled propulsion. Moreover, the matrix shows that for each piece of input and source state, only one target state exists.

Table 4.5-2: Deterministic finite automata for the electrical grid system

State	Valid	Null
Generator	Buss	Generator
Motor	Motor	Cryocooler
Buss	Motor	Batteries
Cryocooler	Generator	Cryocooler
Batteries	Motor	Generator

4.5.2 Non-deterministic Finite Automaton

The main difference in this type of automaton is that one source state can have several transitions with the same input and different targets. In non-deterministic finite automaton (NFA), only the electrical grid system is modelled because the mechanical system will be the same. Moreover, there are only two states in that system, which imitate the deterministic and non-deterministic behaviours.

In the nondeterministic state, the batteries will be the initial state for the finite automaton. In the non-deterministic system design, the system will transit to a different state, although a similar action has been performed in the same state. For the initial state of the batteries, there are two validation behaviours—one for the buss to transit the battery power and data to it. Moreover, in the second scenario with fewer batteries charge, the recharge is requested from the generator state. An ideal scenario is a transition from the buss state to the motor state, remaining at this state as a terminated state while it is valid. However, if the null behaviour for the buss state appears, there are two transit actions even to drain the generator with more absorbed power or to obtain it from the batteries. If the same null behaviour is observed in the batteries state initially, there are no batteries in the propulsion configuration, or it is out of order, and the generator will be in the next state to power up the grid. The generator state has one valid action and one null action. The existence of the power leads to the distribution of the buss in the grid, or the opposite cryocooler needs to be informed about cooling down the increase in the heat in the generator state. The state will remain in the cryocooler until the generator is satisfied. Only one action remains in this analysis for the motor state when the null behaviour exists because there is no power to run the motor, or it is less than the requested power. From that transition, the generator will generate more power through the buss state. Figure 4.5-3 demonstrates the NFA for the electric grid system.

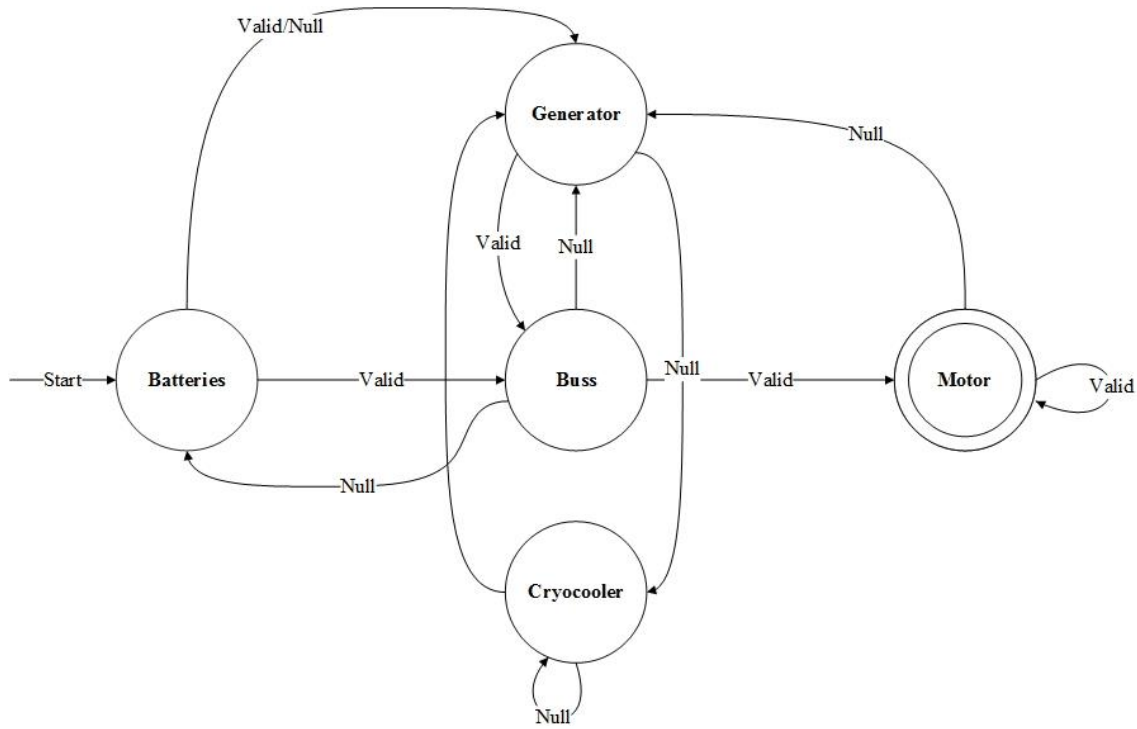


Figure 4.5-3: Non-deterministic finite automata for the electric system grid

In addition, Table 4.5-3 shows the matrix of actions, source states, and target states for on-deterministic finite automata for the electric grid systems.

Table 4.5-3: Non-deterministic Finite Automata

State	Valid	Null
Batteries	Buss/Generator	Generator
Buss	Motor	Generator
Motor	Motor	Generator
Generator	Buss	Cryocooler
Cryocooler	Generator	Cryocooler

4.6 Modelling Behaviour and Analysis

After modelling the behaviour of the electric and mechanical elements in the system, a precise implementation of the research development within the scope was achieved by merging the two types of powers. This study enabled the development of a robust numerical modelling environment that can assist significant electric models in future distribution propulsion systems.

4.7 Chapter Summary

This chapter proposes a notation scheme for system modelling using different study approaches. Different approaches to new elements were preliminarily defined to enhance the legacy simulation systems. Then, UML methods for justifying the relationships in each separated element structure or behaviour were presented. Network architectures of the primary elements were illustrated and developed with their assumptions. Apart from exploring the optimisation construction, the Automata method was included with its two algorithms. The results provided better outcomes for generating advanced integration of the numerical modelling environment for turboelectric systems. The following chapter 5 will apply these outcomes in a real simulation study.

Mechatronics behaviour for TeDP was initialised, modelled, and analysed with the integration of mechanical, electrical, and software engineering methods. This integration simplifies the concepts of physical parameters for numerical modelling and development for any simulation research. The study covers not only turboelectric, but also most hybrid systems in propulsion systems that have electric generators, electric motor, batteries, cryocooler, and buss. The method could estimate the trap in system failure or uncertainty of the integration. The future scope of mechatronics integration should also include complex assimilation of the materials science of each system to study the behaviour of converting power. The management of energy implementation for each system needs to be studied and analysed in further detail. In addition, a novel enhancement method for artificial intelligence (AI) in energy conservation and reduction of losses of the transformation of power.

There are significant limitations in the research of the TeDP model. These limitations are related to the source of real data for the propulsion system. As these technologies are still futuristic in terms of real-life use, there will be some sort of implementation limitations. The method needs to be validated with a large scale of manufacturing data. Moreover, detailed technical parameters that affect the outcomes need to be added to the development of this method. Broader implications of modelling from the viewpoint of more electric to all-electric distribution propulsion systems are required. Realistic turboelectric propulsion systems will gain interest within the next few years, particularly in the aviation transportation sector. This study will contribute to the acceleration of future targets for less emission and costs.

CHAPTER 5

INTEGRATED TURBO-ELECTRIC MODELLING TOOL AND SIMULATION

ABSTRACT

Software tools are highly valued for their cost-effectiveness and functionality in realising engineering ideas. These tools can solve problems in implementation and failure prediction in the operation process. This chapter is an application of chapter 4 includes two software implementation tools for turboelectric engines, engine performance tool and electrical optimisation tool. The two tools are linked in an iterative loop as an extension for the engine performance primary software. Thus, they work in tandem as one system assessment tool depending on the input of distributed propulsion to optimise the electrical components with the mechanical resources. Interdicting electrify power to aircraft propulsion system desire a feasibility study to optimise harmonise configuration. Doing that, an exclusive integrated development environment tool needs to exist for the analysis of the distribution of power. This study aims to provide, verify and analyse the ability to optimise turboelectric electric efficiency. As a result, an electric performance optimisation tool developed to extend the gas turbine performance tool to investigate the capability of reduction of power waste in the system. This was verified on the case study proposed by NASA N3-X with multiple alternative integrations on the turboelectric distribution propulsion (TeDP). From the outcome analysis, it shows that up to 1% of electrical power can be saved if optimised regarding the system configuration upgrade. The conclusion of this study demonstrations a significant impact on accessible assess tool for the development of future propulsion systems. The implication of this study finding on aeronautics integration consistent in appreciation of the mechatronics efficiency for 2050 aviation vision achieves.

5.1 Introduction

To establish a modelling tool for an advanced futuristic turboelectric system amid the limitations of data and practical values is challenging progress. From the modelling inputs and design execution to the output, software simulation can create models of all the subprocesses. For a reliable, more realistic modelling simulation, the simulation process

is divided into two tools. The first one is the engine performance assessment and simulation tool. This part is used to analyse the mechanical power besides the generating of electrical power corporations. The second one is the electrical optimization tool, which is used to study and develop the electrical grid. The combination of the two tools gives the electrical to mechanical integration of turboelectric technical assessment. In addition, it covers all types of hybrid and distribution electric propulsion systems, either to combine the relevant gas turbine case studies with electric or as a full-electric system. This chapter will discuss the two tools developed for turboelectric technical assessment with their upgrades and integrations.

5.2 Engine performance tool

As mentioned before, Engine performance tool is a package of combined models that calculate the engine performance. This tool can give more results depending on the requirement and data entry. In the following TurboMatch tool, upgrade explanation used in this study.

5.2.1 TurboMatch Upgrade

TurboMatch is a Brayton cycle gas turbine performance simulator from Cranfield University. Since its first version, TurboMatch has become more confident with power propulsion developments. Based on its capability of the software, TurboMatch has been upgraded with futuristic components and models to continue to electrify assess on the tool and produce more reliable results for future propulsion.

There are two models upgraded TurboMatch with as it called in the software modules structure new bricks. The first model is the electric generator that converts mechanical energy from the turbine into electrical energy carried by the bus network. The second model is the electric motor, which generates mechanical energy from the electrical grid. These two models are integrated into TurboMatch under the assumption that future engines have these systems built into them. Therefore, the development of the simulation tool includes the two.

5.2.1.1 Electric Generator

The development of an electric generator via TurboMatch has three challenges. The first one is the introduction of a new electrical power parameter and electricity carries that has not been included in mechanical engine performance. The second challenge is the lack of

data and results of real electric generators in aircraft engines and especially for turboelectric engines. The last challenge is the capability and flexibility of the numerical modelling performance simulation tool to extend.

To overcome them, each challenge was broken down into micro-tasks to be solved, and then give the whole solution by accumulating the micro-tasks. This is called the segmentation method. The first challenge in this study was solved in three segments. This method was initiated by first understanding the main TurboMatch structure and then emulating the developed pseudocode and algorithm for the new implementation. The last stage involves linking the electrical and mechanical parameters. Moving to the second challenge, because there is no real and raw data to be used for the validation study, data from Massachusetts Institute of Technology (MIT) was used to design a set of case studies. These data are not real turboelectric generator data, but general aero generators data measured and scrutinised by the scientific community.

The research methodology to simulate the generator model needs some initial assumptions of the electric generator parameter. Table 5.2-1 lists these assumptions. Some parameters have not been included, such as the cryocooler heat because it will affect the generator efficiency in certain conditions only, which cannot be validated. Therefore, this heat was assumed to be zero throughout the simulation.

Table 5.2-1: Assumed values for electric generator simulation

Component	Value	Unit
Resistance (R)	0.31000	Ohm
Generator constant (Kv)	2760.0	Rpm/Volt
Initial current (I_0)	0.77000	Amp

5.2.1.1.1 Inputs

The input data for the TurboMatch upgrade was classified into five different conditions for five case studies. The ranges of conditions represent two flight mode situations and different generator size for the range of 11 to 57 W. There were five conditions help to examine different types of generators and validate the results given from the simulation. Table 5.2-2 lists these data for the generator implementation model in the TurboMach upgrade simulation tool.

Table 5.2-2: TurboMatch generator input data [136]

Case studies	Power shaft (W)	Torque (N-m)
Condition 1 (11-14 W)	11.99	1.10E-02
	13.65	1.32E-02
	14.58	1.46E-02
Condition 2 (20-22 W)	22.6	1.95E-02
	21.61	1.80E-02
	20.04	1.60E-02
Condition 3 (29-32 W)	32.12	2.42E-02
	31.41	2.32E-02
	29.94	2.14E-02
Condition 4 (42-43 W)	43.94	2.99E-02
	43.7	2.96E-02
	42.45	2.79E-02
Condition 5 (55-57 W)	57.31	3.56E-02
	56.83	3.49E-02
	55.92	3.37E-02

5.2.1.1.2 Outputs

Some of the simulation results are presented in Table 5.2-3. These are the main results needed for the generator study and modelling in the stage of categorisation.

Table 5.2-3: TurboMatch Generator output data

Case studies	Current (A)	Voltage (V)
Condition 1 (3-4 A)	3.1735	4.761
	3.8151	4.76
	4.2197	4.763
Condition 2 (4-5 A)	5.636	5.757
	5.202	5.766
	4.624	5.767
Condition 3 (6 A)	6.994	6.76
	6.705	6.762
	6.185	6.758
Condition 4 (8 A)	8.641	7.763
	8.555	7.76
	8.063	7.764
Condition 5 (9-10 A)	10.289	8.759
	10.087	8.76
	9.74	8.76

5.2.1.1.3 Analysis and Validation

In the validation of the numerical model results, we focused on the convergence of voltage, current, and generator efficiency. The voltage results reveal that MIT and TurboMatch data almost entirely converged. The error percentage was less than 1% because of the different generator modelling methods, the assumptions, and ignoring

manufacturing some specification. Figure 5.2-1 shows these results and compares them with voltage data from MIT.

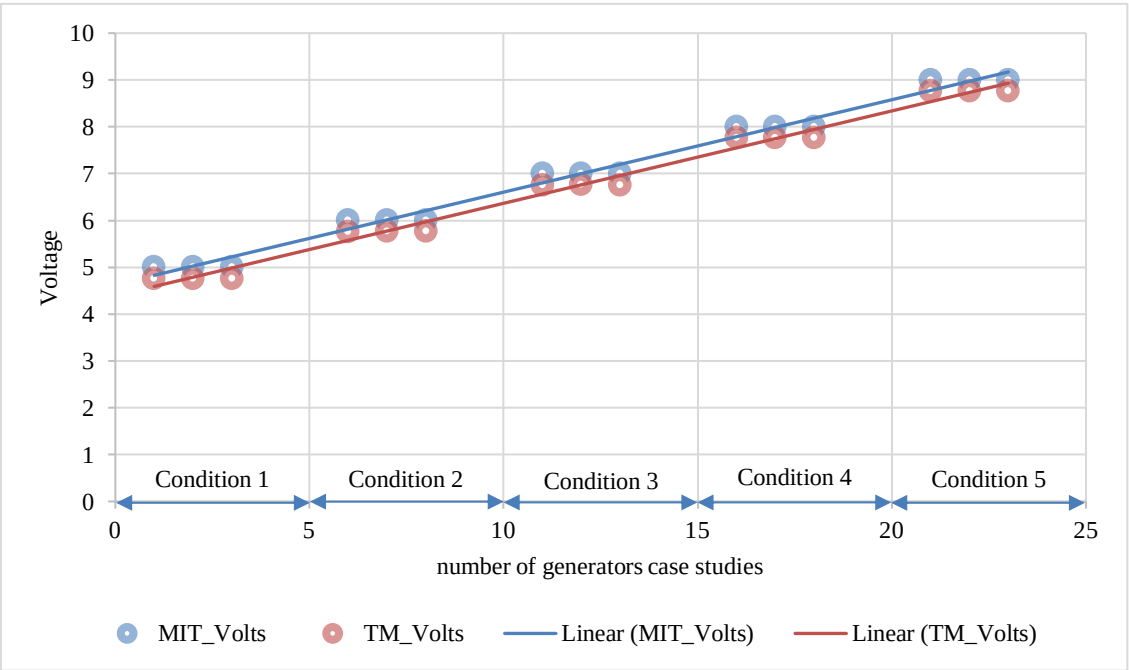


Figure 5.2-1: Generator voltage comparison

Coming to the result of the current produced by the generator. The current has the same error percentage as the generator voltage, which less than 1%. This percentage was expected as current and voltage together produce electrical work. The magnitude of error for both voltage and current in the generator are manageable. The 1% error may be due to the initial assumption of no generator loss. The appearance of this loss because of the generator built material properties and type that effects on the magnetic field. Hence, generator loss is beyond the scope of this study. Figure 5.2-2 shows the various case studies of generators with respect to the current comparison.

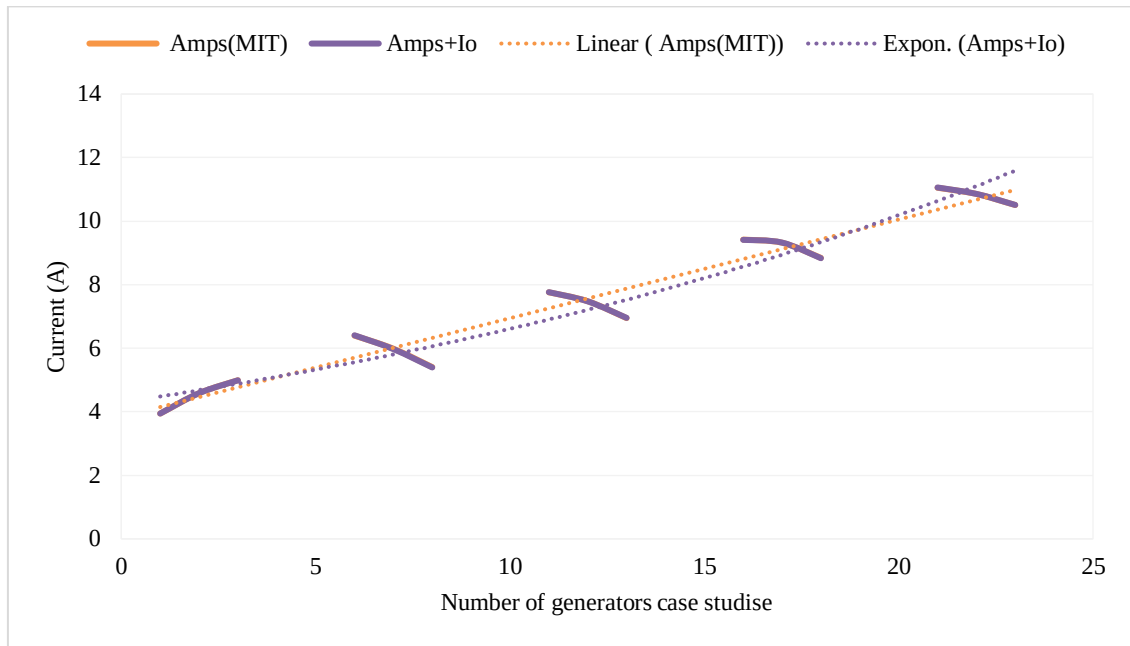


Figure 5.2-2: Generator current comparison

In the final stage of validation, the efficiency of different generators been assessed to investigate the overall numerical evaluation. Before discussing the result, we point out that TurboMatch calculation will yield a higher efficiency value because it does not include any losses. Moreover, the maximum given difference from contrasting the two outcomes is 1.037%. Figure 5.2-3 compares the generator efficiency among different case studies.

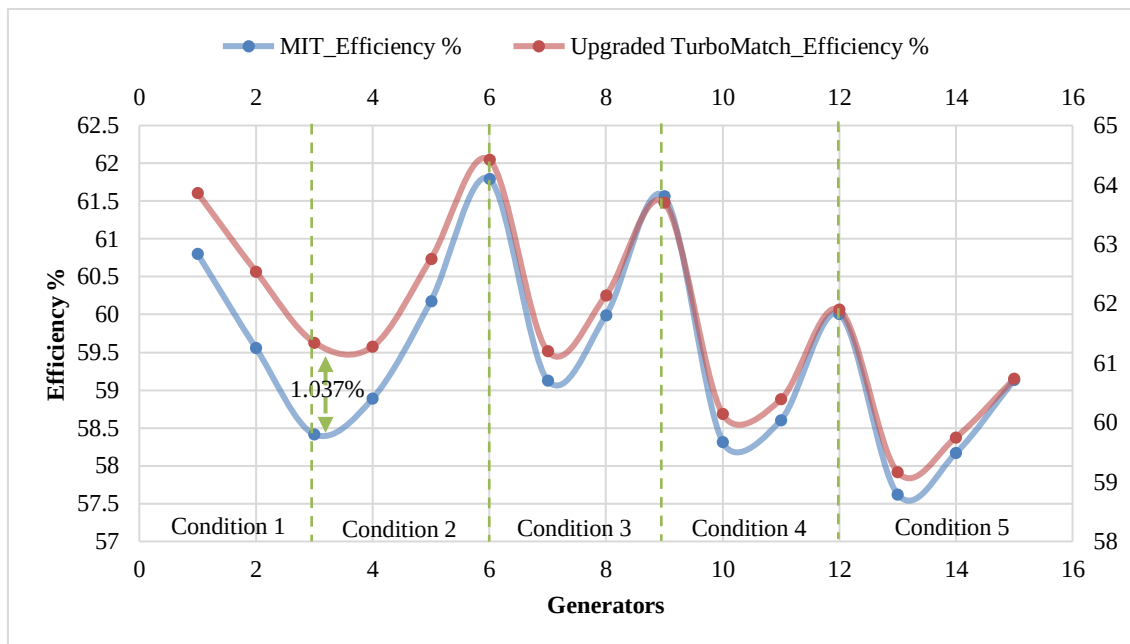


Figure 5.2-3: Generator model validation results

5.2.1.2 Electric Motor

The implementation of the electric motor follows a similar approach as the segmentation method and applies the assumptions as to the generator model. However, it uses different data and validation tool source.

Data and software used for the motor model validation were collected from Scorpion Power System Ltd. The same company manufactured most motors used in this study. In addition, the motors were compared to validate the error percentage from the company's software tool 'Scorpion Calc'.

5.2.1.2.1 Inputs and Outputs

The simulated data input contains the motor parameters required for the calculation of parameters such as voltage, resistance, motor constant and motor current, and the estimation of efficiency. These data were different for each motor, depending on its motor type and model.

The outcome from the motor simulation on both software tools represented in Table 5.2-4. This data shows each motor with its efficiency result based on the input data and motor manufacturing specification. The range examines for the motors covered 77% to 91% of efficiency. There are other motors proposed for the turboelectric propulsion system. However, they lack data for research.

A comparison of ten different types of motors was made, each motor having its manufacturing performance specifications. The error convergence estimated using the industrial motor assessment tool along with the developed TurboMatch upgrade. Although more outputs can be derived, such as mechanical and electrical power, motor efficiency was the main target of this research and all results based on motor performance calculation.

Table 5.2-4: TurboMatch and Scorpion results comparison

Motor number	Motors case study samples	Scorpion (Efficiency %)	TurboMatch (Efficiency %)
1	S 2503-1960	77.3	76.4
2	S 1805-2250	74.5	74.8
3	S 1804-1650	74.2	74.5
4	MII 2204-2300	81.1	79.6
5	M 2205-2350	81.6	80.2
6	SII 2205-1900	75.2	75.1
7	S 2205-32	75.3	73.8
8	SII 2205- 1585	76.5	76.1
9	HK 7050-340	89.2	87.6
10	SII 6540-155	91.8	90.5

5.2.1.2.2 Analysis and Validation

As mentioned before, a margin of error is expected due to the assumption and methodology used for numerical modelling. Calculated based on the case studies, this margin was 0.986% on an average and a maximum of less than 1%. This value is assumed to reflect the loss due to the motor material and motor design specification. Figure 5.2-4 illustrates the electrical motor validation.

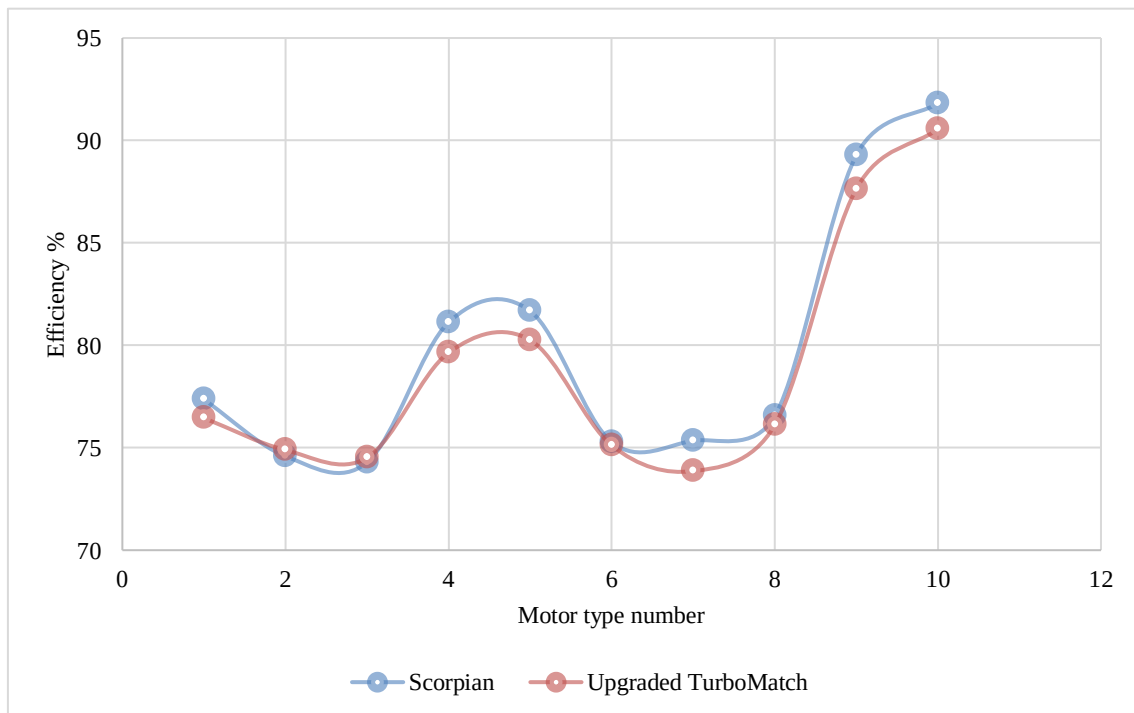


Figure 5.2-4: Electric motor model validation

5.3 Electrical Optimisation tool

Due to electrical power and network gridding, an integrated development environment in the turboelectric model for power, optimisation has become essential. This is because the optimised energy transformation efficiency affects the total efficiency of distributed propulsion. There are three types of optimisation methodologies used in research and development studies. These methods range from simple to complex ones; deterministic methods, stochastic algorithms, and artificial intelligence. See Figure 5.3-1 for the general three types of optimisation methodologies. Which method to use depends on the raw data type and complexity.

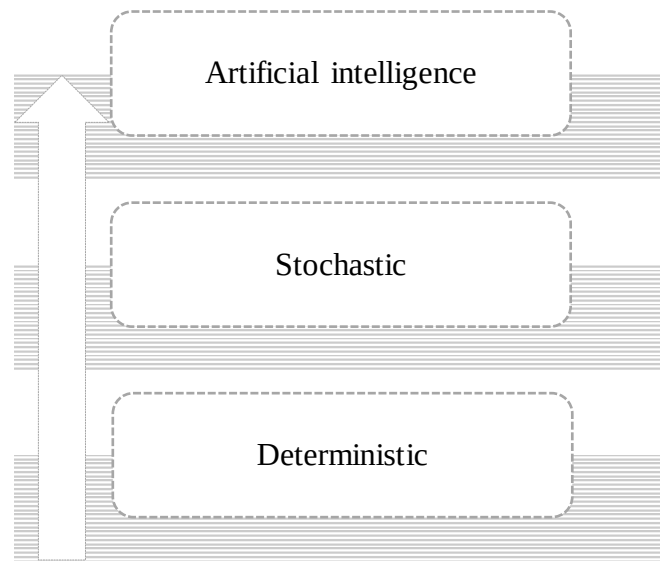


Figure 5.3-1: Three classifications of optimisation

A TurboMatch extension called GridMatch was developed for optimisation requirements and analysis the aircraft propulsion power electrical grid. It covers only the two types of optimisation methodologies, deterministic and stochastic. Future works should consider artificial intelligence (AI) to develop an automated optimisation technique for any electrical grid within any aircraft.

5.3.1 TurboMatch Extension

GridMatch was built on python as a TurboMatch extension to assist with electrical components of electric propulsion systems or more powerful hybrid systems such as turboelectric engines. Figure 5.3-2 presents the structure of GridMatch. This figure starts with the input data to find the power flow and stability. The power flow can be determined using three methods LM, NR and HELM also the time series can be simulated. The power

stability can be determined for the voltage and transient. After finding the power then the optimal power flow applied to define the mixed integrated programming then the quantitative risk analysis. The quantitative risk analysis can be simulated for two methods Monte Carlo and Latin Hypercube. From this methods voltage, load and current can be calculated and then standard deviation and CDF used to estimate the error in results. In the end, post-process used to convert the outcome results to a plot.

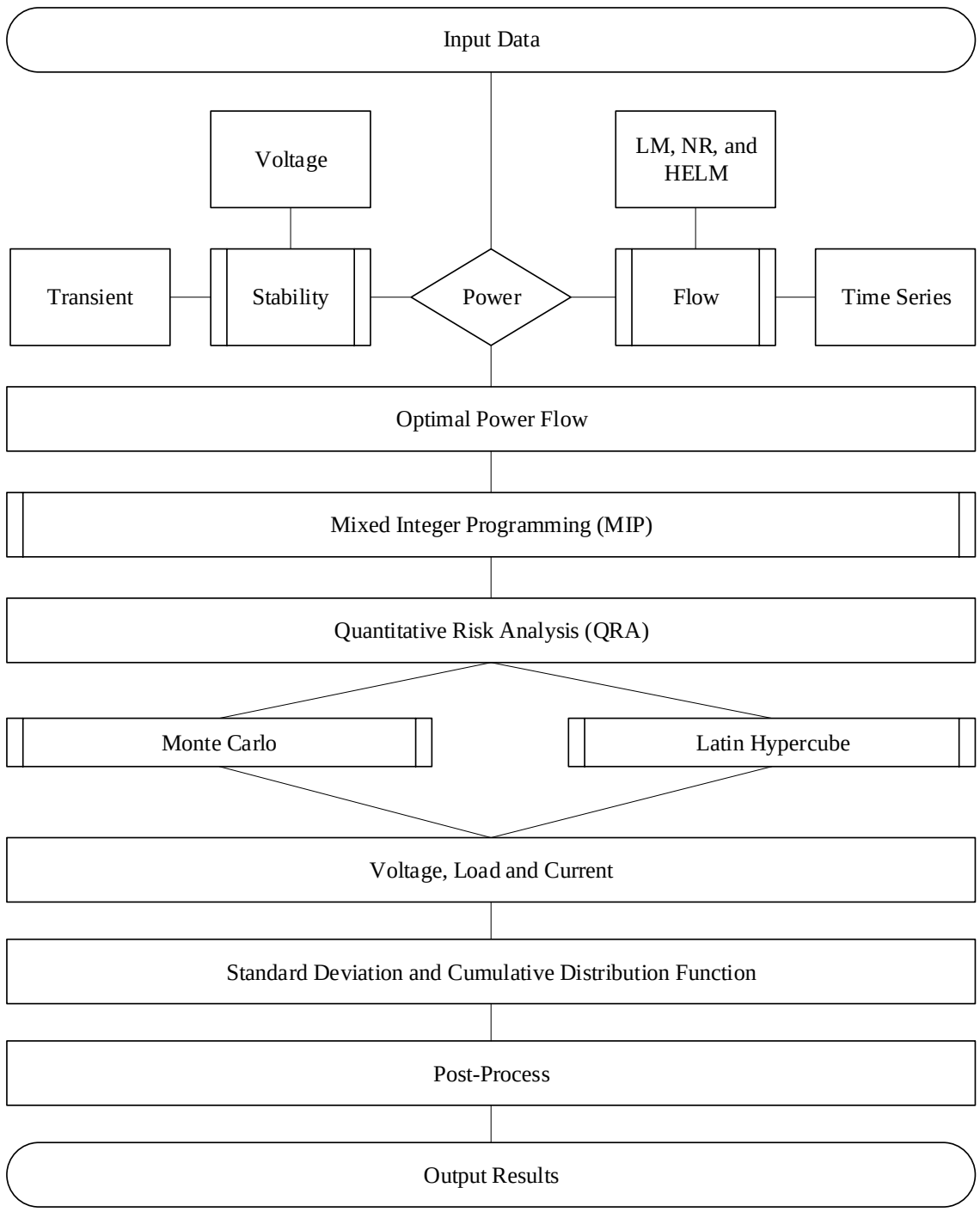


Figure 5.3-2: GridMatch Structure

5.3.1.1 Implementation

To optimise the electrical grid network in an aircraft, it is necessary to calculate the electrical elements in it. Nodes, buses, and branches to calculate the voltage, current, and power in each sector or place first illustrate the electrical grid. The power flowing through each bus or branch can be optimised and modified for better modelling. As an example, Figure 5.3-3 illustrates a simple turboelectric model with one AC generator connected to an AC to DC power converter through bus one and the voltage at node 1. After that, the converter as branch two connected through node 2 with two buses 2 and 3 for DC motor as branches three and branch four, which is the cryocooler.

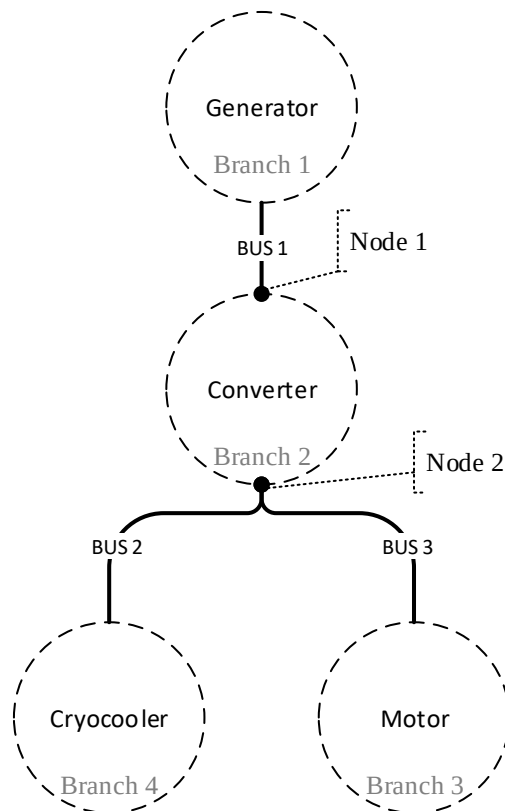


Figure 5.3-3: Simple Turboelectric network (4 braches, 2 nodes, and 3 buss)

5.3.1.2 Execution

To process the electrical grid, an admittance matrix was used for the electrical circuit to convert the proposed propulsion model for numerical analysis. The numerical model was built based on three main parameters: power, current and impedance for each bus and each element. These elements were connected over the admittance matrix using the nodal model by considering the real and reactive power. The general formula for the nodal current source is [137]:

$$I_i = \sum_{j=1}^n Y_{ij} V_j \quad (5-1)$$

Where, I = current in specific bus.
 Y = electrical elements connected to the node.
 V = voltage in a specific bus.

5.3.1.3 Deliverable

The outcome from the electrical optimisation tool can be explained as follows:

- Each electrical part and each element in the grid were optimised.
- The electrical grid was analysed and the best configuration for the required power was established.
- The assurance probability for voltage, current, load, and power flow availability were studied.
- Quantitative risk assessment for the electrical grid was performed.
- The error could be estimated using more than one method.
- Post-process for electrical power, grid, and elements performance was conducted.

5.3.2 Power Flow

The critical task of determining power flow in a grid involves calculating the minimum power and voltage required by for the electrical elements. There are several methods to calculate these values. The three methods used in numerical modelling to solve the electrical power flow are Levenberg–Marquardt, Newton–Raphson, and holomorphic embedding. These methods are used as iterative approaches to solve linear and nonlinear problems. If there exists a voltage in the node, the solution is a nonlinear mathematical equation. If there is no power and only current, then the solution is in linear.

5.3.2.1 Levenberg-Marquardt

This method was established to solve nonlinear problems, especially least squares, by minimizing the sum data point and the nonlinear function. This reduction was performed by combining two methods, gradient descent and Gauss–Newton. This combination works in two cases: first, with gradient descent, i.e. if the values are at a point far from

the function, and Gauss–Newton, i.e. if they are near [129]. The algorithm for the Levenberg–Marquardt method is as follows:

$$(J^T J + \lambda I)\delta = J^T r \quad (5-2)$$

Where, J = Jacobian matrix
 λ = damping parameter
 r = residual vector
 δ = initial guess adjustment

The numerical analysis of this algorithm was implemented in four simplified stages as follows:

- i. Calculate the divergence in power.
- ii. Estimate the error.
- iii. Error sample size.
- iv. Find the best fit and loop, if not converged.

5.3.2.2 Newton-Raphson

Another iteration approach in numerical methods for value minimisation within a function is the Newton–Raphson method. This method uses Gaussian elimination to solve nonlinear power flow problems. The advantage of this method is its reliability over a large number of iterations [138]. The formula of the Newton–Raphson method is:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (5-3)$$

Where, x_n = point or value.
 x_{n+1} = next point or value.
 $f(x_n)$ = valued function.
 $f'(x_n)$ = line slope or derivative of the function.

The numerical algorithm for Newton–Raphson was built in the same stages as Levenberg–Marquardt but with different sizing method depending on the principle formulation.

5.3.2.3 Holomorphic Embedding

This novel method, which has two patents to the credit of Antonio Trias, was introduced to solve the complex analysis of power flow. The main novelty of this method is its non-iterative and deterministic approach to solving power flow. As a lean application in power quantitative analysis, this method reduces memory and error margin in the expected results. In terms of complexity of the analysis solver, the holomorphic embedded load flow method (HELFM) inspired by Taylor's method was intended for electric power flow, but it was built with different algebraic variables on a software problem-solving programme [132].

The numerical algorithmic method for HELFM follows three steps:

- i. Settle holomorphic complex embedded parameters.
- ii. Determine the power series with respect to the reference solution.
- iii. Use a Padé approximation (function approximation method) to determine a generalised solution.

5.3.2.4 Time Series

This method differs from previous methods in terms of the error estimation concept employed. The idea of the time-series method is to study the behaviour of different electrical elements with respect to time and the voltage in the electric grid with respect to varying load and electric parts status. The numerical algorithm for this method contains three stages: firstly, read the profile of each element; secondly, specify the period; and finally, with those conditions, simulate the power flow.

5.3.3 Power Stability

The overload of each electric bus in power flowing through it can be determined using the voltage consumed by the load parts. This will give the stability of each electric part in terms of voltage and its transient capability. The stability can be approximated by estimating the load in each bus over different iterated or non-iterated method [139].

5.3.3.1 Voltage

The meaning of voltage stability is to have a sustainable amount of voltage within each electric grid under the same conditions. In different flight conditions the electric loads

within time period power consuming, voltage collapse could happen. The electric grid in this study was examined and tested using alternative power-system utilisation methods for voltage stability at nodes. The voltage variation between the two points is calculated through a current flow [140].

$$Current = \frac{Voltage_{point\ A} - Voltage_{point\ B}}{Resistance + Impedance} \quad (5-4)$$

5.3.3.2 Transient

The loss in power flow is a tangible issue faced in electricity distribution, especially in electromechanical elements such as generators and motors. Preventing these losses will save a significant amount of energy, mainly in large electricity distribution grids with numerous generators and motors. The importance of transient stability comes from the minimisation of waste to increase power-saving and through the optimisation [141].

5.3.4 Mixed Integer Programming Solver

The boost capability and functionality of mixed-integer programming (MIP) enabled it to the application of a larger scale; from two classic algorithms for data simulation to more than six advanced algorithm types. The uniqueness of this method is that it can optimise the samples iteration levels for a variety of problems including significant linear progress, scattered numerical data systems, nodes problem, and flexible variables selection using integer value [142,143].

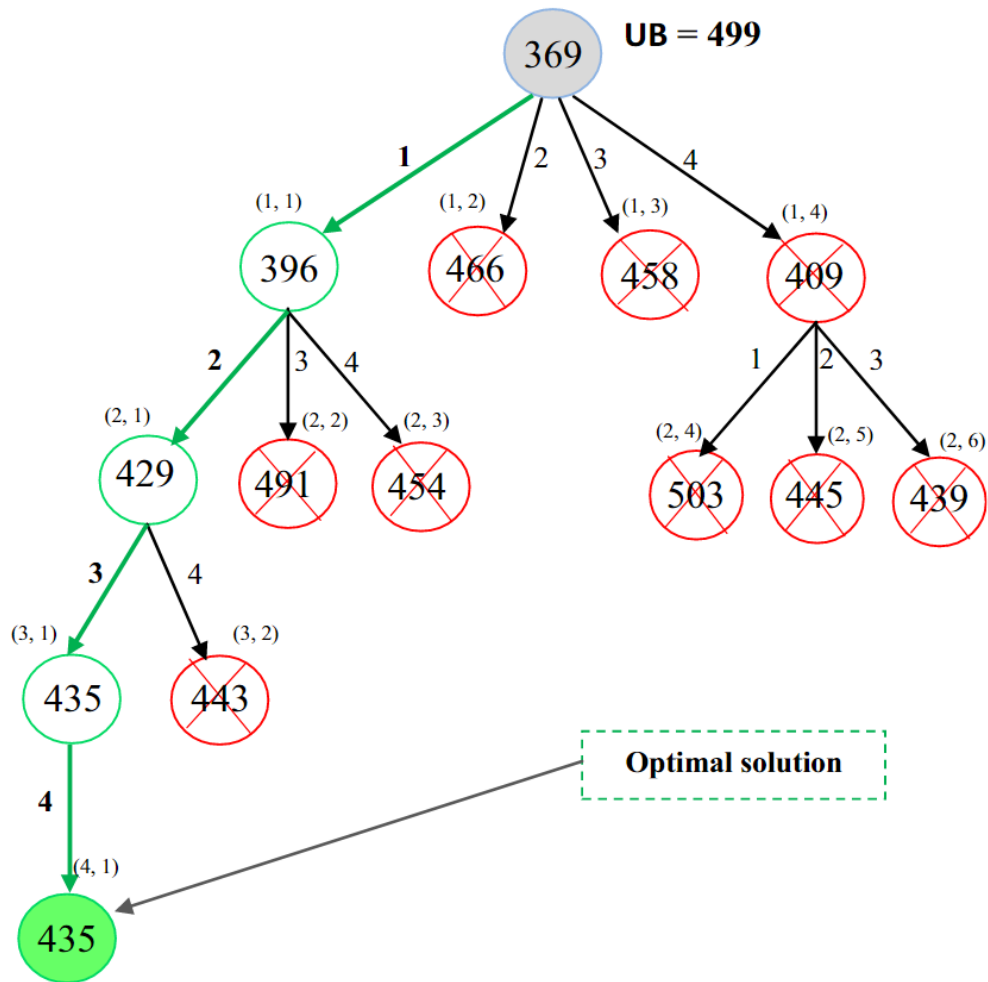


Figure 5.3-4: Branch and bound tree optimisation (UB= upper bound) [144]

One of the solvers used in the MIP of this study is the branch and bound tree for an electric node grid. Figure 5.3-4 illustrates an example of this method. This reflects in the project graphical user interface (GUI) structure and links to convert the input data into an electrical skeleton. Moreover, the outcomes that MIP gives are live results on the GUI skeleton for software friendly use and analysis.

5.3.5 Case Study: NASA N3-X

The case study used to verify the new electrical optimisation tool is NASA N3-X. The reason for studying N3-X as it represents futuristic turboelectric distributed propulsion aircraft concept. The proposed concept has 16 electric motors and 4 electric generators. Each of the turboshaft or turbofan shaft are connected to two generators. The case study was examined under three scenarios—rolling to take-off (RTO), take-off (TO), and cruise. Table 5.3-1 lists the input data used for each scenario for verification and study. The power factor used in NASA N3-X was assumed to be 0.85. As in real life electrical

power factor typically between 0.8-0.9, the average power factor taken in this study assumption.

Table 5.3-1: GridMatch input data

Component	Cruise	RTO	TO
Generator	4.452 (MW)	12.2 (MW)	14.56 (MW)
Motor	1.113 (MW)	3.05 (MW)	3.64 (MW)

The aircraft modelled in GridMatch is illustrated in Fig. 5.3-5. This model shows the mesh topology of 4 generators and 16 motors. There are two connected generators, which are the primary generators in the gas turbine engine, and each motor is connected to a different generator. This is done for risk management and failure alternatives.

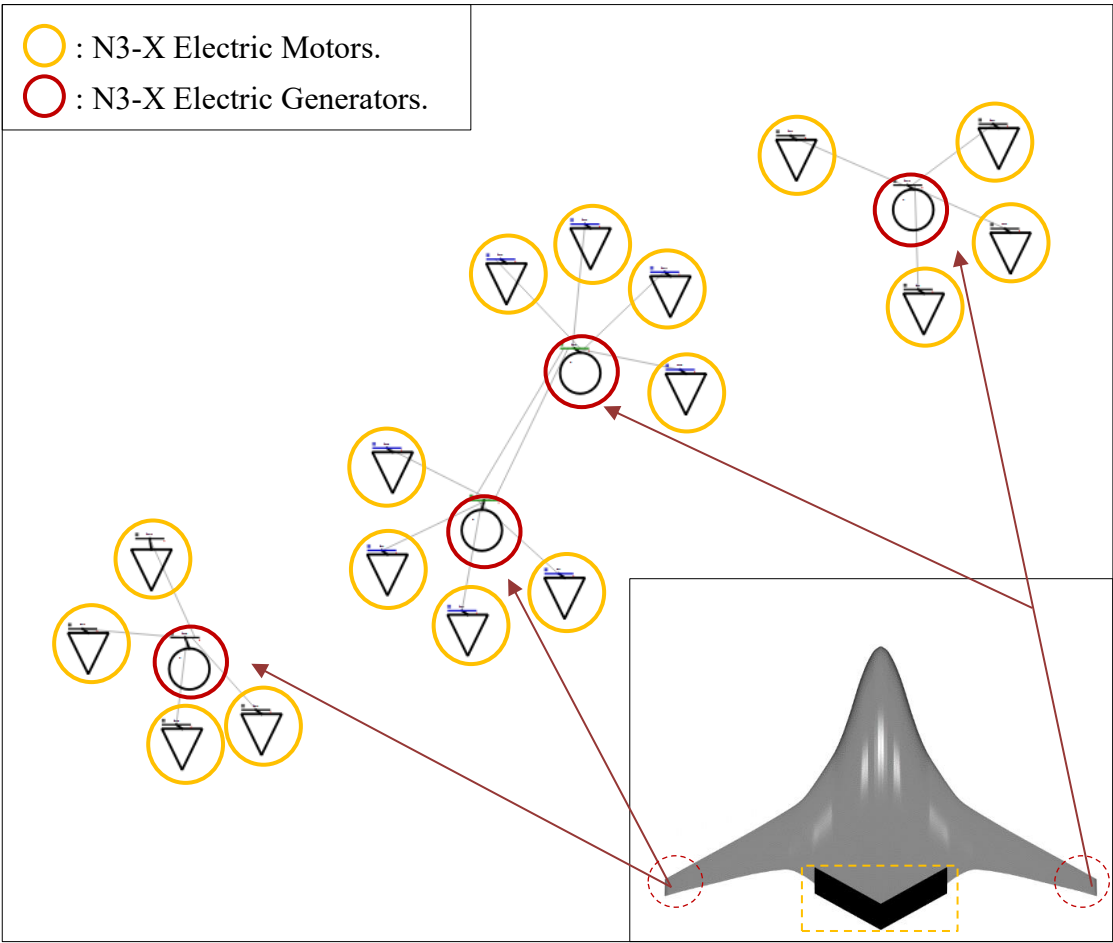


Figure 5.3-5: NASA N3-X electrical GridMatch model

Figure 5.3-6 is a design graph from NASA illustrating the connection between the generators and motors. In addition, Fig. 5.3-7 transfers this design to the case study model used in GridMatch.

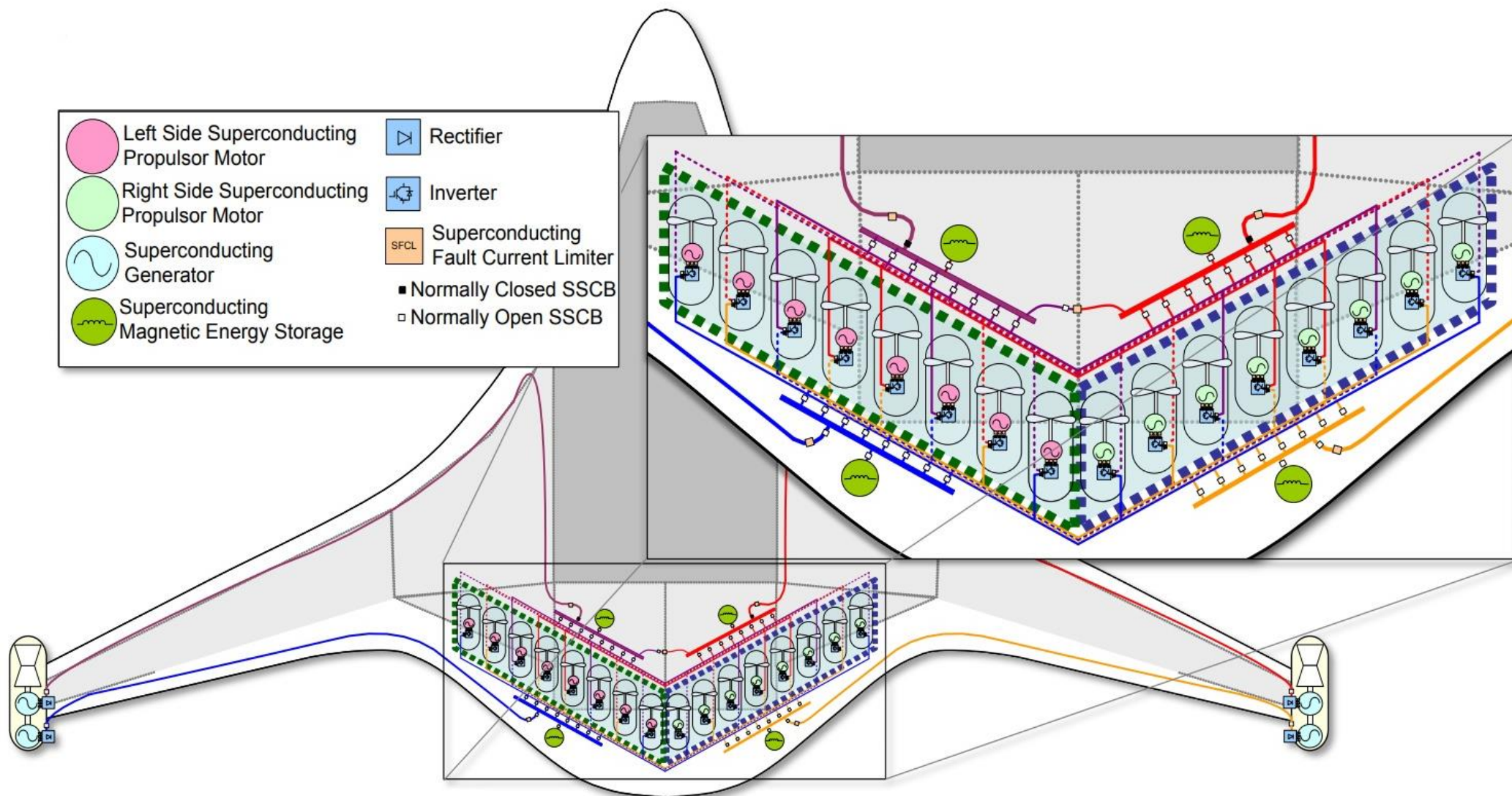


Figure 5.3-6: NASA N3-X architecture overview [145].

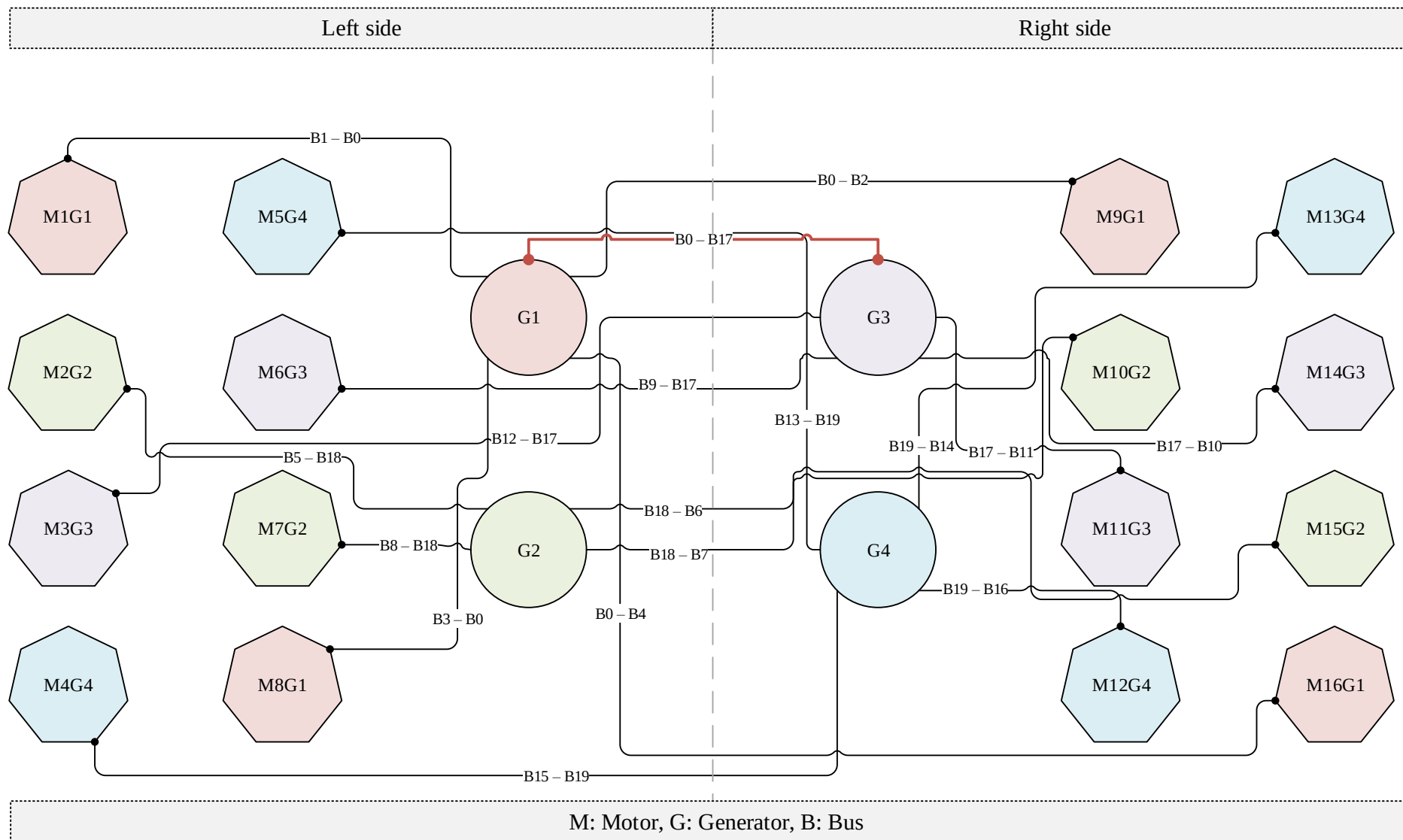


Figure 5.3-7: NASA N3-X electric model

The next step to transfer the model to numerical logic is presented in Table 5.3-2. The numbering style used for motors name modelling as the last digit in the name number represents the generator number connected to it. For example, motor 161 means motor 16 connected to generator 1. Moreover, “bus from” value represents the value of a bus in each component, such as bus 4 for motor 161.

Table 5.3-2: NASA N3-X network input model

Branch	Name	Bus from	Bus to
0	Generator 1	bus 0	bus 17
1	Motor 11	bus 1	bus 0
2	Motor 91	bus 2	bus 0
3	Motor 81	bus 3	bus 0
4	Motor 161	bus 4	bus 0
5	Generator 2	bus 18	bus 18
6	Motor 22	bus 5	bus 18
7	Motor 102	bus 6	bus 18
8	Motor 152	bus 7	bus 18
9	Motor 72	bus 8	bus 18
10	Generator 3	bus 17	bus 0
11	Motor 63	bus 9	bus 17
12	Motor 143	bus 10	bus 17
13	Motor 113	bus 11	bus 17
14	Motor 33	bus 12	bus 17
15	Generator 4	bus 19	bus 19
16	Motor 54	bus 13	bus 19
17	Motor 134	bus 14	bus 19
18	Motor 44	bus 15	bus 19
19	Motor 124	bus 16	bus 19

Output results from GridMatch simulation based on the scenarios are as follows:

5.3.5.1 Rolling to Take-Off (RTO)

This scenario covers rolling to take-off, which is the taxing operation or movement before take-off and after landing. A medium power in this station expected to be between TO and cruise values. According to this, the results should verify the median usage of energy and losses. Figures 5.3-8 and 5.3-9 illustrate the results of the power flow modelling simulation of NASA N3-X. From the calculated results, four generators in the RTO scenario produced approximately 14.3 MVA for the 12.2 MW from the gas turbine. This load represents 74% of the generator load. Moreover, each of the 16 motors consumes 18.5% of the power from the generator connected to it with 3.5 MVA. These values verify the power factor of 0.85 assumed in the modelling process.

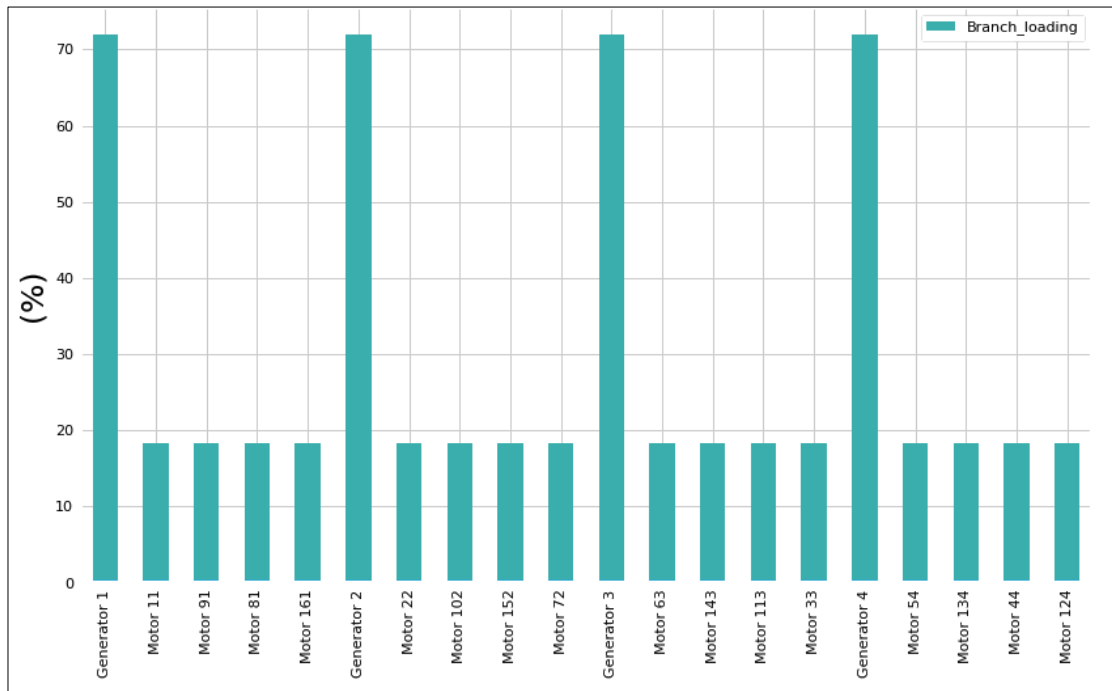


Figure 5.3-8: NASA N3-X branch loading

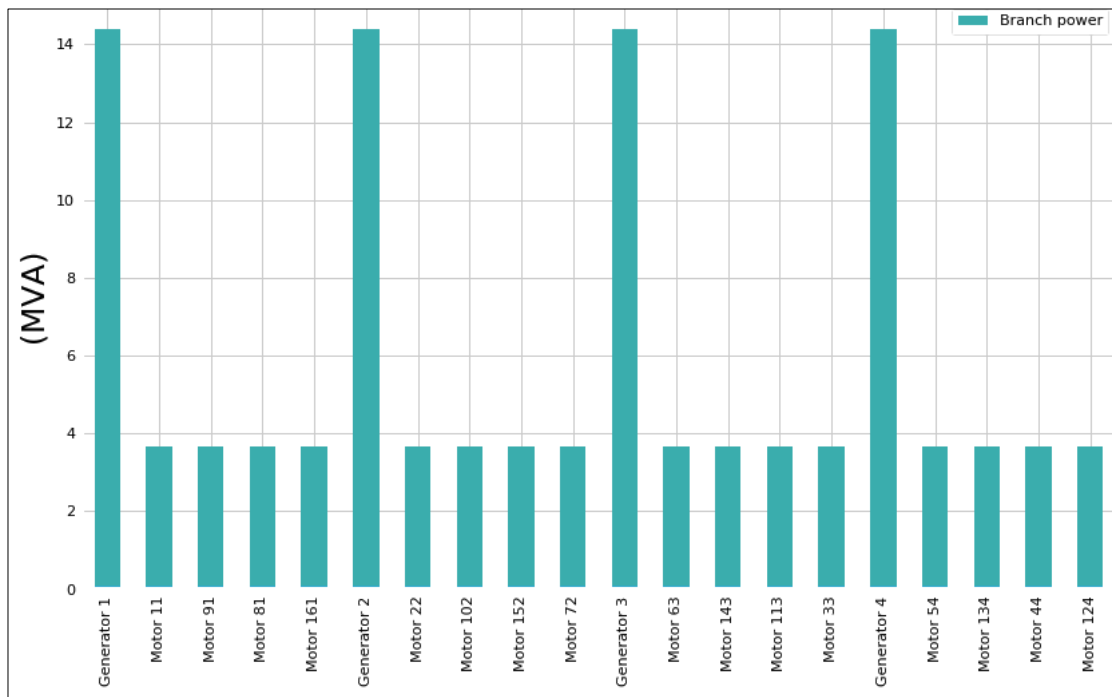


Figure 5.3-9: NASA N3-X branch power

For the time domain analysis, time-series random power sampling fluctuating during the time for the system generators and motors studied to clarify the reliability and losses optimisation. To minimise the grid violations and slack generators, a random power change was applied each 15 min for the time of a full-day operating assessment (2020-01-01 00:00:00 to 2020-01-01 23:45:00). The results shown in Figure 5.3-10 are the bus voltage stability for the prime power generator system distribution during a full day, with

random fluctuations in the power. The outcome indicates that the applied power is distributed through the grid bus with 97.5% as the worst-case scenario and 99% as the general case. However, there is 1% change of overload, which could result in faraway motors connected to the generator.

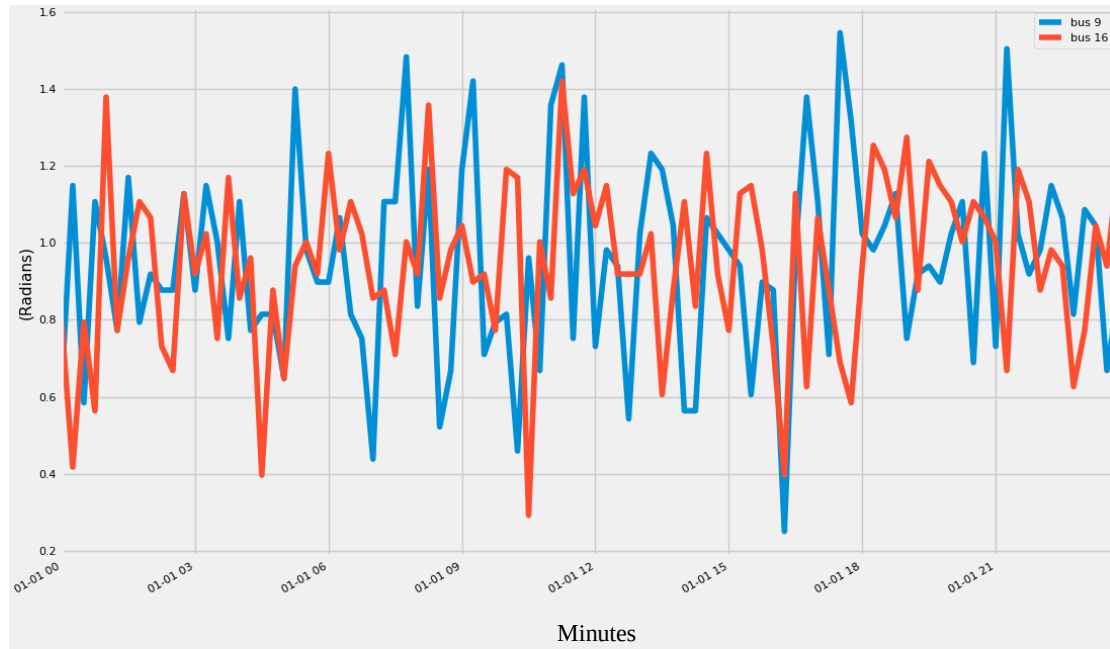


Figure 5.3-10: NASA N3-X time series bus voltage radians for two prime electric generates

The time series results reveal the application of optimal power flow (OPF) to supply the demand with minimised loss and increased reliability of the system. The OPF results indicate that the power consumed by the motors dropped to 17.9% of the generators' power. This suggests a reduced generator load of 71.7% and ensures the highest efficiency power within the risk limits. The following figure 5.3-11 represents the optimised power flow in the grid.

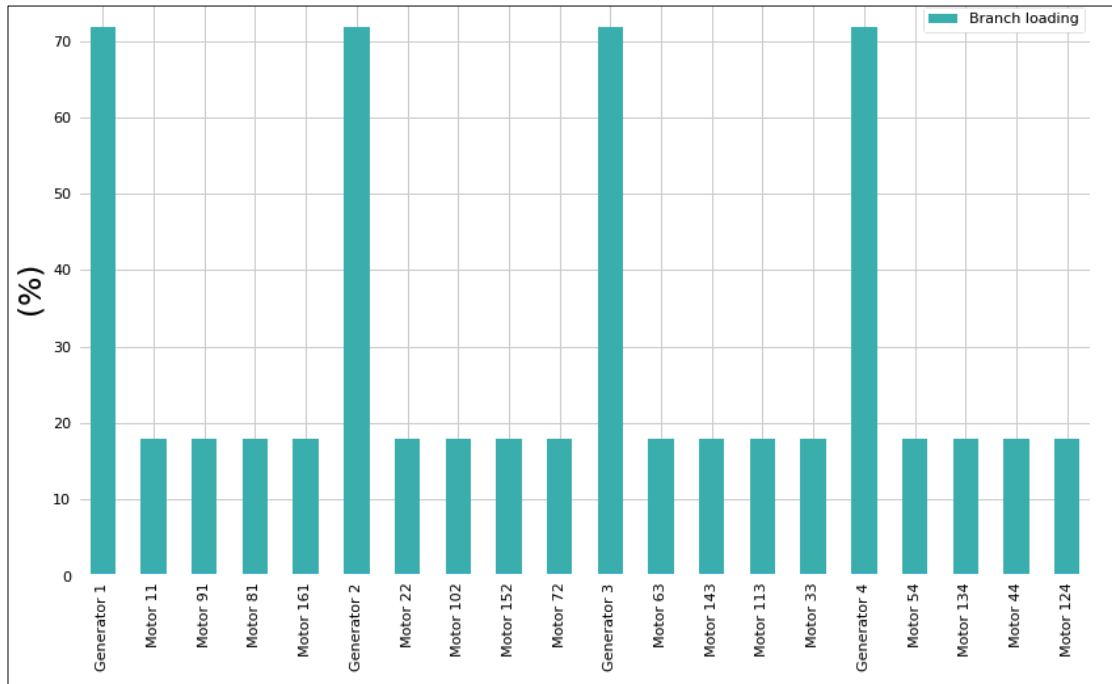


Figure 5.3-11: NASA N3-X RTO OPF branch loading

5.3.5.2 Take-Off (TO)

This scenario studies the extreme behaviour of electric components under the requirement of a full power load. The simulation results of TO reveal that each motor consumed 21.9% of the generator power. In addition, the power load used for electrical performance is 90% of its capacity that translated to 18 MVA for each generator and 4.3 MVA for the motor. Figures 5.3-12 and 5.3-13 illustrate the power flow results for TO.

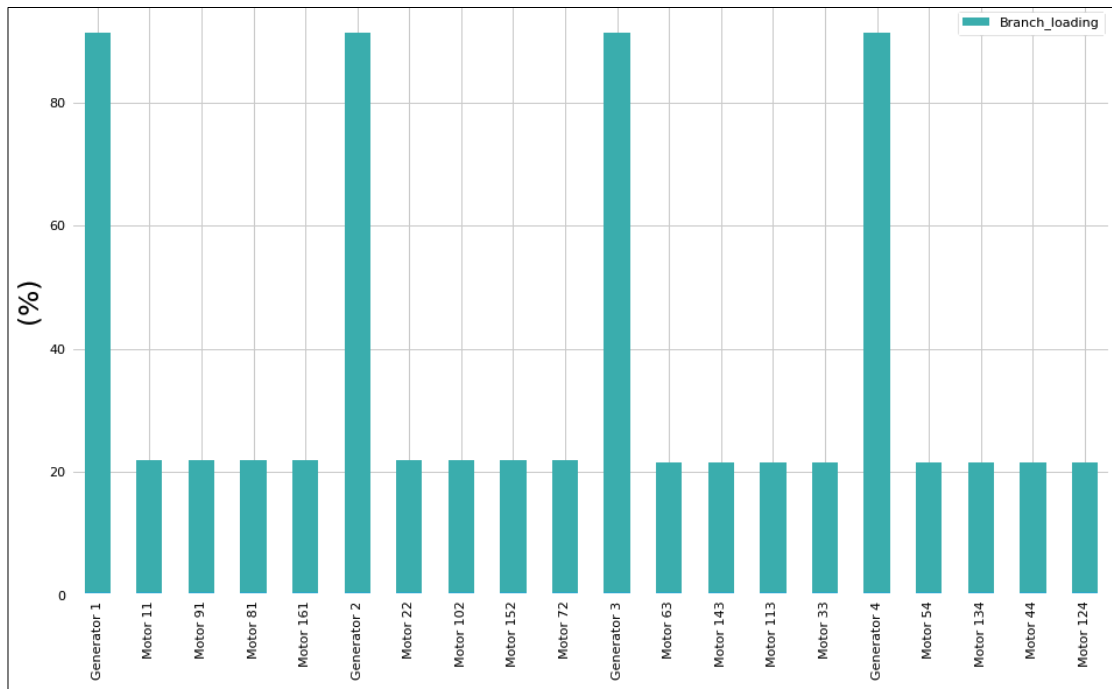


Figure 5.3-12: NASA N3-X TO branch loading

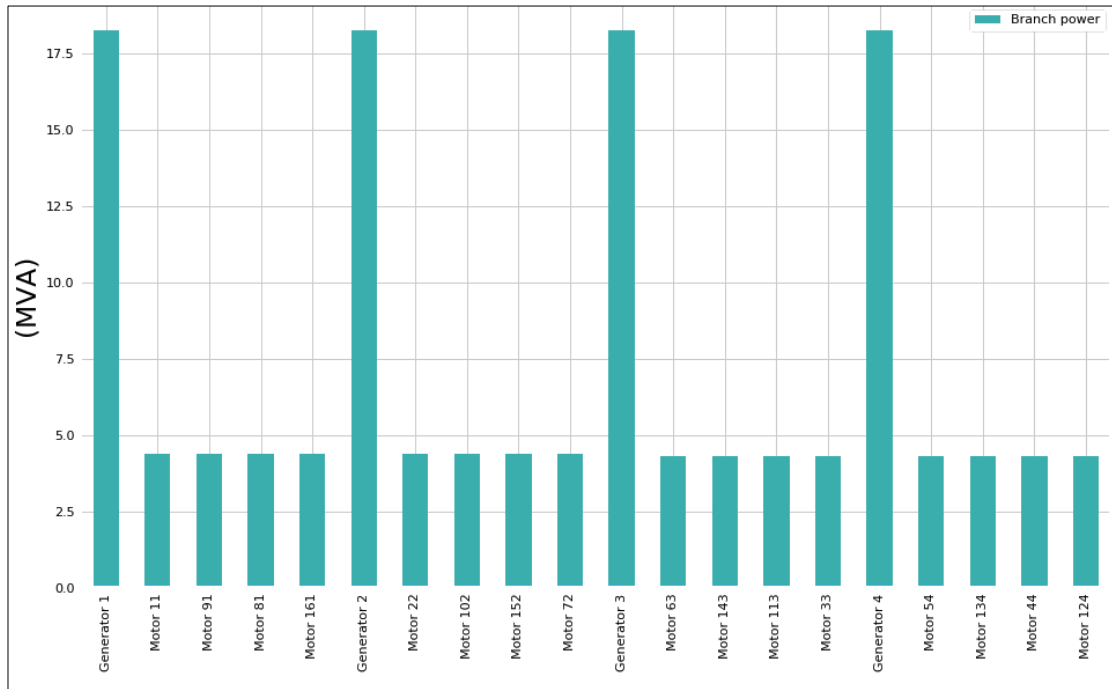


Figure 5.3-13: NASA N3-X TO branch power

The same assumptions as for RTO were used to assess TO within the stipulated time period. The simulated results for RTO were similar with those for TO because the time series assumption within the electrical component configuration was still the same. Figure 5.3-14 illustrates these results. From the figure, the worst case for bus voltage distribution throughout the grid is 97% for stability and 99% on average. The risk probability assessment for voltage overload in the electrical grid calculated around 1.3% this because of increase fluctuating consequence of generator load level. Figure 5.3-15 illustrates the optimised power flow for TO by decreasing the load on generators to 82.3% and motors to 21.4%, to keep the voltage within a reasonable margin.

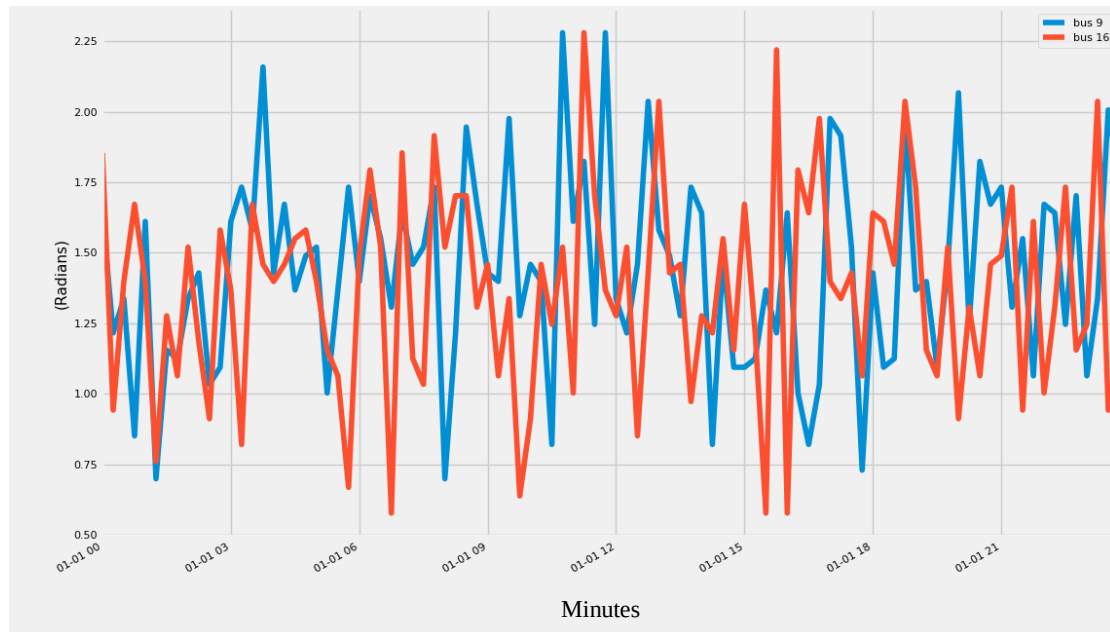


Figure 5.3-14: NASA N3-X TO time series bus voltage

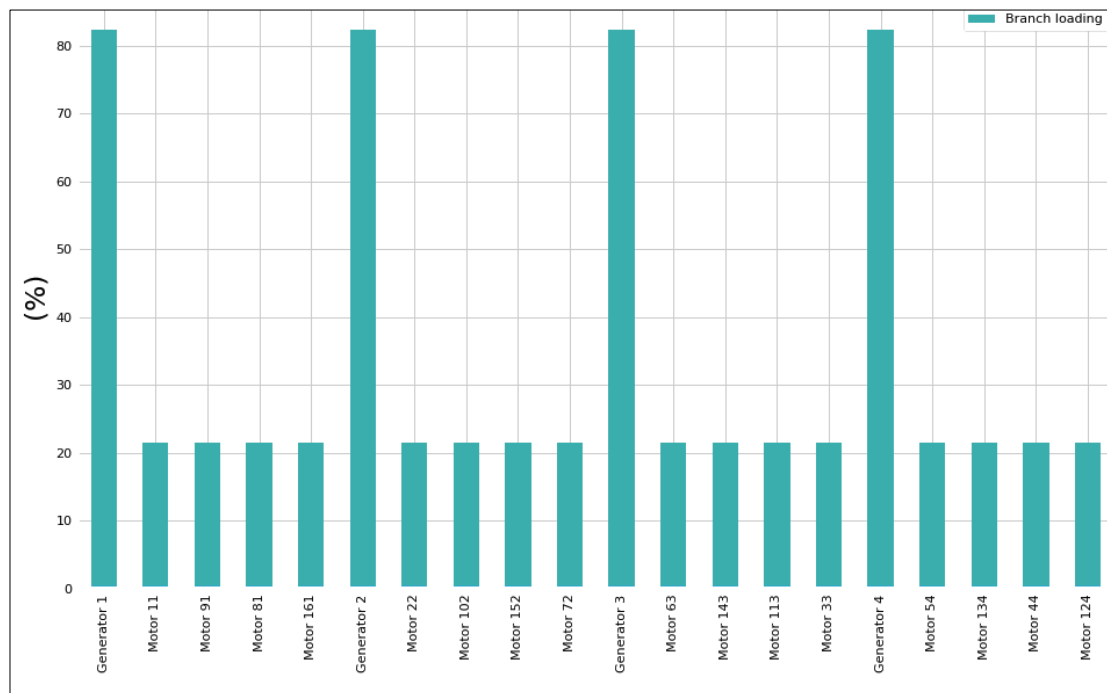


Figure 5.3-15: NASA N3-X TO OPF

5.3.5.3 Cruise

This case consumes and generates the least power. The simulation result of GridMatch shows that the branching load for the electric generator, in this case, is 25.6% and 6.5% for each motor. These outcomes reveal 5.11 MVA for the generator power and 1.31 MVA for motor power, as illustrated in Figures 5.3-16 and 5.3-17.

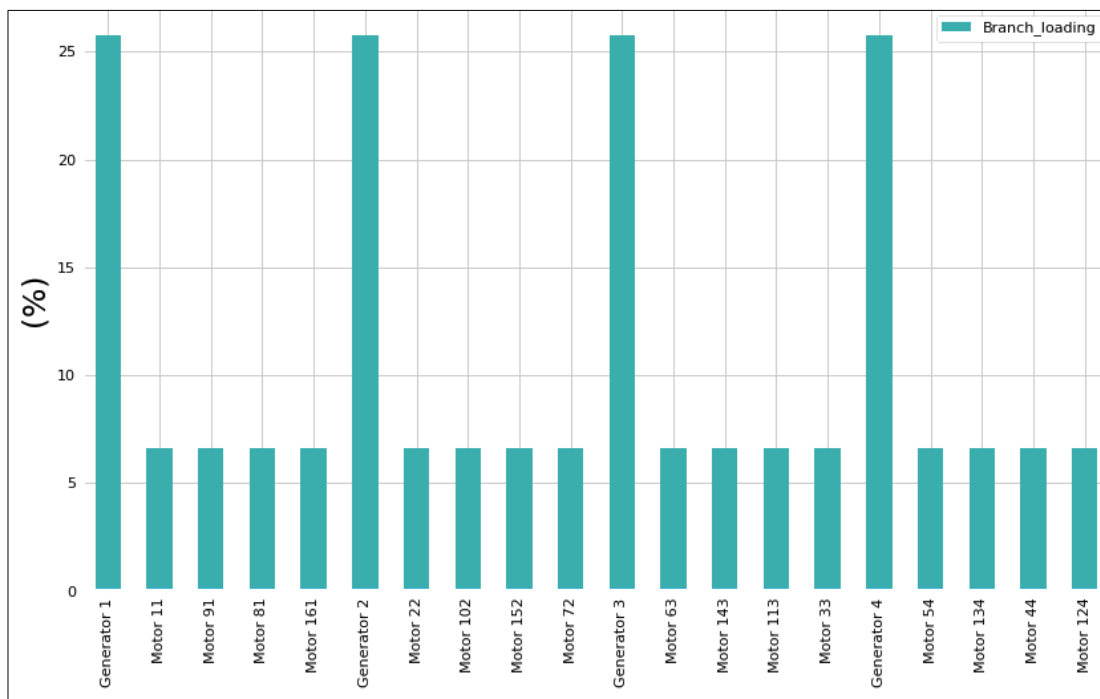


Figure 5.3-16: NASA N3-X cruise branch loading

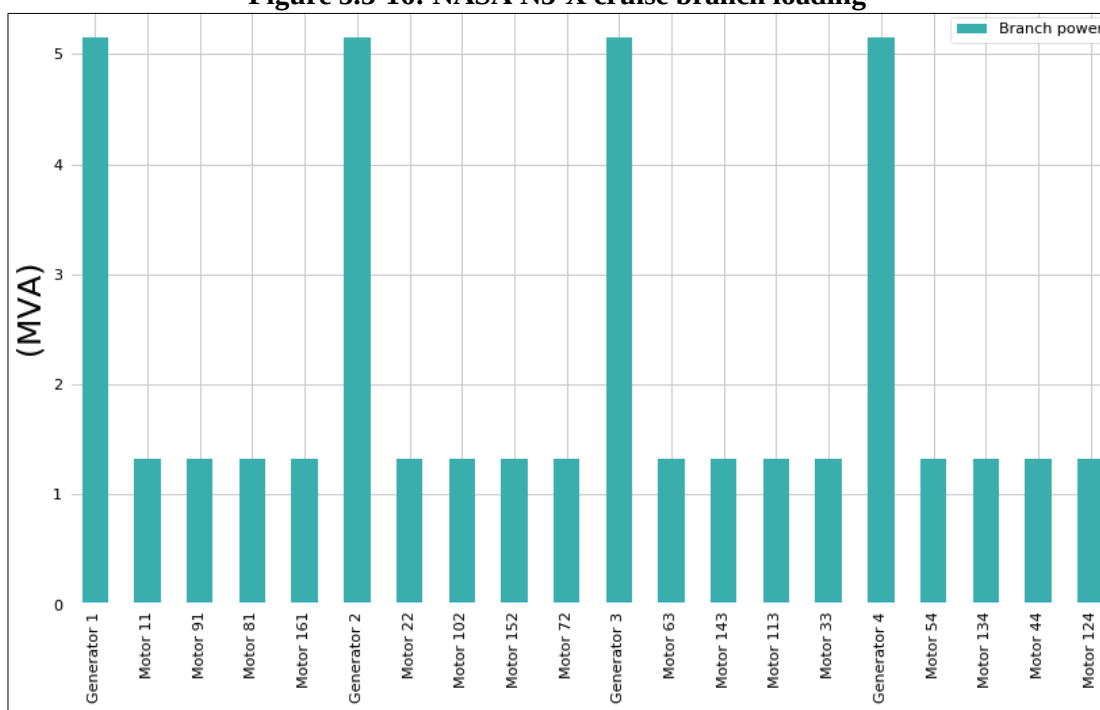


Figure 5.3-17: NASA N3-X cruise branch power

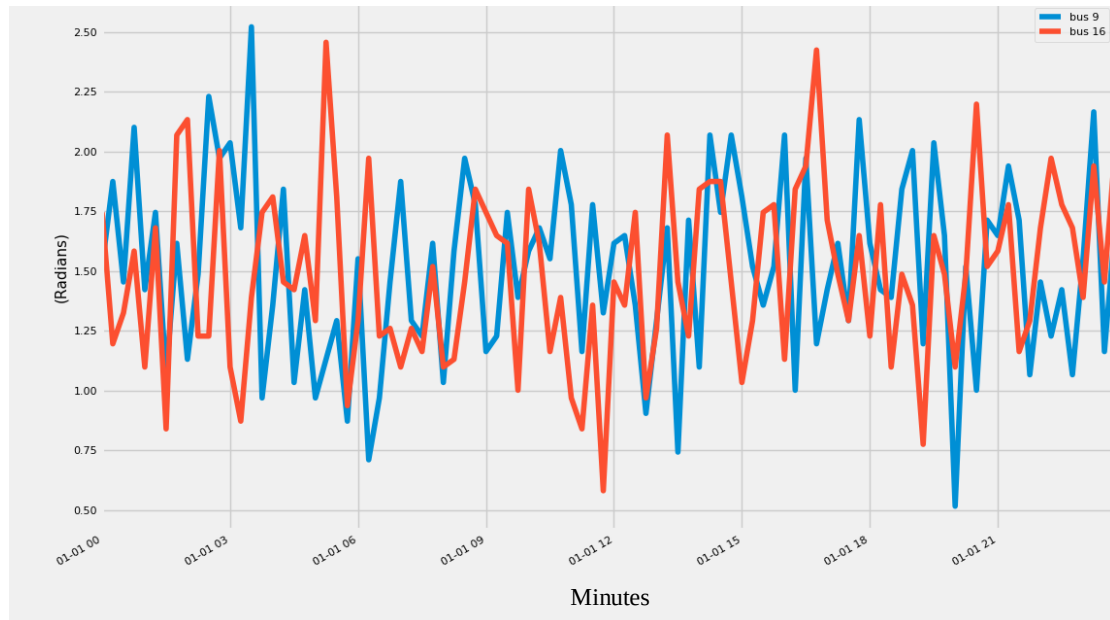


Figure 5.3-18: NASA N3-X cruise time series bus voltage

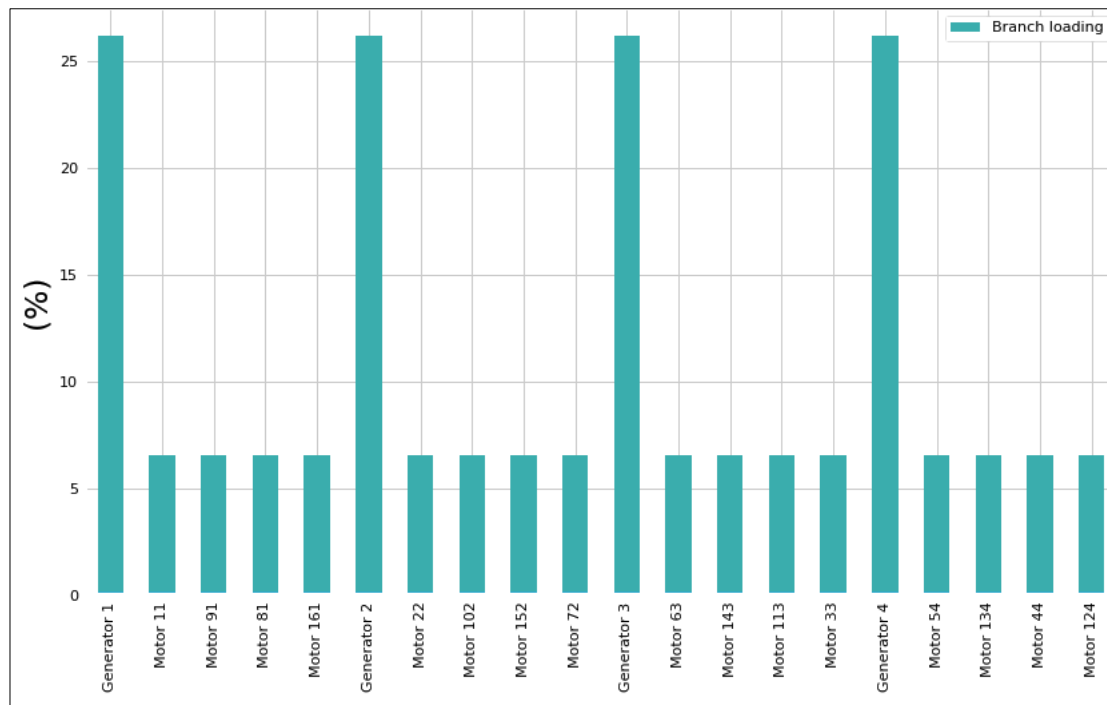


Figure 5.3-19: NASA N3-X cruise OPF

For the time demand of bus voltage within the electrical grid network, the expected voltage outcome is given from the generators and motors. This is because of the fixed manufacturing design of the electric components. A risk of 1% still exists, as shown in Fig. 5.3-18, under the same conditions. Optimisation for the power flow shows that the losses in the grid could be minimised by increasing the branch load by 0.57%. This will lead to a more stable power flow with fewer slack generators and reduced motors loads by 0.04% on the grid. Figure 5.3-19 illustrates the OPF for the cruise condition.

5.4 Chapter Summary

This chapter signifies the fundamental numerical modelling tools established for turboelectric and other futuristic distributed propulsion systems. These tools are related to the primary performance tool called TurboMatch, developed at Cranfield University. The first novel modelling tool in this study is a TurboMatch upgrade with a mechatronic integration that introduces electrical power into the legacy systems. Linking mechanical and electrical produced in the mechatronics of converting turbine power to electric power using the generators and reversal for electrical power to propulsive torque in motors. After the initiation, other electric parts needed to be added to the distribution system and power flow to close the power circuit. This led to the second part of the novel method of modelling called GridMatch. This method was developed to study the electric components and can be used in any electric propulsion system, including turboelectric aircraft. These tools were validated and tested with several case studies and authentication methods.

The modelling study and optimisation performed in this study consist of ordinary and optimal solutions and consider the reactive and active powers. The result of the simulation of a case study (NASA X3-X) shows the ability to enhance the electrical power system in terms of reliability and stability. The following table compares existing data on NASA X3-X and the enhanced results of this study. Table 5.4-1 represents the electrical grid results comparison.

Table 5.4-1: Electrical grid results comparison

Model name	NASA	Cranfield Optimisation
CRUISE		
Generator power (MW)	4.45	4.47
Motor power (MW)	1.113	1.112
RTO		
Generator power (MW)	12.2	11.9
Motor power (MW)	3.05	3.01
TO		
Generator power (MW)	14.56	13.43
Motor power (MW)	3.64	3.62

The following chapter 6 will study the verification of outcomes of this chapter to ensure the uncertainty qualification of the study.

CHAPTER 6

UNCERTAINTY QUANTIFICATION AND ERROR ESTIMATION IN TURBOELECTRIC NUMERICAL MODELLING

ABSTRACT

Turboelectric systems can be considered complex systems that may comprise errors and uncertainty. Uncertainty quantification and error estimation processes can, therefore, be useful in achieving accurate system parameters. Uncertainty quantification and error estimation processes, however, entail some stages that provide results that are more positive. Since accurate approximation and power optimisation are crucial processes, it is essential to focus on higher accuracy levels. Integrating computational models with reliable algorithms into the computation processes leads to a higher accuracy level. Some of the current models, like Monte Carlo and Latin hypercube sampling, are reliable. This chapter focuses on uncertainty quantification and error estimation processes in turboelectric numerical modelling which been discussed in chapter 4 and 5. The current study integrates the current evidence with scholarly sources to ensure the incorporation of the most reliable evidence into the conclusions. It is evident that studies on the current subject began a long time ago, and there is sufficient scholarly evidence for analysis. The case study used to obtain this evidence is NASA N3-X, with three aircraft conditions: rolling to take off, cruising, and taking off. The results show that the electrical elements in turboelectric systems can have decent outcomes in statistical analysis. Moreover, the risk of having overload branches is up to 2% of the total aircraft operation lifecycle, and the enhancement of the turboelectric system through electrical power optimisation management could lead to higher performance.

6.1 Introduction

Uncertainty is a common occurrence in engineering systems. It entails the process of accurately computing the extent to which a mathematical model can describe the relevant physics. It also concerns the impact of model uncertainty, which is either parametric or structural, on the outputs of the model. Error estimation, on the other hand, entails the task of determining the accuracy of a particular numerical technique in its approximation

of a given output. It is also common in engineering systems due to there being several mechanical factors that are involved in their composition. A turboelectric aircraft utilises combustible fuel for the storage of energy, but it also uses electric power transmission, and not mechanical transmission, to drive the propulsors. A turboelectric design is just a different configuration or architecture for hybrid-electric or all-electric models. Turboelectric models are hybrids that lack batteries. Uncertainty quantification and the error estimation process, however, entail the use of various techniques for different types of uncertainties.

This chapter studies the uncertainty in turboelectric distributed propulsion (TeDP) systems and estimates the error in their utilisation. In addition, it fills in the gap of quantitative risk analysis in numerical modelling for futuristic propulsion systems.

6.2 Impact of Model Uncertainty

Apparently, during the development of numerical models, uncertainty quantification tasks can lead to a suitable framework for the allocation of computational resources. They most often lead to an efficient investigation in activity role model standardisation and a robust design [41]. During turboelectric numerical modelling, several uncertainties can emerge due to assumptions associated with unavoidable circumstances. It is crucial to account for those uncertainties. Uncertainty quantification can enable the prediction of the effects of the sources of uncertainties on numerical models and the effects of the inherent assumptions they make about the models. Uncertainty quantification strategies affect modelling processes because they can enhance the optimisation processes and sound design. The process of uncertainty quantification entails processes, such as effect screening, forward uncertainty propagation, parametric studies, and sensitivity analysis.

In modelling and simulation, however, the uncertainty quantification process typically entails the utilisation of parametric studies. In that regard, the uncertainty sources refer to the sources delineated by the model parameters. In turboelectric numerical modelling, aspects like the crashworthiness of an aircraft constitute a possible area of beneficial research, but there is a high level of uncertainty [41]. The uncertainty associated with the airworthiness of an aircraft increases the risk of an accident because of the inability to obtain reliable results. Uncertainty also affects the predictability of the possible outcomes. In this regard, it can amount to a negative impact due to cause inaccuracies in selecting the best action to take to enhance the safety in the utilisation of an aircraft. For example,

the aerospace industry tends to replace liquid fuel with batteries because liquid fuel tends to worsen the situation when a crash occurs.

Model uncertainty cannot help in predicting the possible outcomes of the numerical modelling process of a turboelectric system. However, it prevents accurate determination of the sensitivity of input power. In particular, with increased model uncertainty, it becomes difficult to predict the input power of the cryogenic system in an aircraft [146]. Due to the inability to predict the input power, owing to the model uncertainty, it also becomes difficult to determine the mass of the single-stage and two-stage reverse-Brayton cycle cryocoolers (RBCCs) for distributed electrical aerospace propulsion (DEAP). The challenges can also extend to the parameters necessary for the operation of the RBCCs. Inaccurate estimation of the input power and probable effects on the power transmission fluctuations throughout the system make it challenging to predict the correct temperature required for cryocooling power [146].

The effect of model uncertainty is that several crucial parameters become unpredictable and the system can only be operated on the basis of estimates which, in turn, exacerbates the effect of the error. For example, the current-carrying capacity of a superconducting material depends on essential parameters, such as the temperature, current density, and magnetic field density. The effect of model uncertainty can, therefore, affect significant measures of aircraft systems. Power optimisation becomes almost unachievable, and this leads to difficulties in producing accurate approximations. Addressing model uncertainty is vital to enabling accurate uncertainty quantification and error estimation in turboelectric numerical modelling. Considering all the parameters is key to an accurate estimation of aircraft operating conditions in turboelectric systems.

6.3 Accurate Approximation

Computational efforts develop with the increase in the number of random variables used in making accurate approximations of the input. An upsurge of random variables can slightly reduce the accuracy levels due to the associated approximations [147]. The problem tends to increase in the stochastic collocation version. The increase in computational efforts is necessary for enhancing the accuracy of the interpretation of high-dimensional space. In some case studies, the improvement of uncertainty quantification and error estimation processes using computational models is essential. Computational models, similarly to the Bayesian model, which is a statistical model that

uses probability for the uncertainty model, can enhance and utilise the approximation optimality and improve the general accuracy level if incorporated with the Monte Carlo algorithm. This can enhance the accuracy, which enables the values to be spread correctly and the sample to be selected correctly, and this is also representative of the intervals across the entire iteration [147,148].

Approximation accuracy is crucial because of the error that the approximations can introduce into the uncertainty quantification process and the turboelectric numerical modelling process. Uncertainty quantification and error estimation processes should be accurate when developing relevant solutions to and representatives of the parameters involved in the turboelectric numerical modelling of an aircraft. During error estimation procedures, it is necessary to ensure those accurate approximations serve as the source of the conclusions that are eventually made.

It is crucial to consider integrating the most representative sample values to achieve an accurate data interpretation. These data determine the effectiveness of the turboelectric numerical modelling process and the way it can address any issues arising in aircraft systems that affect the safety of the aircraft. The uncertainty quantification and error estimation processes should not only indicate the safety or efficiency of the system, but also the cost minimisation process to ensure that a reliable alternative is always available in technical, environmental, or economical terms. The outputs of several approximations simultaneously enable the enhancement of the accuracy and computational efficiency of the model. The simultaneous application of the computational models resembles a mixture of the expert models used in statistical applications. Every approximate solver provides some incomplete data concerning the high-fidelity model. The model undergoes aggregation to achieve the best possible estimate. The more the approximation models are incorporated, the higher the achievable accuracy level. The accuracy of approximation is therefore crucial to the success of the uncertainty quantification process because it determines the accuracy of the turboelectric numerical modelling process. Computational modelling strategies aid in the enhancement of the accuracy of the output results. The more the computational models are used, the greater the chances of achieving higher accuracy levels. Accurate approximation also entails the use of models with reliable algorithms, such as Monte Carlo.

6.4 Quantitative Risk Analysis

There are several types of quantitative risk analysis methods for error estimation. This research focuses on two types: Monte Carlo and Latin hypercube. These two were chosen because of the advantages that each has in the study of uncertainty. The Latin hypercube algorithm, also known as the memory analysis method, allows for less sampling, which will provide better performance. However, it decreases the computational complexity in the numerical modelling process. On the other hand, Monte Carlo, also known as the memoryless method, enhances the simplicity in numerical modelling, allowing for the processing of more samples, which increases the performance.

6.4.1 Monte Carlo

The Monte Carlo technique is a standard method used in uncertainty quantification because it is simple and generates the desired or accurate statistical results. This technique, however, has a low computational cost, which tends to be reasonable in most cases [149]. Since the Monte Carlo algorithm is parallelisable, this can allow the Monte Carlo method to be utilised in simulations in which the computation of one realisation is inexpensive. The idea of the Monte Carlo method is to produce several samples of the random factors based on their distributions. All samples outline a deterministic problem, resolved using a deterministic method, and produce a particular measure of data.

In uncertainty quantification, the Monte Carlo system uses mixed model statistics to obtain the results of a random system. The Monte Carlo strategy entails a GridMatch tool comprising three stages. The three phases, which include the stochastic model, random sampling, and deterministic model, are the components of the optimisation approach used in the analogous implementation of the TeDP of the Monte Carlo method. To obtain samples of random parameters, an individual can use a pseudorandom number generator. The generator tends to construct a sequence of numbers in a deterministic fashion, in which it indexes the numbers based on the value of a seed. The seed emulates a cluster of random numbers. If any two categories of responsibilities have common varieties of seeds, they can generate a conventional system of random numbers. To avoid the production of conventional seeds, it is imperative to employ a vital seed scattering tactic for all the electrical components. The appropriate approach can create a seed for each electric bus, without replication. The tactic must also warrant exclusive categorisation of

the numbers from each electric bus. Figure 6.4-1 represents an overview of the Monte Carlo algorithm.

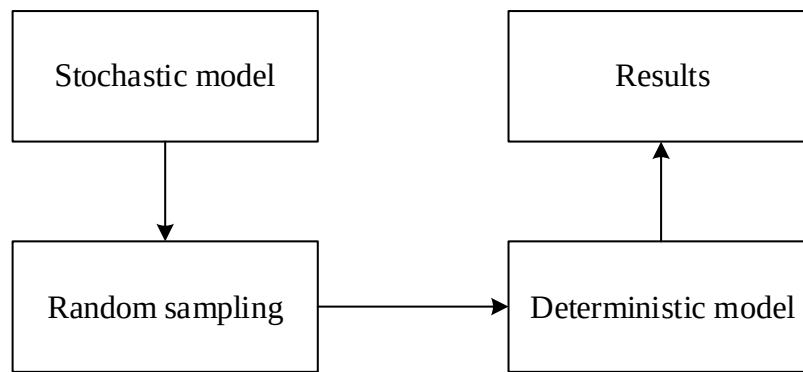


Figure 6.4-1: Exemplification of the Monte Carlo algorithm

6.4.1.1 NASA N3-X Case Study

The case study used for TeDP uncertainty and error estimation is NASA N3-X. The aircraft is modelled with 16 motors and four generators with different data inputs, depending on the system situation. Three types of aircraft condition assist in the uncertainty and error estimation to test the reliability of each state. The three examined conditions are rolling to take off (RTO), taking off (TO), and cruising. Quantitative risk analysis was conducted using Cranfield University’s in-house software extension for “TurboMatch,” called “GridMatch.” The assumptions were used in Monte Carlo 3 precision for a maximum of 1000 iterations.

6.4.1.1.1 Rolling Take-Off (RTO)

In this state of NASA N3-X, the modelled power for each motor is calculated to be 3.588 MVA, and that of each generator is 14.352 MVA. There is a connection between generator 1 and 3, as a risk redundancy plane, which is the same for generator 2 and 4. Moreover, the 16 motors are connected in a mixed prime generator, and every fourth motor is aggregately connected to one generator.

Figure 6.4-2 illustrates the risk analysis result of NASA N3-X for the branch loading average. The results show how confident the probabilistic power flow of the modelled system is. It indicates that the initial 20 samples have a higher probability of overload, and then there is a stabilisation in confidence. The average confidence probability results for the primary and secondly generators are 70% and 50%, respectively, where the motors are from 15–17%. This means that the system is reliable for the RTO condition in terms

of the load, as the calculated determined load need for motors is 68%, and this is covered by 70% of the Monte Carlo consequence.

Next, Figure 6.4-3 shows the NASA N3-X bus voltage average from the Monte Carlo analysis. Appositive outcomes are given from the analysis, with a fixed voltage, through the electric bus from the power supply generators to the motors. The confidence percentage of the motor bus is from 98.4% to 99%, based on the bus condition. From these analyses, the bus loss was found to be within 0.6%–1% of the total electric grid resonance of the inductance of the magnetic field and produced heat.

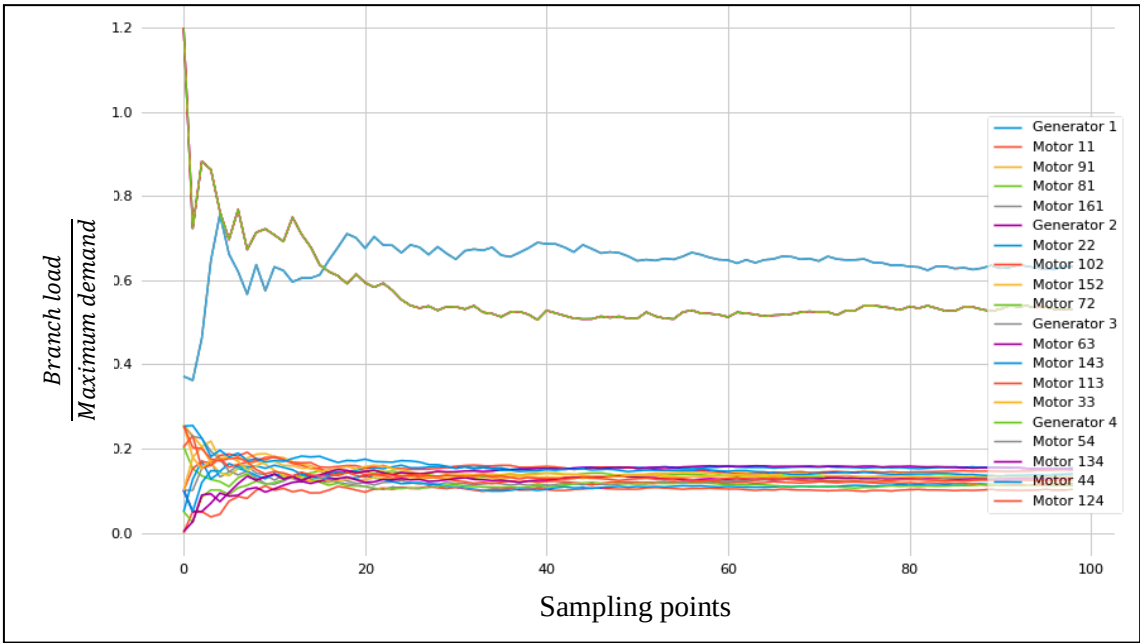


Figure 6.4-2: NASA N3-X RTO Monte Carlo branch loading average

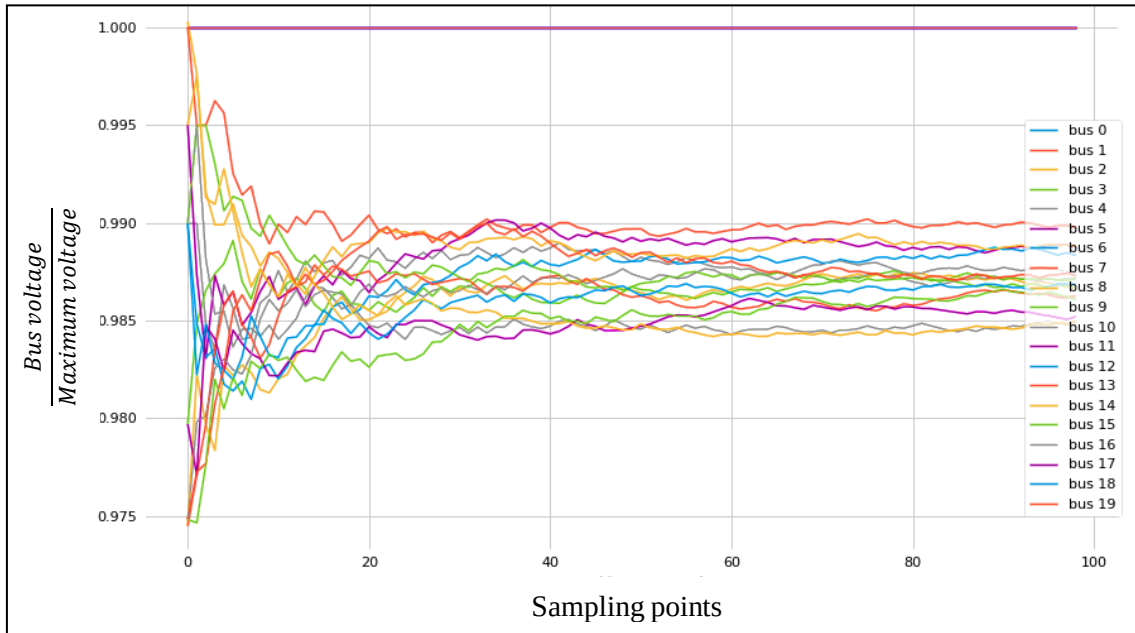


Figure 6.4-3: NASA N3-X RTO Monte Carlo bus voltage average.

6.4.1.1.2 Take-Off (TO)

This assessment scenario represents a supreme load of energy and, as in taking off (TO), the full thrust is needed to drag the aircraft. The same assessment and tools in RTO are used in TO, except the input power calculated for the motors, which is 4.282 MVA and 17.129 MVA for each generator. In Figure 6.4-4, the results confirm that the load for both generators average 70%–78%, while those for the motors remain the same as for TO. Additionally, in Figure 6.4-5, the confidence of the voltage average through the bus is reduced from 98.7 to 98.1 in terms of the fixed power voltage from the generator source. This means that the inductance and heat resistance increased under this risk assessment condition.

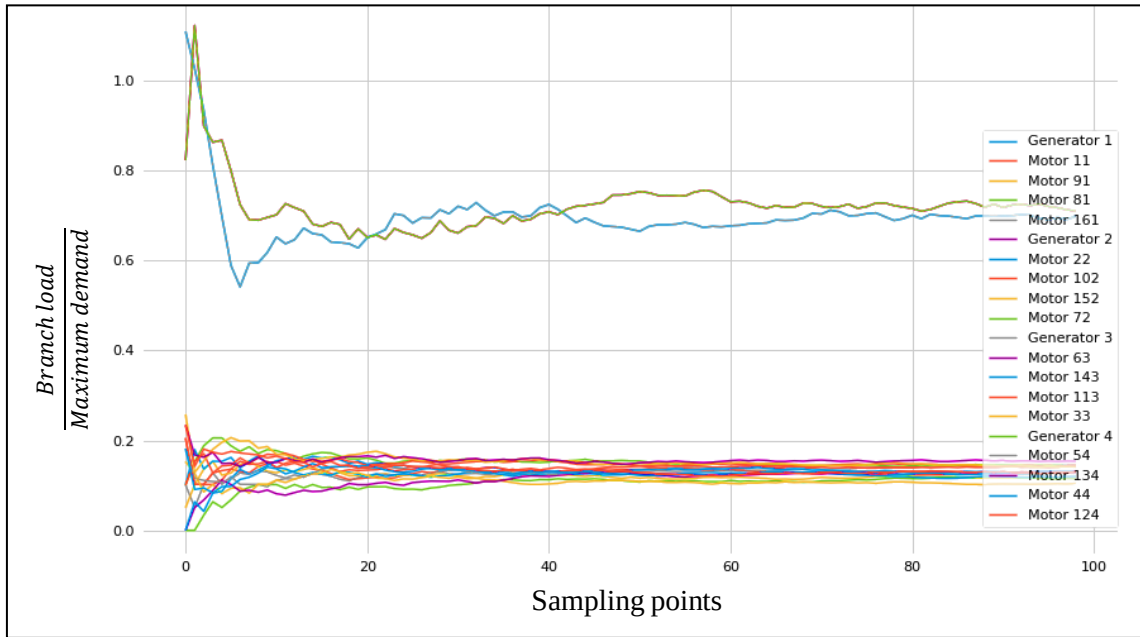


Figure 6.4-4: Monte Carlo TO NASA N3-X branch loading average.

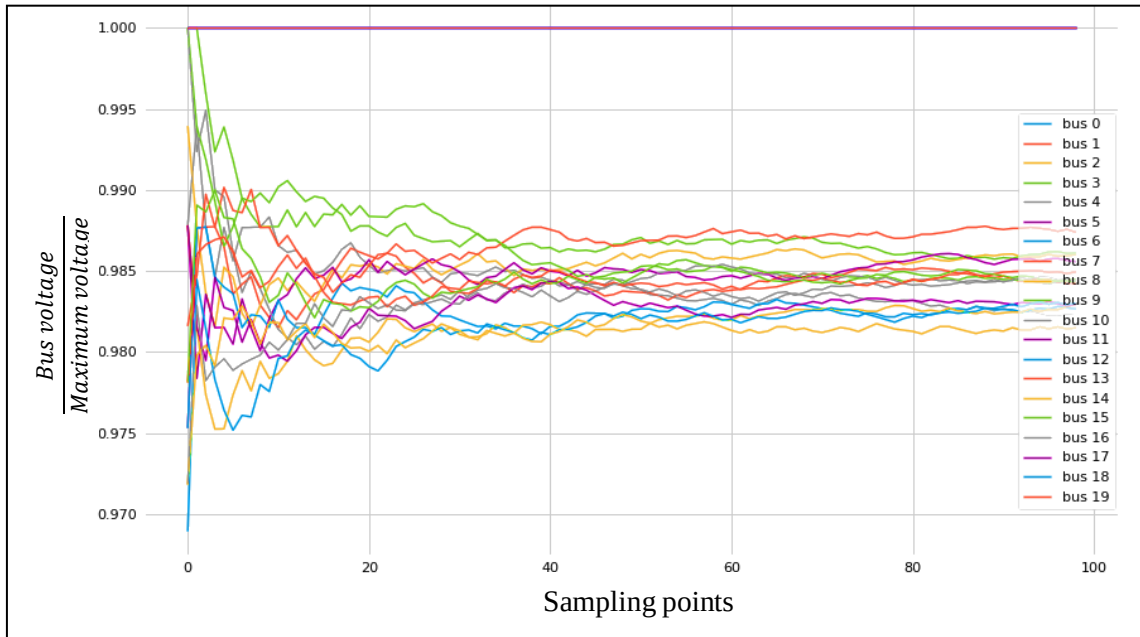


Figure 6.4-5: Monte Carlo TO bus voltage average for NASA N3-X.

6.4.1.1.3 Cruising

This situation was considered as the lowest in terms of power consumption and confidence in precision. In the cruising condition, the generators were calculated to be 5.237 MVA, and the motors were calculated to be 1.309 MVA, with the same assumptions for RTO and TO. The average confidence possibility for the branch reliability of the power is 68% for primary generators and 81% for the secondary generators. However, the reliability of the motor remains the same for the motors, as in

RTO and TO, as shown in Figure 6.4-6. For the voltage bus risk assessment, the outcomes, as presented in Figure 6.4-7, illustrate projected certainty levels of 98.1%–98.7%.

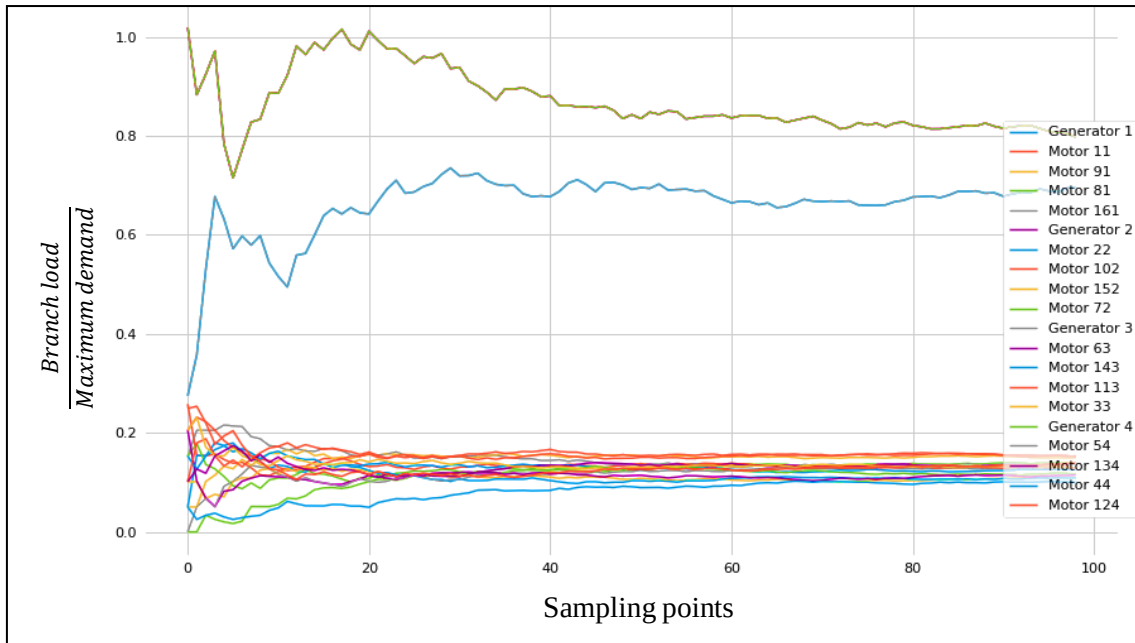


Figure 6.4-6: Monte Carlo load average for NASA N3-X under the cruising condition.

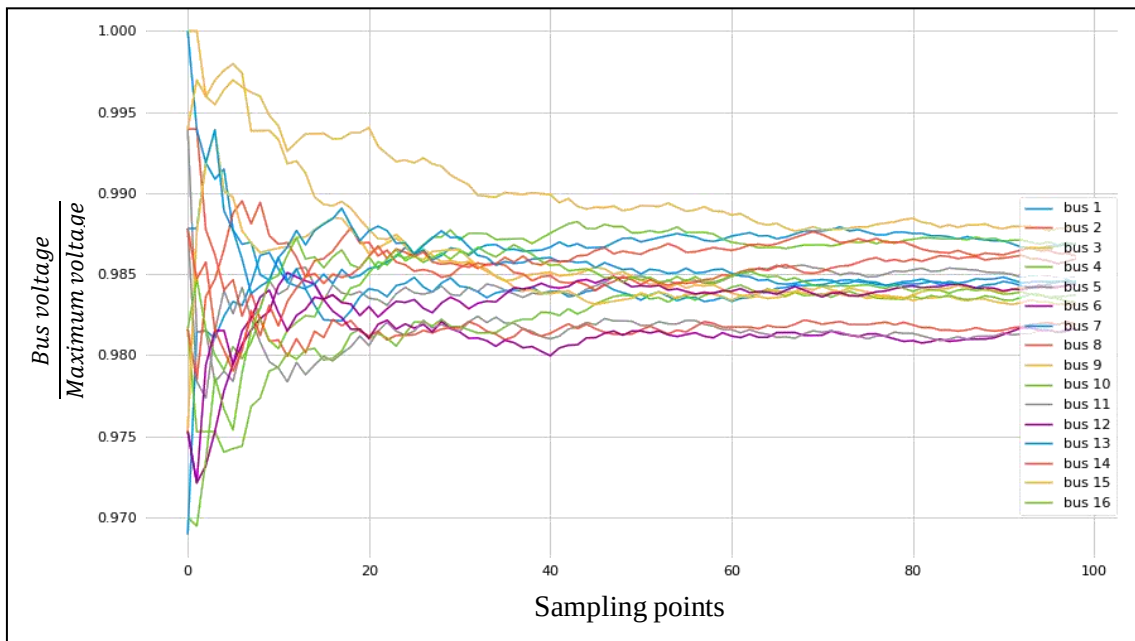


Figure 6.4-7: Monte Carlo bus voltage average for NASA N3-X under the cruising condition

6.4.2 Latin Hypercube

The Latin hypercube algorithm involves a stratified sampling methodology that applies to several variables. It mainly serves as a technique through which users can reduce the

number of runs necessary for a Monte Carlo simulation to enhance the accuracy of the random distribution [150]. It is possible to integrate a Latin hypercube sampling technique into a Monte Carlo model and operate it with the variables involved based on any analytical probability distribution. As for the uncertainty quantification and error estimation, risk optimisers can distribute the cumulative curve into equivalent intervals, based on the cumulative probability scale [151,152]. The subdivision can enable the risk optimiser to pick a random value from every interval of the input distribution. It is evident that, with Latin hypercube sampling, risk optimisers can work with a predetermined number of values because the number of intervals achieved must be equivalent or correspond to the number of available iterations. It is essential to understand that there are no longer pure random samples. As a result, the central limit theorem of statistics is not applicable [153]. Latin hypercube sampling, however, entails stratified random samples. In uncertainty, consistent monitoring of the process can be achieved from the beginning to the end regarding the quantification and error estimation processes in turboelectric numerical risk modelling optimisation. Ideally, it can constrain the information for every simulation to ensure that it can correspond very closely to the input distribution. The uniformity of all iterations becomes achievable across the simulation. It is crucial to understand, however, that although it is possible to constrain the data for the iterations of a simulation to correspond to the input distribution as a cluster, it is impossible to achieve that for any particular subsequent iteration.

The benefit of the Latin hypercube technique is that even for the modest amounts of iterations, the Latin hypercube technique can converge all the sample means, allowing them to fall into a small segment of the standard error. It should be recalled that the objective of Latin hypercube sampling is to spread the sample points uniformly across all the possible values. As a result, during the uncertainty quantification and error estimation processes, the Latin hypercube sampling method can enable a wide range of parameters involved in the turboelectric numerical modelling process to be considered. Therefore, it can incorporate these parameters into the uncertainty quantification and error estimation procedures. As a result, it can generate common and reliable mean values, from which relevant and accurate predictions can be made. Latin hypercube sampling is flexible because although it generates a sample from each interval in an iteration and ensures that there is no correlation between different inputs, it can also enable determination of the correlation [154]. In other words, the Latin hypercube algorithm is a method mechanism for sorted random iterations of multidimensional distribution values. The algorithm of

this method starts with median Latin hypercube sampling, integrating the median value of every equiprobable interval, and then random Latin hypercube sampling picks a random point within an interval. The following Figure 6.4-8 illustrates the Latin square, where each row and column has one sample (right), compared with the ordinary random grid (left).

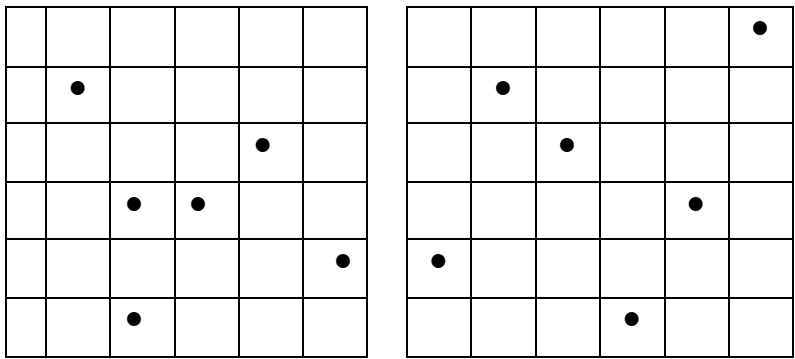


Figure 6.4-8: comparisons between Latin hypercube and ordinary random grid

6.4.2.1 NASA N3-X Case Study

The Latin hypercube method, used for NASA N3-X in 100 sampling points, results in realistic outcomes. The same three scenarios—RTO, TO, and cruising—are subject to quantitative risk analysis using a similar tool. The purpose of this assessment of pure randomness is to associate the Monte Carlo outcomes.

6.4.2.1.1 Rolling Take-Off (RTO)

With similar inputs as those in RTO in Monte Carlo, the Latin hypercube simulation provides more accurate results after 38 sampling points, and the system shows a 60% average load power for primary generators and 63% for secondary generators. The equivalent accuracy for the motors at the same sampling points is 15%–16% of the confidence percentage, as shown in Figure 6.4-9. The voltage stability in this method of analysis in RTO shows 98.6% to 99% for the motor buses, with the assumption of a fixed power source. Figure 6.4-10 illustrates the outcome of the Latin hypercube for each bus in the electrical model grid for NASA N3-X under the RTO condition.

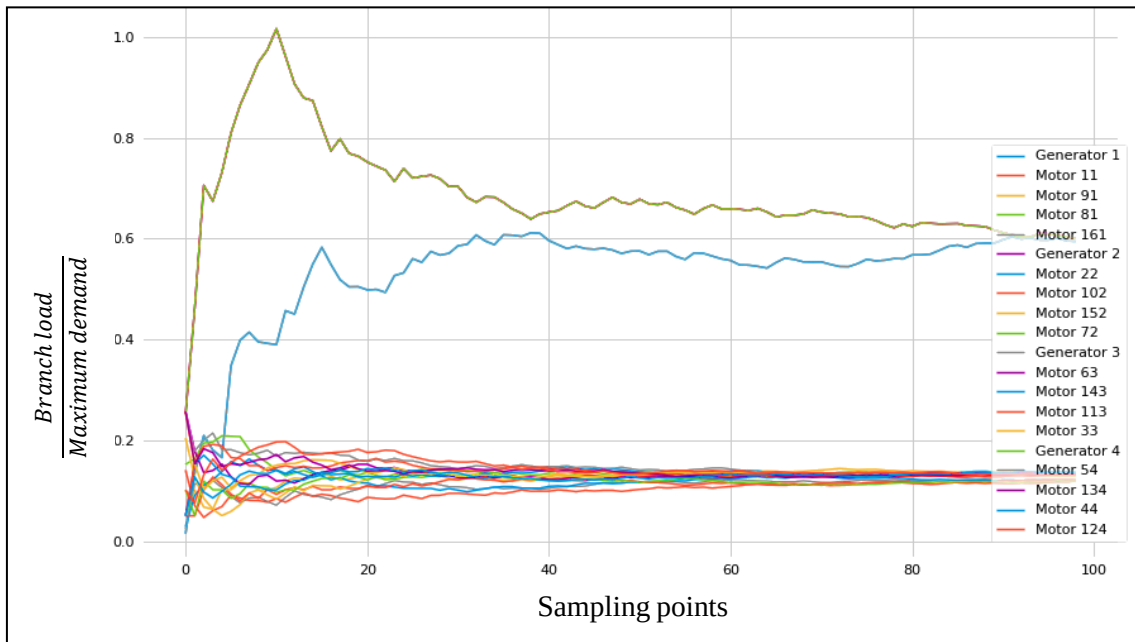


Figure 6.4-9: Latin hypercube RTO load average for NASA N3-X.

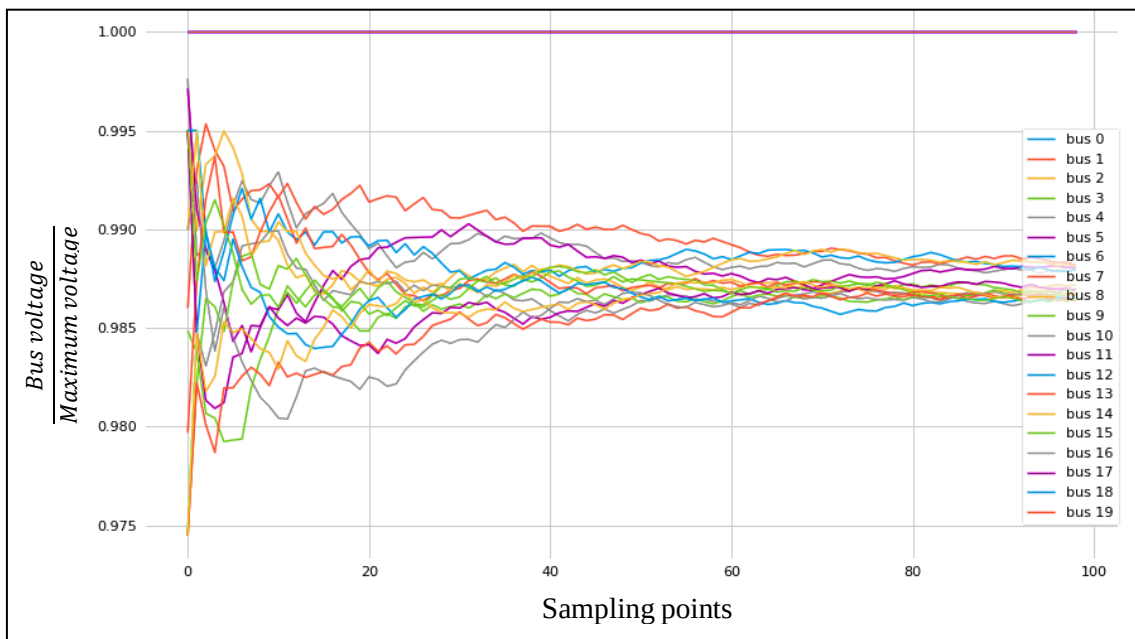


Figure 6.4-10: Latin hypercube voltage load for NASA N3-X.

6.4.2.1.2 Take-Off (TO)

The result in this stage, with the same inputs used in TO in Monte Carlo, shows that the stability load of the generators has a lower number of sampling points than RTO in the 18 samples, and the primary and secondary generators fluctuate between 70% and 73% of the power load. However, the motors are 1% higher than those in TO using the same analysis method, and the load percentage is within 16%–17%, as presented in Figure 6.4-

11. In the bus analysis, the confidence reliability is 0.3 to 0.7, in 98% of the motors, as shown in Figure 6.4-12.

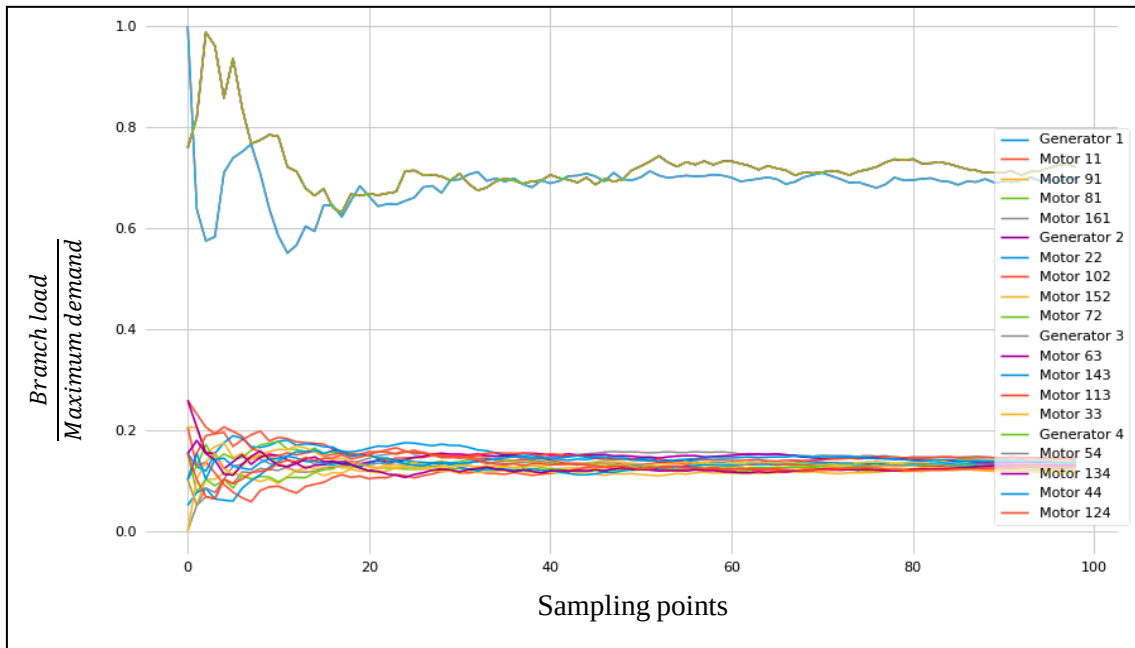


Figure 6.4-11: TO Latin hypercube branch loading average for TeDP NASA N3-X.

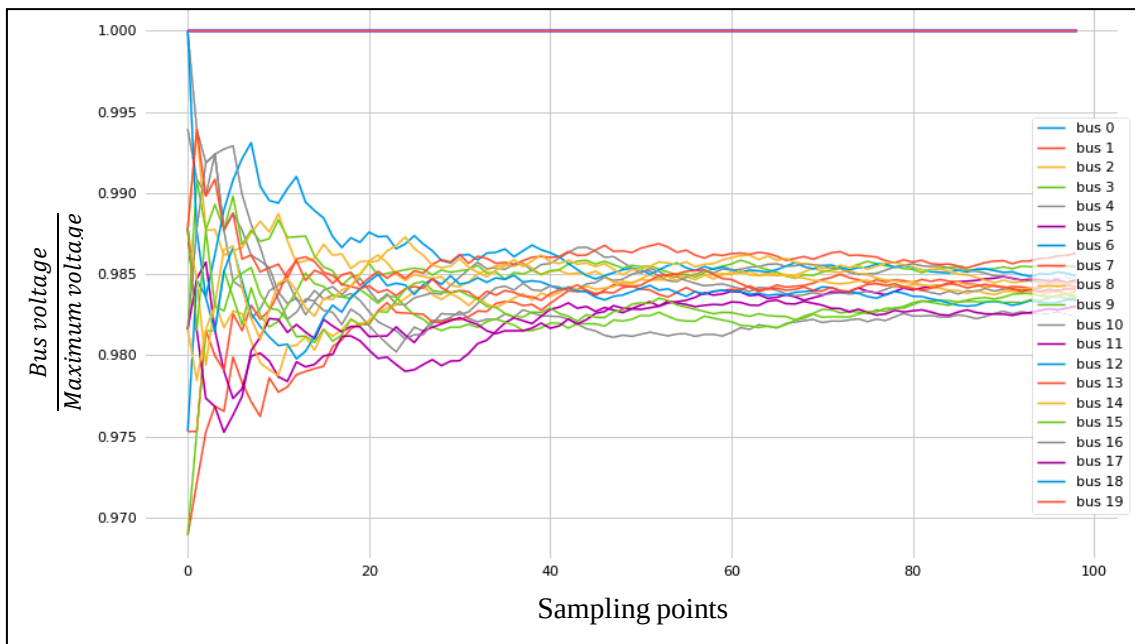


Figure 6.4-12: Latin hypercube TO bus voltage average for NASA N3-X.

6.4.2.1.3 Cruising

The last station to test with the Latin hypercube is the cruising state. The inputs, as in Monte Carlo, show that the confidence reliability for both the primary and secondary generators range from 71% to 76%. In addition, the motors are considered to be within

14%–17% of the branch load, as shown in Figure 6.4-13. Moreover, Figure 6.4-14 shows the bus voltage average to be between 98.3% and 99.3% of the probability confidence.

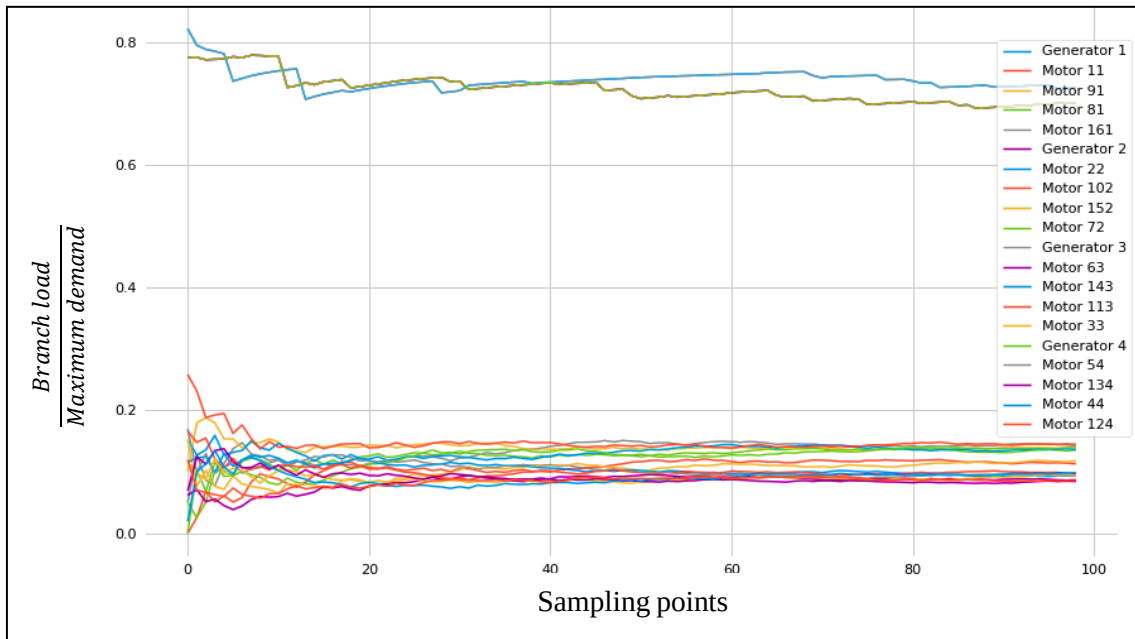


Figure 6.4-13: NASA N3-X branch loading average, calculated by Latin hypercube, in the cruising condition.

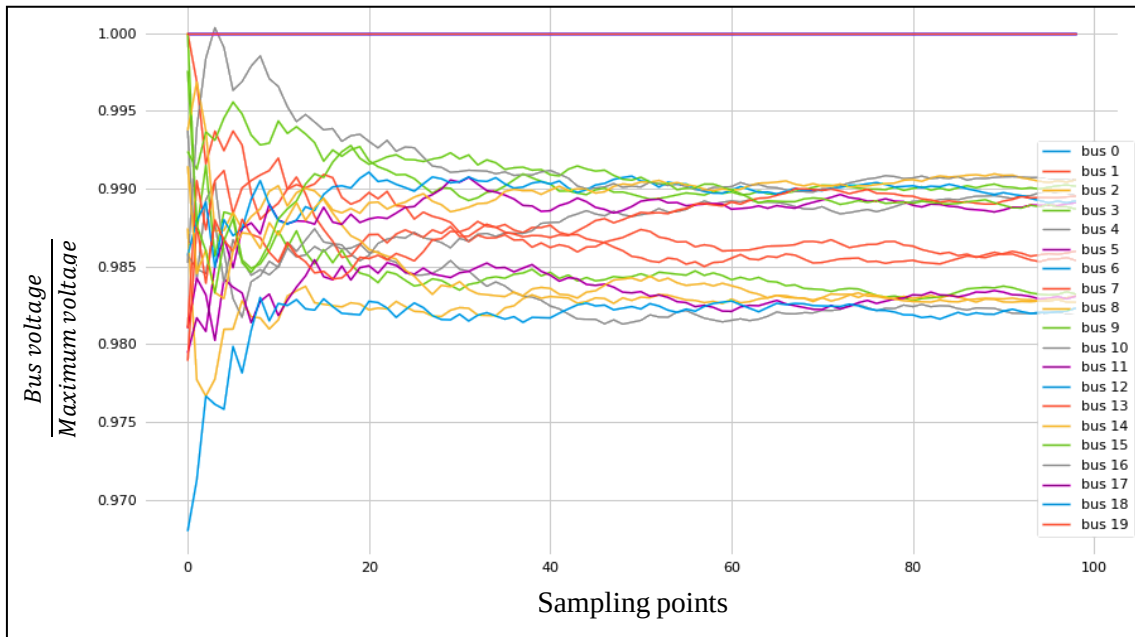


Figure 6.4-14: NASA N3-X bus voltage average, calculated by Latin hypercube, in the cruising condition.

6.5 Standard Deviation

As a significant number of sampling points are used in the Monte Carlo (MC) and Latin hypercube (LH) methods, error limitation is performed using the standard deviation. It was applied in all flying conditions and for both analysis methods. The following results can be observed:

- RTO: This stage shows an error estimation for MC analysis of less than 0.01% for the motor branches and 0.17% and 0.16% for the primary and secondary generators, respectively, as shown in Figure 6.5-1. On the other hand, the error eviction of LH was less than that of MC with the same inputs and case studies, as shown in Figure 6.5-2.

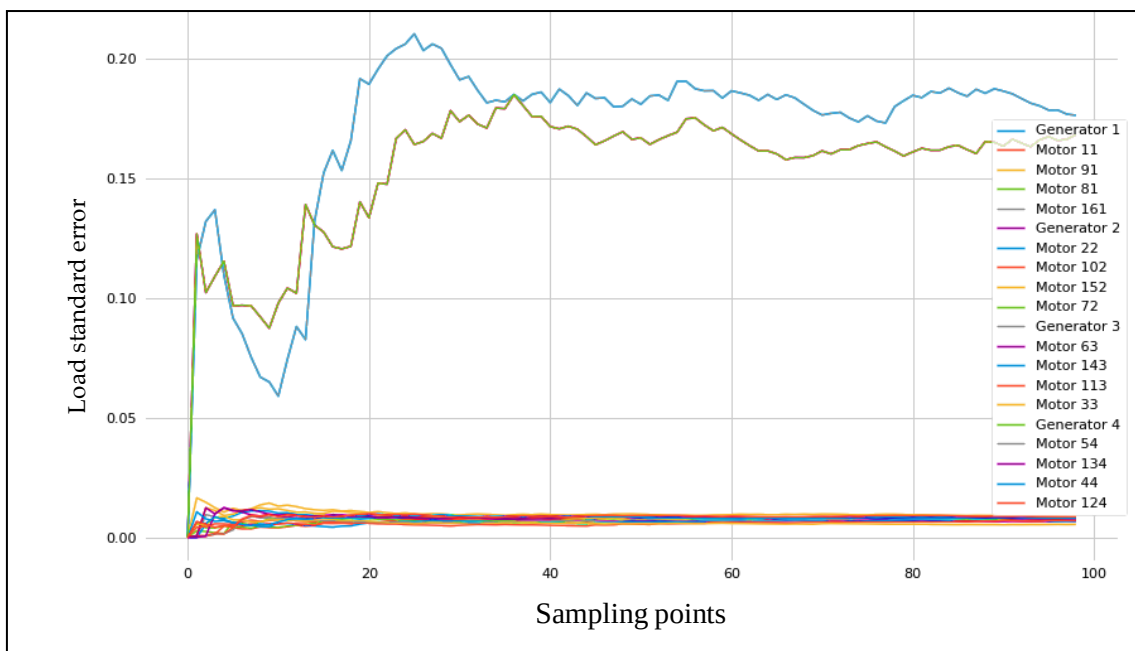


Figure 6.5-1: Monte Carlo standard deviation for the RTO study.

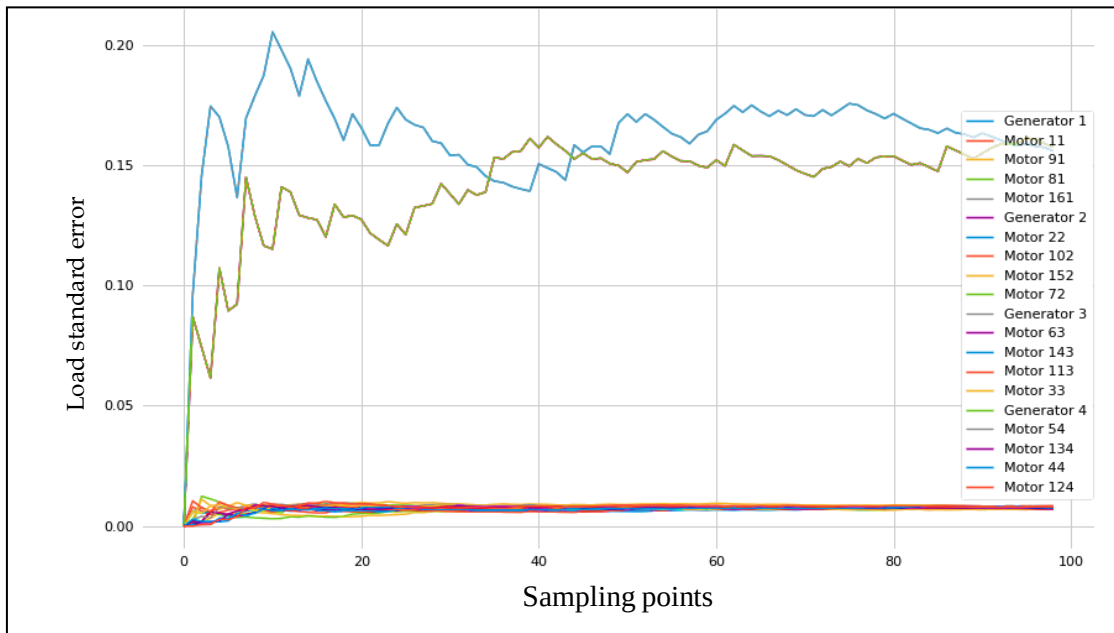


Figure 6.5-2: Latin hypercube standard deviation for the RTO case study.

- TO: This stage shows an error limitation of less than 0.01% for the motor branches and 0.14%–0.16% for the generators as an outcome of the MC method. Figures 6.4-3 and 6.4-4 illustrate the MC and LH standard deviations for the TO case study.

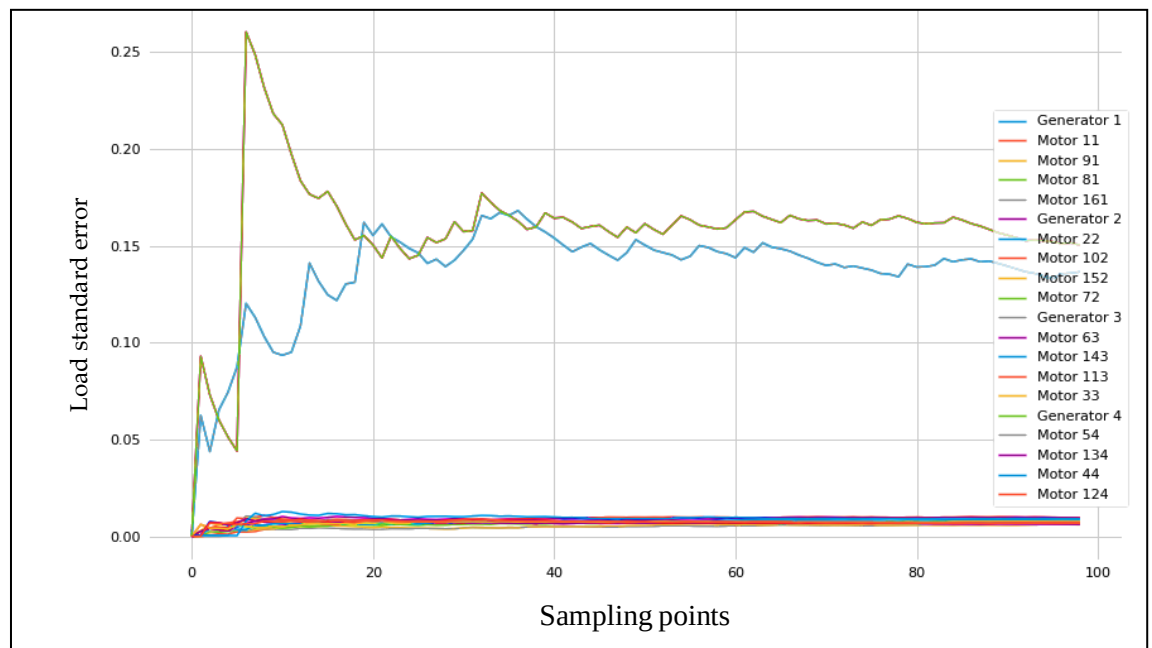


Figure 6.5-3: Monte Carlo standard deviation for the TO case study.

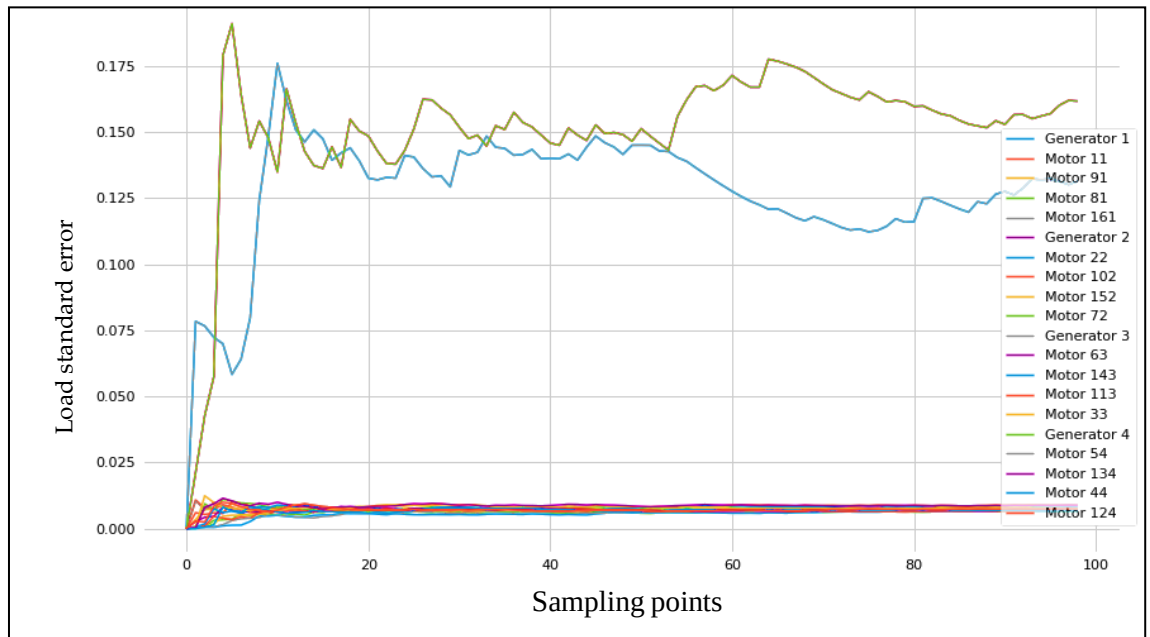


Figure 6.5-4: Latin hypercube standard deviation for the TO case study.

- Cruising: In this stage, MC and LH have practically matching results in terms of the error margins, and Figures 6.5-5 and 6.5-6 show these data.

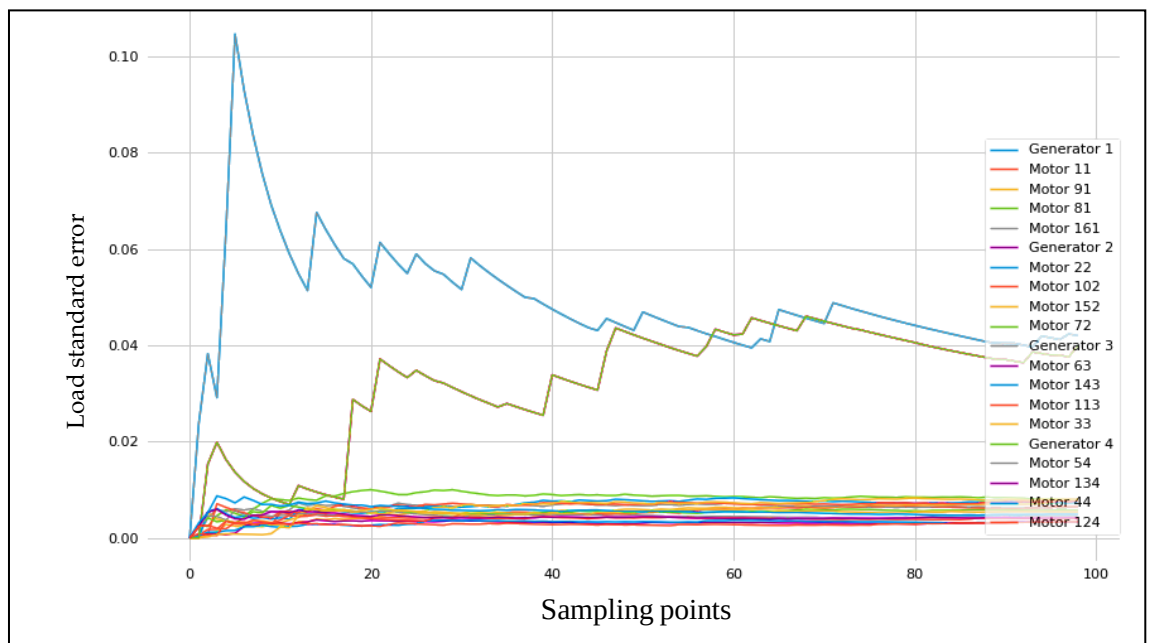


Figure 6.5-5: Monte Carlo standard deviation for the cruising case study.

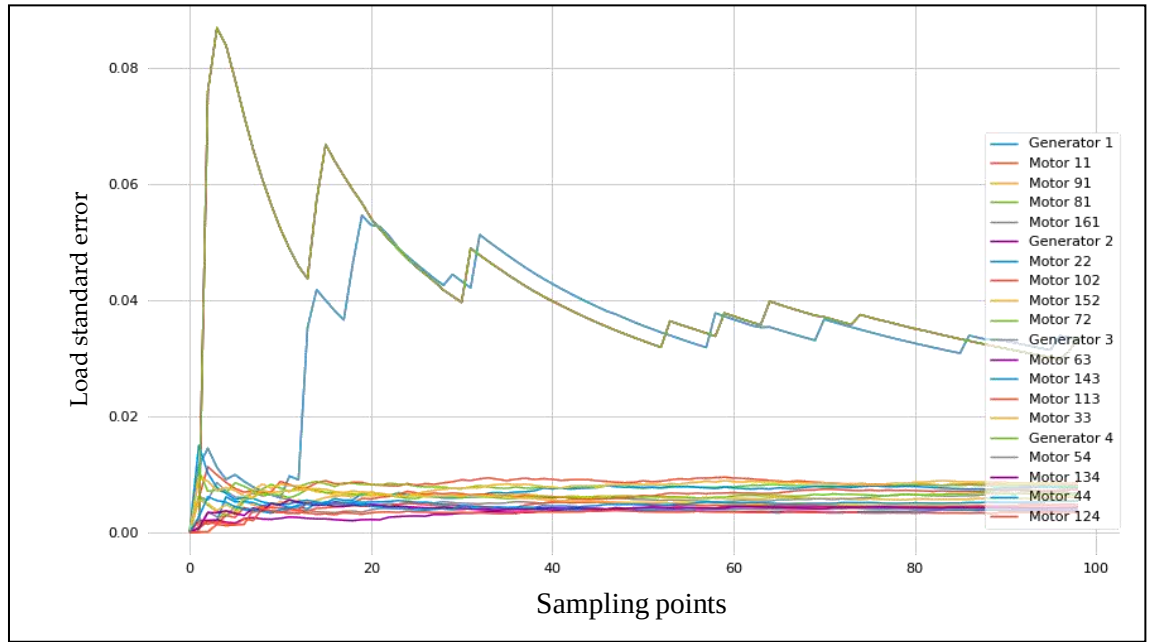


Figure 6.5-6: Latin hypercube standard deviation for the cruising case study.

6.6 Cumulative Distribution Function

This probability density function, called the cumulative distribution function (CDF), is the probability that the function of a variable will take less than or equal to r , and all variable submissions are equal to one. It can be expressed as follows:

$$f(x) = P(X \leq r) \quad (6-1)$$

Where,

X = added variables

r = random variables

CDF is a statistical method used to eliminate the probability limits between 0 and 1 to study the branch load level on the electrical grid. This analysis includes MC and LH results with the three scenarios, RTO, TO, and cruising. The outcomes of this analysis are shown in Figures 6.6-1–6.6-6. The x-axis represents the probability values, and the y-axis represents the per unit (p.u.) system.

$$per\ unit = \frac{Actual\ load}{Base\ load} \quad (6-2)$$

As the MC and LH outcomes are almost identical, the motor results for the simulations with different case studies can be presented in the following Table 6.6-1:

Table 6.6-1: Motor CDF results.

Motor Probabilities (RTO, TO, Cruising)						
Load (%)	0	5	10	15	20	25
CDF	0	≤ 0.2	≤ 0.4	≤ 0.6	≤ 0.8	≤ 1

The MC and LH generator results also have similarities, but change, depending on the aircraft condition. The results presented in the following Table 6.6-2 are based on this condition.

Table 6.6-2: Generator probabilities.

RTO						
Load (%)	0	5	10	15	20	25
CDF	0	≤ 0.43	≤ 0.64	≤ 0.75	≤ 0.83	≤ 0.98
TO						
Load (%)	0	5	10	15	20	25
CDF	0	≤ 0.26	≤ 0.5	≤ 0.77	≤ 0.92	≤ 0.98
Cruise						
Load (%)	0	5	10	15	20	25
CDF	0	≤ 0.1	≤ 0.15	≤ 0.97	-	-

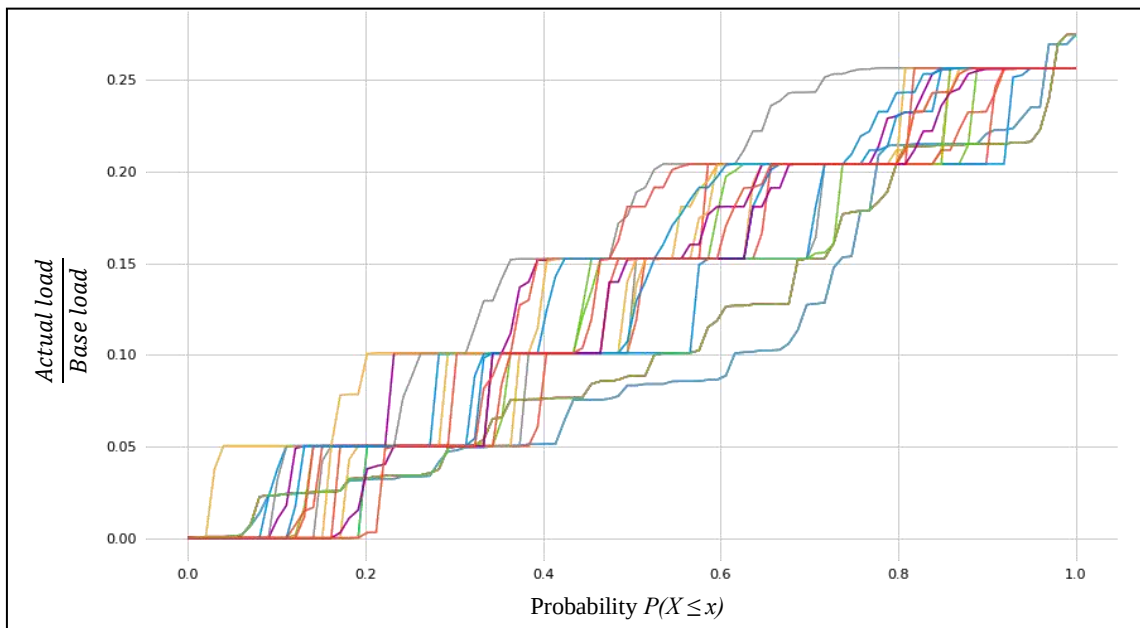


Figure 6.6-1: MC RTO branch load probability.

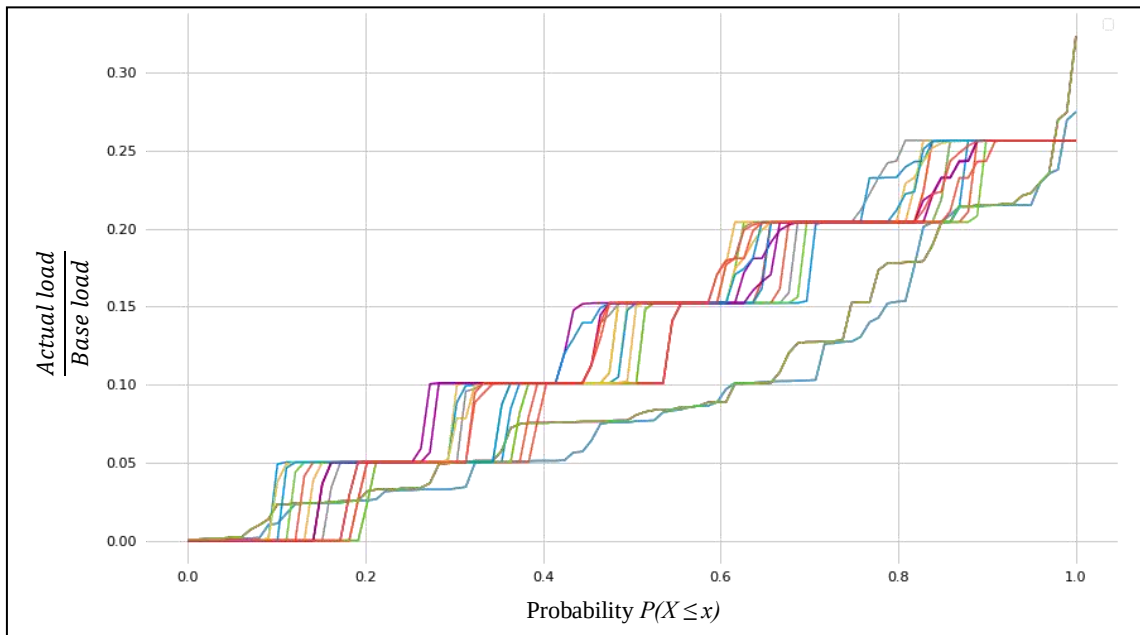


Figure 6.6-2: LH RTO branch load probability.

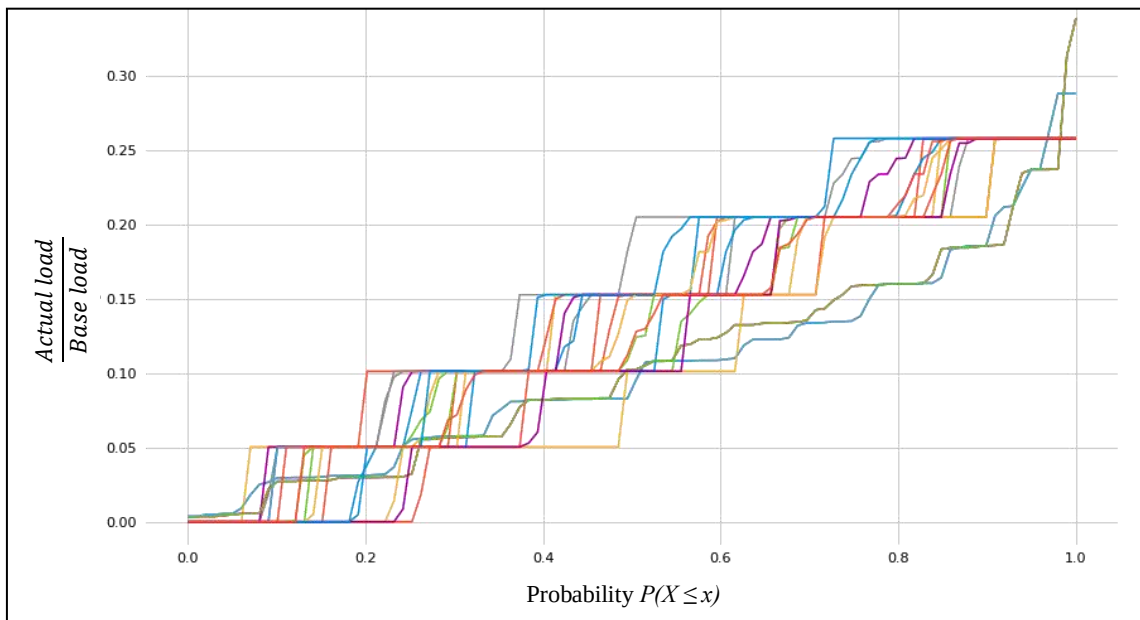


Figure 6.6-3: MC TO branch load probability.

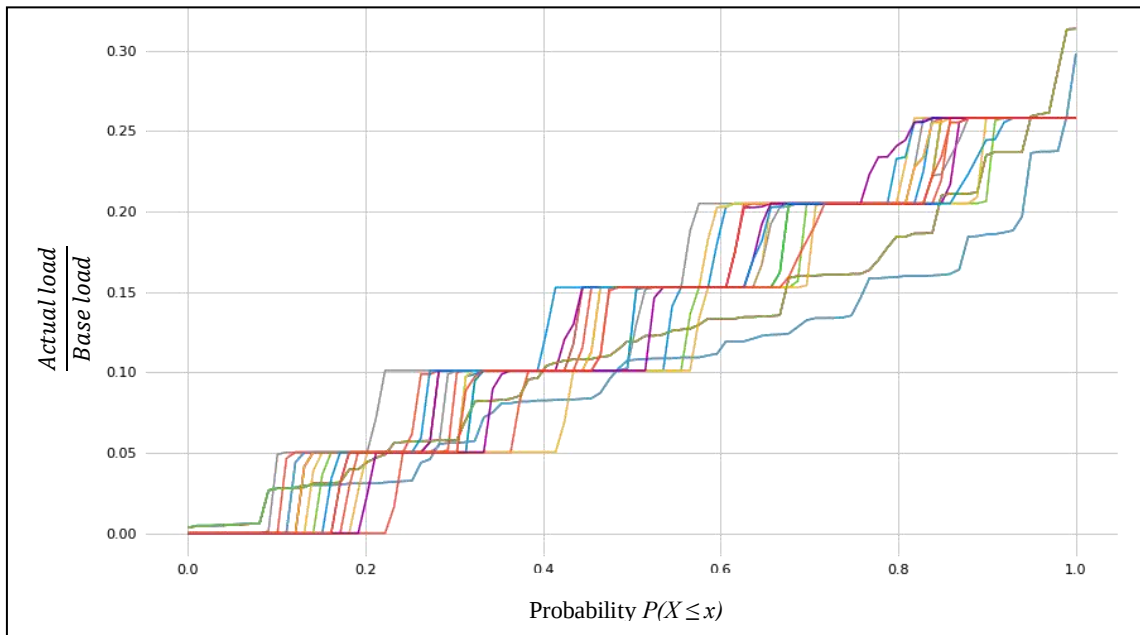


Figure 6.6-4: LH TO branch load probability.

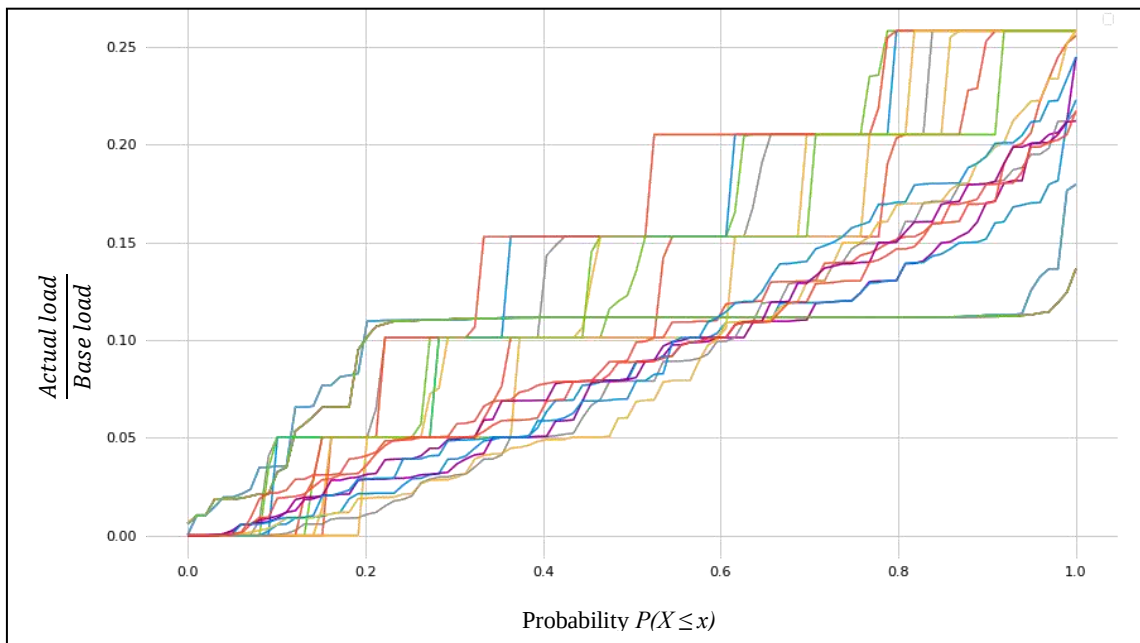


Figure 6.6-5: MC cruising branch load probability.

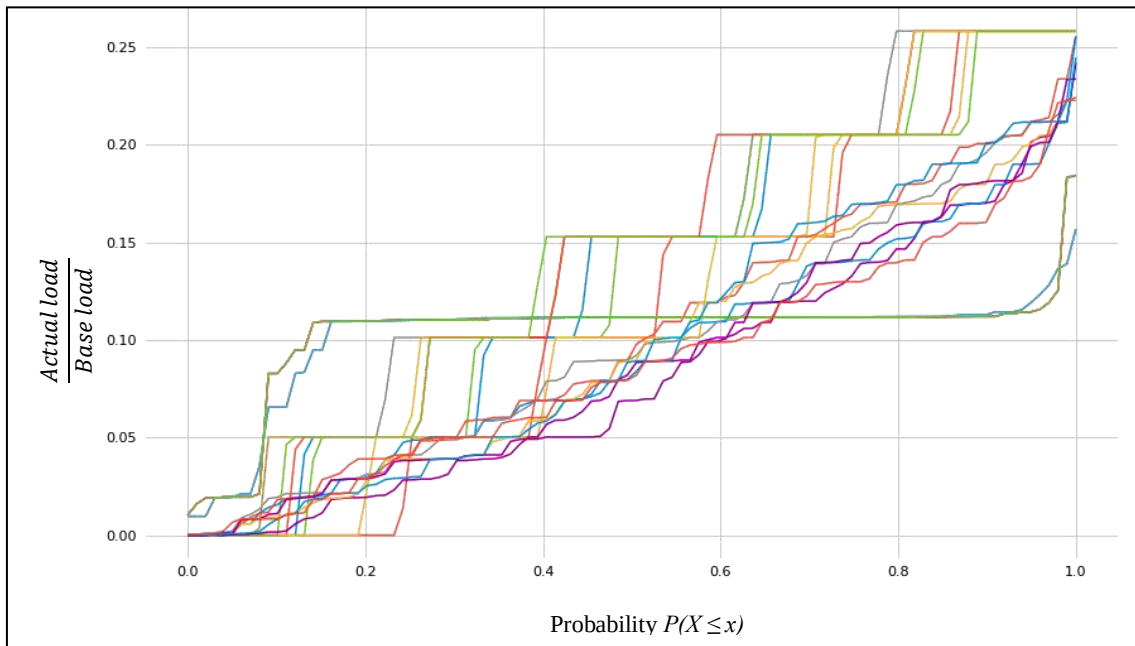


Figure 6.6-6: LH cruising branch load probability.

6.7 Conclusion

The uncertainty quantification and error estimation in the turboelectric numerical modelling processes is crucial and complex. These processes entail many crucial factors that also affect the efficiency of the system used. A turboelectric system entails sets of technical systems that must be considered when developing uncertainty quantification strategies. Different computational models can aid in the achievement of the desired outcomes because they can minimise errors. They can facilitate an active subdivision of the data and available intervals to achieve small workable intervals across a long iteration and random number systems. The subdivision of the intervals and picking of a representative interval randomly makes it easy to achieve an accurate estimate. The Monte Carlo and Latin hypercube sampling techniques were demonstrated to be effective in aiding the uncertainty quantification and error estimation processes. The following Table 6.7-1 shows the comparison between Monte Carlo and Latin Hypercube.

Table 6.7-1: Monte Carlo and Latin Hypercube comparison

Monte Carlo	Latin Hypercube
More samples for better performance	Fewer samples for better performance
Memoryless	Memory
Increases computational complexity	Decreases computational complexity

Moreover, the standard deviation and cumulative distribution function provide critical data convergence for error assessment and validation. The following Table 6.7-2 shows the comparison between Standard deviation and cumulative distribution function.

Table 6.7-2: Standard deviation and cumulative distribution function comparison

Standard Deviation	Cumulative Distribution Function
Error sizing	Represents the sampling from 0 to 1
Data convergent margining	Examines the data distribution

By applying the uncertainty methods, the results show a desirable turboelectric system with high scalability capacity. Thus, this article demonstrates the advent of a turboelectric system that can become an essential enabler for the adoption of the MC and LH methods in the computation of the propagation of uncertainty in complex stochastic models.

The following chapter 7 will investigate the contribution of the economic and environmental impacts on the technical results gain.

CHAPTER 7

ECONOMICAL AND ENVIRONMENTAL VIABILITY ASSESSMENT OF NASA'S TURBOELECTRIC DISTRIBUTION PROPULSION

Abstract

In engineering, the concept of turboelectric distributed propulsion (TeDP) has become integral because of its ability to generate electricity as demonstrate in previous chapters. However, social science compels careful evaluations of TeDP's environmental and economic impacts—out of caution, such elements must be taken up before TeDP is put into practice. Responding to this call, this chapter investigates TeDP's economic and environmental viability with a case study of NASA's proposal for a TeDP aircraft, N3-X, using technical aspects and real data integration. The economic assessment measures NASA's N3-X economic added value (EAV) for aviation manufacturing, operations, and investors as well as net present value (NPV), internal rate of return (IRR), and payback period (PP). Meanwhile, the environmental assessment looks at carbon monoxide and dioxide (CO & CO₂) and oxides of nitrogen (NO_x). The results show valuably of TeDP for economic and environmental evaluation.

7.1 Introduction

Aviation sustainability becomes a desirable achievement for major of the environmental organisations and intends legislation in the government's future canon. One of the global goals for aviation projected by the international civil aviation origination (ICAO) is sustainable aviation fuels (SAF) 2050 vision [155]. This vision consists of emission reduction by targeting technologies, standards and operation improvement. Not only ICAO, the advisory council for aeronautics research in Europe (ACARE) also published a flight path for the same year 2050 for up to 90% of emission reduction [156]. Constant increases in air traffic have produced several motley environmental challenges for aviation research and development. While carbon monoxide and dioxide (CO and CO₂), and oxides of nitrogen (NO_x) emissions play integral roles in the organisational and

governmental activity, the world is increasingly focusing on quickly reducing carbon emissions to address environmental threats. Such emission reduction demands a high level and velocity of technological change over the next decade; this will require a complete shift in aircraft designing, modelling, and integration.

Turboelectric system is one of the processing technologies to electrify the legacy proportion system. This technology should enter into the service by 2030, which mean to merchandise it. The concept of turboelectric distributed propulsion (TeDP) is quickly emerging as an alternative for future transportation. It uniquely offers a gas turbine engine that moves generators that yield electric power to drive the motors and propulsions [49,157]. According to Nalianda and Singh, turboelectric transmission uses electric generators to transform a turbine's mechanical energy into the electric energy [40,158]. Turboelectric transmission has several advantages: 1) it can facilitate the adaptation of high-speed turning turbines to slow wheels to manage a sophisticated gearbox; 2) it can provide large vehicles, such as aircraft, trains and ships, with the necessary amount of electricity; 3) it can provide electricity to a radar system, communication equipment, and computers; and 4) TeDP produces emissions at a lower node [30]. As a green energy TeDP stands, in these ways to decrease the environmental and economic losses currently plaguing aero, ground, and marine transportation.

Therefore, a wide-ranging investigation of TeDP's economic and environmental costs and benefits will surely accelerate its use in the field. This study takes on this task by conducting economic and environmental assessments of NASA's N3-X, a TeDP aircraft. In this chapter, a gap of economic and environmental viability assessment was covered for real-life feasibility to use TeDP in commercial aviation. To understand the importance of the economic and environmental aspects of the aviation sector, section 7.2 provides an overview discussion about aviation impact on global economy and emission. Afterwards, section 7.3 represents the methods used in this study for both economic and environmental assessments. It includes the practical case study used NASA N3-X within the same section. Next, the qualitative TeDP results gain from the assessment reviewed and discussed in section 7.4. Finally, conclude the finding from this study and illustrate the limitation to spot on future financial trends or promising TeDP areas of research.

7.2 Environmental Economics Overview

The relation between the environment positive impacts led the economic model to perform in the environmental economic studies. This economic model distinguishes the maximum visible use of power resources based on emission limitations [159]. Economic analysis motivates on the cost-effective properties of each component in the power system concerning environmental aspects. Analysing the two sectors would evaluation the benefits gained from the system to the environment from the positive cost add [159,160]. To maintain environmental quality, alternative economic solutions need to discuss and consider overcoming the outcomes challenges.

Several methods and case studies done to the area research of environmental economic analysis. These researches customised on a specific area of investigation to overcome the optimum alternative solution. As an example, a method developed to evaluate the cost-benefit relationship in prognostics and health management for commercial aircraft. This analysis methodology estimates the economic feasibility by eliminating degradation in legacy aircraft [161]. Another research discussed the benefit of using electrical power in airport ground taxing and its relation to financial impact. The analysis showed the suitable ground operation benefits from the electric power added with a correlation of economic challenges [162].

Sensitivity of environmental economic analysis upraised during the regulation and legislation for future plan in emission reduction. Therefore, this study implements a method to assess turboelectric propulsion system within the environmental economic analysis.

7.3 Methods of Assessment

There are two models used to assess TeDP system: 1) economical model 2) environmental model. These two were modelled as universal use within the hybrid propulsion system and especially for turboelectric.

7.3.1 Economical Assessment

Strategic management and lean studies provide an economic model built on the business model canvas. This method can illustrate an entity's economic constitution and valuation. Accordingly, this study uses the economic canvas model to evaluate the financial costs

and benefits of TeDP along with any technologies that may be integrated into it in the future, such as batteries. The reason for this further integration is to make the canvas model useable and flexible well into the future.

The economic canvas model involves the following four types of cost centres in conducting economic analyses and projecting prospective revenues:

- **Capital cost:** a one-time cost to get a business off the ground; capital cost varies by propulsion model
- **Annual cost:** a period cost that must be accounted for each year; annual cost varies in line with economic factors and by propulsion models.
- **Emission cost:** the cost of tax and penalties charged against emissions.
- **Investment cost:** additional costs necessary to keep the business running. In other words, it is the total costs needed to establish and operate the project.

Following, Table 7.3-1 illustrates the economic canvas model and its diverse finance parameters.

Table 7.3-1: TeDP economic canvas model.

Economic Canvas - Turboelectric Distributed Propulsion Model			
Capital Cost	Annual Cost	Emission Cost	Economic Analysis
• Turbofan • Turboshaft • Motorfan • Generator • Rectifier • Cryocooler • Inverter • Motor • Battery • High-Temperature Superconductor ○ Buss ○ Cable • Cryoflex	• Inflow ○ Cargo ○ Tickets • Outflow ○ Fuel cost ○ Operating and maintenance cost ○ Electricity Tariff for Batteries	• CO • CO₂ • NO_x • Acoustic Noise	• Payback Period • Net Present Value • Internal Rate of Return • Profitably Index • Economic Value Added
Investment Cost		Revenue	
• Manufacturing Costs • Electrical Equipment and Materials • Engineering and Supervision • Consulting and Contingency • Science and Technology • Research and Development		• Operation Hours • Fuel Cost • Maintenance Cost • Emission Cost	

This part of the assignment is relating to identifying economic assessments. There are four different elements, which are likely to cover under the same tandem. It is required to identify the economic assessments along with the identification of the formulas.

7.3.1.1 Net Present Value

Net Present Value (NPV) is an essential element and tool that falls under the umbrella of capital budgeting. In finance, NPV is applied to a series of future cash flows. This tool has the capacity to discount future cash flows to analyse the actual worth of an item in the present and, in this way, it idealises the concept of the time value of money (TVM) put differently, NPV identifies the present worth of an entity's anticipated future cash flows [163]. A high NPV is desirable—it draws investment to a business, promising a good return. The selection criteria of NPV is clear: if the NPV is positive and higher than the initial investment outlay of the business, then it should be accepted; otherwise, it should be rejected [164]. Accordingly, NPV is one of the most powerful and widely used tools used in capital budgeting; economic and organisational decisions are often made specifically based on NPV because the measure gives a strong sense of a project's feasibility. Moreover, as already noted, NPV indicates an expected cash return, which is one of the main concerns involved in establishing business and reducing investor risk [165]. To be sure, the insights of NPV are applicable for TeDP. Based on the application of NPV, the installation of TeDP should be considered only if the NPV is better or higher than the initial outlay. The formula of the NPV is as follows [166]:

$$NPV = \sum_{t=0}^n \frac{x_t}{(1 + R)^t}$$

Where,

- x_t : represents future net cash flows,
- R : represents the average periodic rate to invest, and
- t, n : represents the time period.

7.3.1.2 Internal Rate of Return

Apart from NPV, there is another significant method under the authority of capital budgeting: the Internal Rate of Return (IRR). It is generally a point at which a project's NPV becomes equal to zero. Moreover, it is a method that studies the ability for maximum

investor confidence in an accessible and highly effective capital budgeting. While investment returns are always significant for a company to pursue, and can help a company to visualise their growth and plan accordingly [167], IRR is unable to convey to management a sense of monetary return. Therefore, IRR is not as vital as NPV [167]. The selection criteria of IRR are simple: if the computed IRR is higher than the discount rate, the project should be accepted. For example, if the discount rate of the project is 12% and the IRR is 20%, then the project should be accepted; otherwise, it should be rejected. This can be applied to any project, including that of this study. Management that applies the integrity of TeDP should emphasise increasing the cash flow accordingly in order to materialise their growth. They should focus on the fact that IRR should be higher than the discount/hurdle rate. The formula of IRR is as follows [168]:

$$\sum_{t=0}^n \frac{C_t}{(1 + IRR)^t} = 0$$

Where,

- C_t : represents future cash flow,
- IRR : Internal rate of return, and
- t, n : represents the total period.

7.3.1.3 Payback Period

Payback period (PP) is yet another popular method for capital budgeting. The period in which a project must pay back its initial investment is known as PP, that is, the period before the initial outlay equals accumulated cash flow. The development and efficiency of NASA's TeDP can be analysed using this tool. Here, it may be helpful to note that this tool is of mere interest to investors because they are likely to buy into companies with low payback periods. Having a low payback period indicates that a business has the tendency and ability to rationalise its operational costs, while a high payback period is often a red flag. On the other hand, PP has nothing to do with the financial competitiveness of a project. As a metric, it only informs investors about the ability of a project to overcome its original cost. Therefore, it should not be used for analysing the financial competitiveness of a project [169].

The payback period is usually divided into two parts: undiscounted payback period and discounted payback period. An undiscounted payback period indicates that future cash

flow will not be discounted in the present, and the discount rate will not be used in the same analysis [170]. On the other hand, a discounted payback period signifies that the future cash flow will be discounted in the present at a specific discount rate. Contrary to the undiscounted payback period, the latter type is of great use for the management of a business in rationalising its decisions because it gives a complete and thorough idea of the cash flow of a project. The PP formula is as follows:

$$PP = \frac{I_o}{C_a}$$

Where,

- I_o : represents the initial investment and
- C_a : represents net annual cash inflow

To find discounted payback period, discounted in cash flow should be estimated with the expected rate. This means that the annual cash inflow is not constant and can be found using the following formula [171–173]:

$$\text{Discounted Cash Inflow} = \frac{C_a}{(1 + r)^t}$$

Where,

- C_a : represents net annual cash inflow
- r : represents discounted rate and
- t : represents cash inflow period

7.3.1.4 Economic Added Value

Economic added value or economic value added (EVA) is a financial method for estimating the economic profit of a business. It is the value created by the required return of shareholders. It is closely linked to the return on capital employed. The economic value added to a project increases with capital employed [163]. The formula of EVA includes return on invested capital (ROIC) and weighted average cost of capital (WACC). A project with a high EVA is always more effective than one with a lower EVA. This metric is very helpful for comparative work, such as that which compares the effectiveness of two projects [174–176]. Moreover, EVA is equally effective for analysing financial competitiveness before and after a merger (if any). This tool is particularly useful for

evaluating TeDP because it can yield a sense of the value added by technology's productivity, especially over the long run. The formula for this metric as follows:

$$EVA = NOPAT - (WACC \times Capital\ investment)$$

Where,

- *NOPAT* : represents net operating profits after tax and
- *WACC* : represents Weighted Average Cost of Capital

7.3.1.5 Case Study: NASA N3-X

The data for NASA's N3-X were collected and calculated from authentic published sources. The following assumptions anchor the economic assessment of N3-X:

1. Passenger and cargo cost per nautical mile = 0.29 cents (based on KAYAK data [177], 1 mile = 0.868976 nautical mile, and 1 USD = 0.77 GBP).
2. The N3-X operates with the full load and cargo of 300 passengers, including their luggage [178]. (Ideal passengers and cargo = 300 X 0.29 = 87.0 USD per nautical mile)
3. A 30-year lifetime is the operation block hour assigned for the N3-X until it is retired.
4. The average block hour assumed is 5,219.5 hours a year (based on Boeing 777-200LR's 14.3 hours per day [179] and 365 days in a calendar year).
5. The N3-X has average speed of 434.488 nautical miles per hour (500 miles per hour).
6. The distance to fly each year assumed to be 2,267,810.116 nautical miles.
7. Crew cost is USD 978 per block hour of operation [180] (USD 5,104,671 per year).
8. The income cash flow is constant for the N3-X's entire 30-year operation life cycle.
9. The net present value of NO_x emissions = USD 1,922M over 30 years [181].
10. Hydrogen fuel price is equal to USD 5.843 per nautical mile (IATA Fuel Price Monitor [182]).
11. Some data have been taken or calculated based on the Boeing 777-200LR, as both aircraft are in the same segment category of aircraft (i.e. 47,890 US gallons = 1140.2380952380952 bbl [180,183]).

12. Investment cost assumed for research and development of the material, manufacturing, electrical enhancement and generating, engineering and supervision, consulting and contingency, science and technology to be 2B USD [110,184,185].

7.3.2 Environmental Assessment

After the description of the economic assessment, the next important thing, which has been associated with the same analysis, is environmental assessment. Figure 7.3-2 illustrates the environmental model for assessing the impact of TeDP. This model examines two types of emissions: acoustic and air pollution. Acoustic emission is evaluated by the level of noise the system is expected to generate. Meanwhile, air

pollution is evaluated by the level of harmful gases added to the atmosphere. Three different monoxides gases, listed below, are central to the analysis.

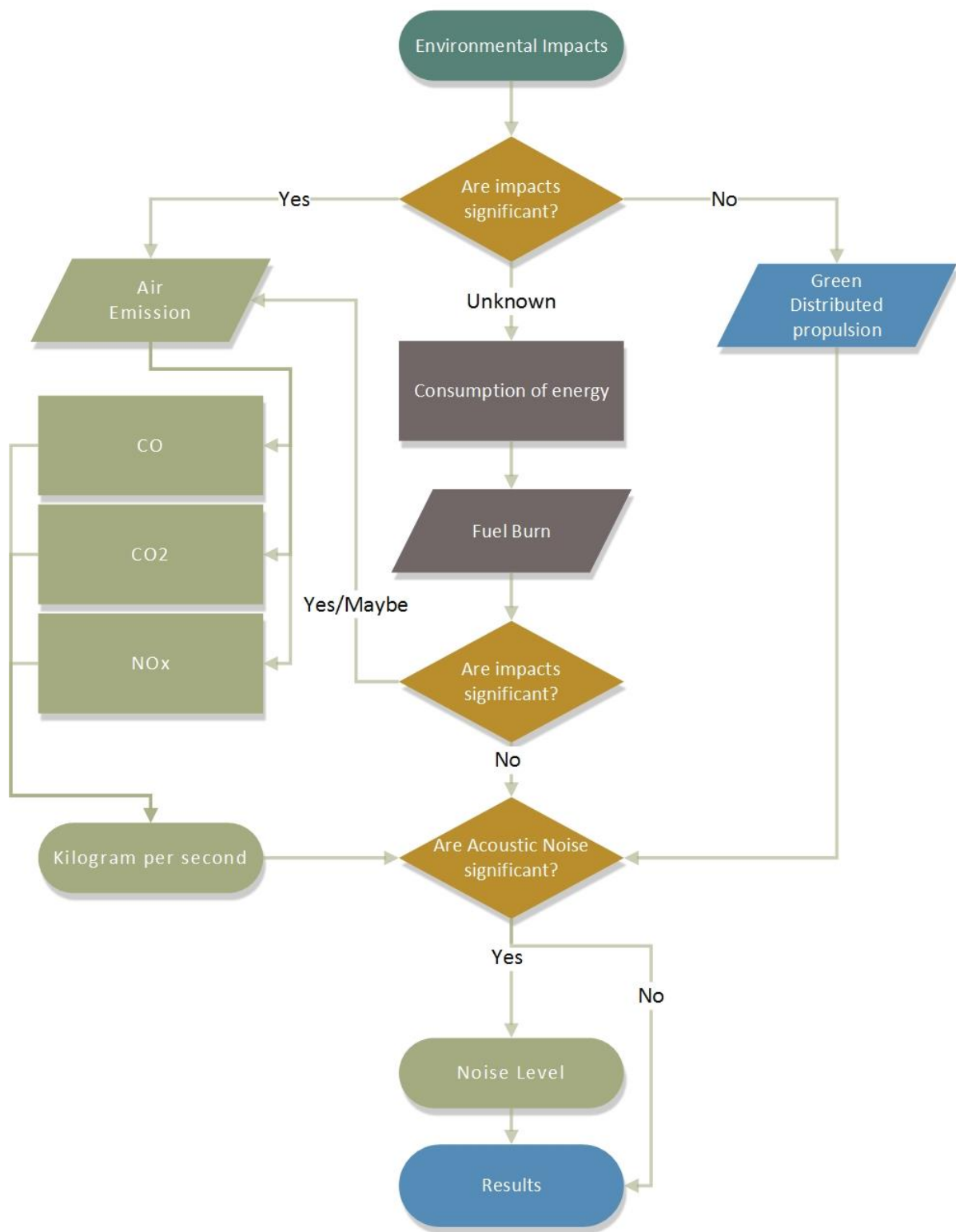


Figure 7.3-2: Environmental model flow chart

7.3.2.1 Carbon Monoxide

Carbon monoxide (CM) is a colourless, tasteless, and odourless gas which is slightly lighter than air. This gas is toxic to humanity because it uses haemoglobin as an oxygen carrier. These gases consist of one oxygen atom and one carbon atom. It means that the dominance of one element of carbon has been managed and decreases with the oxygen. Carbon monoxide emerges with the intermediate oxidation of a carbon-containing mixture—when there is not enough oxygen to produce carbon dioxide, carbon monoxide is formed (for example, in an enclosed space or when working on a furnace that is burning internally) [186,187]. Some of today's innovative programs—such as iron purification—still generate carbon monoxide as a side effect. A large amount of CO results during synthesis in the oxidation process.

7.3.2.2 Carbon Dioxide

Carbon dioxide, denominated as CO₂, is yet another colourless gas with a specific density of around 60% way higher than that of dry air. Unlike carbon monoxide, this gas consists of one carbon atom and two oxygen atoms. CO₂ is found naturally in the earth and is referred to as a 'trace gas'. Natural sources of carbon dioxide include hot springs, geysers, and carbonate rocks. CO₂ has a great capability to dissolve with water and occurs naturally in groundwater, ice caps, and seawater. Moreover, CO₂ can be found in natural gases and petroleum. CO₂ is odourless until concentration, when it develops a mild but sharp odour [186,187]. CO₂ is produced by all forms of life that consume oxygen when it provides energy through breathing by treating sugar and lipids. It returns to the water through the sputum and returns to the air through the lungs of the inhaled local organisms (including humans). CO₂ is produced when extracting natural materials from the ground such as Hydrogen, natural gas and petrol. Burning wood and other natural materials as well as non-renewable energy sources such as coal, peat, and petroleum gas yield CO₂. To be sure, CO₂ is an adaptable modern material used as inert gas for welding and discharge incinerators, compressed air guns, pressurised gas for oil recovery, synthetic raw materials, and decaffeinated coffee.

7.3.2.3 Oxides of Nitrogen

Oxides of nitrogen (NO_x) refer to the mixture of gases composed of oxygen and nitrogen. The two main compounds explicitly found in these oxides are nitric oxide (NO) and nitrogen dioxide (NO₂). These gases are usually found in the batteries of cars and other vehicles. Both oxygen and nitrogen do not react with each other at a specific ambient

temperature of 288.15K and need more than 1800K to react [188]. NO_x is very harmful to human health; therefore, proper precautions are necessary when using or producing NO_x. Otherwise, it will create numerous issues and problems for human health. All these environmental aspects should be considered by management using TeDP because they will impact its efficiency and productivity levels. The assumption in this chapter, as per NASA's proposal, that N3-X is hydrogen-fuelled. With this in mind, the economic and environmental assessment was conducted using an input-output method.

7.4 Viability Results

This section represents the assessment of the results of economic and environmental.

7.4.1 Results of the Economic Assessment

The results for the turboelectric capital costs estimated especially for NASA N3-X model and generally for turboelectric presented in table 7.4-1. These analysed results estimated based on the current (2020) available technologies and assumptions.

Table 7.4-1: Estimated capital cost for NASA N3-X [57–64]

TurboElectric Propulsion Capital Cost			
Unit	Cost	Number of Units	Total
Turboshaft	\$ 3,760,000.0/per engine	2	\$ 7,520,000.0
Motor	\$ 625,000.0/per motor	16	\$ 10,000,000.0
Generator	\$ 625,000.0/per generator	4	\$ 2,500,000.0
Rectifier	\$ 1,000.0	4	\$ 4,000.0
Superconductor Bus	\$ 40.0/meter	67.5	\$ 2,700.0
Cryocooler	\$ 2,000,000.0	1	\$ 2,000,000.0
Cryoflex	\$ 240.0/meter	67.5	\$ 16,200.0
Total Capital Cost (TCC)			\$ 22,042,900.0
Airframe estimation			\$320,000,000.0
Total Aircraft cost			\$342,042,900.0
Investment Cost			\$2,000,000,000.0
Total			\$2,342,042,900.0

From the results, the heights effects on the capital cost in TeDP are the motors. That means a significant number of electric motors can change economic efficiency and need to be enhanced in developing, manufacturing, and material cost. The second sorted in cost affection is the turboshaft, which can be eliminated with evaluating the alternative gas turbine engines and models. Theses sorting of the most two costs pushing from the total budget of cost side, but from the unit side cryocooler is one of the economic challenges.

The need for cryocooler depending on the material used for generators and motors that in the end cause a cost chain. This means if the motor model type and even generator used NANO technology materials that could stand for a high temperature of heat and keep the stability of the system performance, then the cost can be waived. From the analysis, the three main cost holders for TeDP are airframe, motors and turbofan engines.

Next part of the economic assessment is to cover the cash flow estimation for TeDP. Based on the economic canvas modelled the inflow calculated for passengers and cargo for a NASA N3-X segment of aircraft. This segment could carry 300 passengers with their cargo for each trip. The estimation was calculated as the worst-case scenario of income for one trip a day for a year until 30 years. The outflow with the same segment estimation based on real fuel and maintenance cost. Table 7.4-2 represents these results of estimation for TeDP cash flow in USD as the assumption of the 30-year running project.

Table 7.4-2: NASA N3-X cash flow estimated [177–183]

TurboElectric Propulsion cash flow			
Inflow (\$/nautical mile)		Outflow (\$/nautical mile)	
Passengers and cargo	87.0	Fuel	-5.843
		Maintenance	-18.476
Total	87.0	Total	-24.319
Total Income		62.681	
Total in USD			
Income for a year		142,148,605.9	
Income for 30 years		4,264,458,176	
Total in USD			
Reduction of Crew cost		-5,104,671.0 (per year)	
Absolute total in USD			
Income for a year		137,043,934.9	
Income for 30 years		4,111,318,047	

By having the results of cash flow for TeDP, the net present value can be calculated to estimate the amount of profitability of investment in TeDP project. Figure 7.4-1 represent the future steam for TeDP and the discounted value of today. From the results, profitability for the worst case with 3.0% discount rate around 2,686,121,608.0 USD as a net present value. This value gain from TeDP project means the investment in this project is accepted and economically positive.

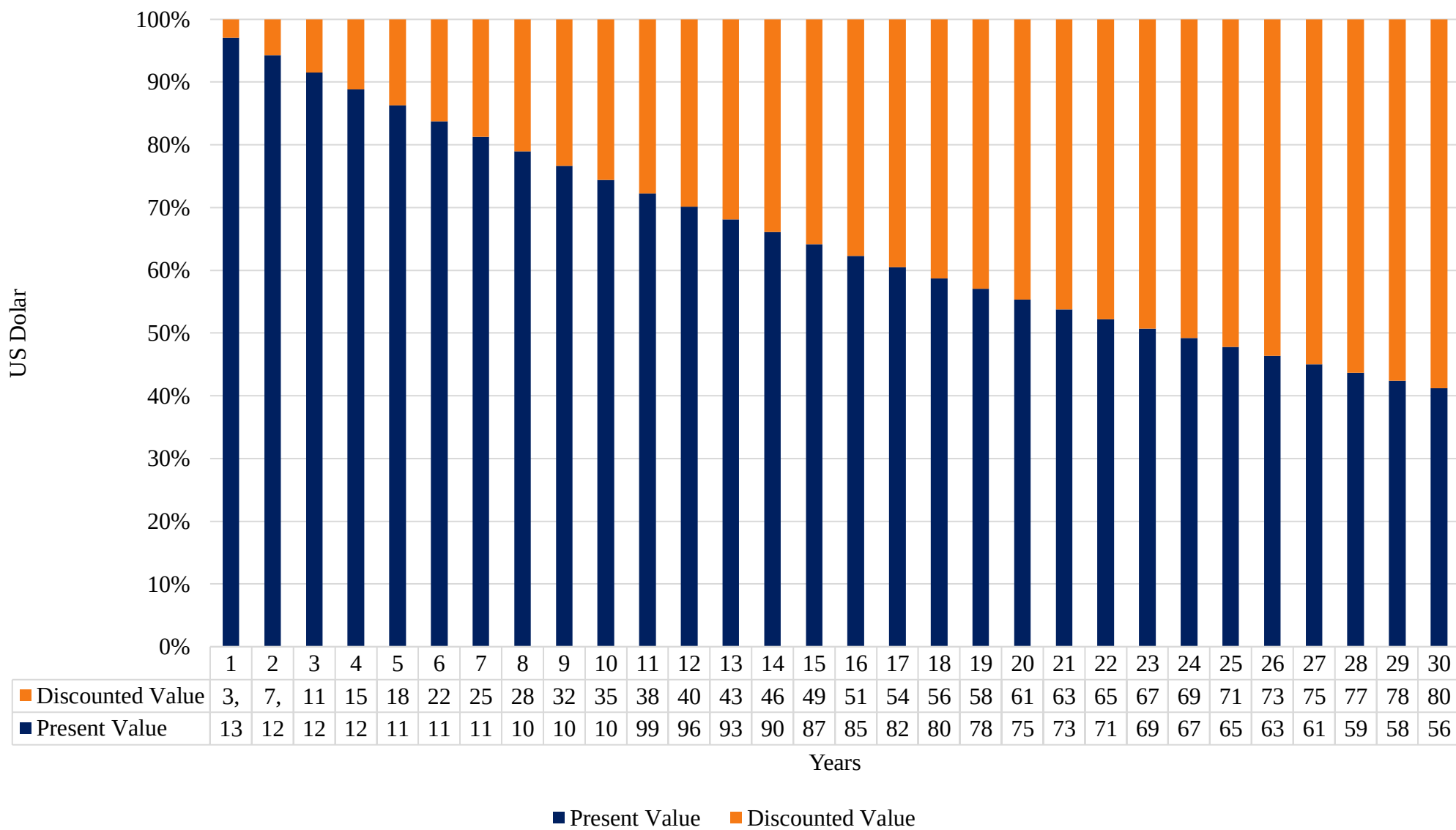


Figure 7.4-1: Net present value chart for NASA N3-X

Table 7.4-3 shows the data used for NPV analysis considered for NASA N3-X aircraft. It analyses the range of discount factors from 0.97% for the first year until 0.41% for the last year (year 30).

Table 7.4-3: Net present value for NASA N3-X

Net Present Value	
Discount Rate	3.0%
Year	1-30
Discount Factor	0.97-0.41%
Undiscounted Cash Flow	137,043,934.9
Present Value	133,052,364-56,460,287
Net Present Value	2,686,121,608.0
Discounted Value	3,991,571-80,583,648

Internal rate of return for TeDP used to evaluate the profitability of potential investments. It is applied to find the correct discounted percentage needed for TeDP project for all cash flow to reach zero NPV. Table 7.4-4 shows the results of NASA N3-X IRR for 30 years of running project. The results show that NASA N3-X has 3.95% IRR that is a significantly high potential for economic investment with less risk of return.

Table 7.4-4: Internal rate of return for NASA N3-X

IRR	3.95%	Years 1 to 30		
		1	...	30
		\$	\$	\$
		- 2,342,042,900.0	137,043,934.9	137,043,934.9

For more accuracy and flexibility in the period, XIRR (Excel Internal rate of return) used to calculate for specific dates. Accordingly, the result given from the date 30/06/2019 until 31/12/2047 is around 4.11% XIRR. This percentage value is still acceptable for investors and project running. Table 7.4-5 shows the XIRR results.

Table 7.4-5: Extended internal rate of return for NASA N3-X

XIRR	4.11%	Years 1 to 30		
		30/06/2019	...	31/12/2047
		\$	\$	\$
		-2,342,042,900	137,043,934.9	137,043,934.9

Figure 7.4-2 illustrates the IRR chart for TeDP project, which the result shows the breakeven point between present value and discount value among year 23 and 24.

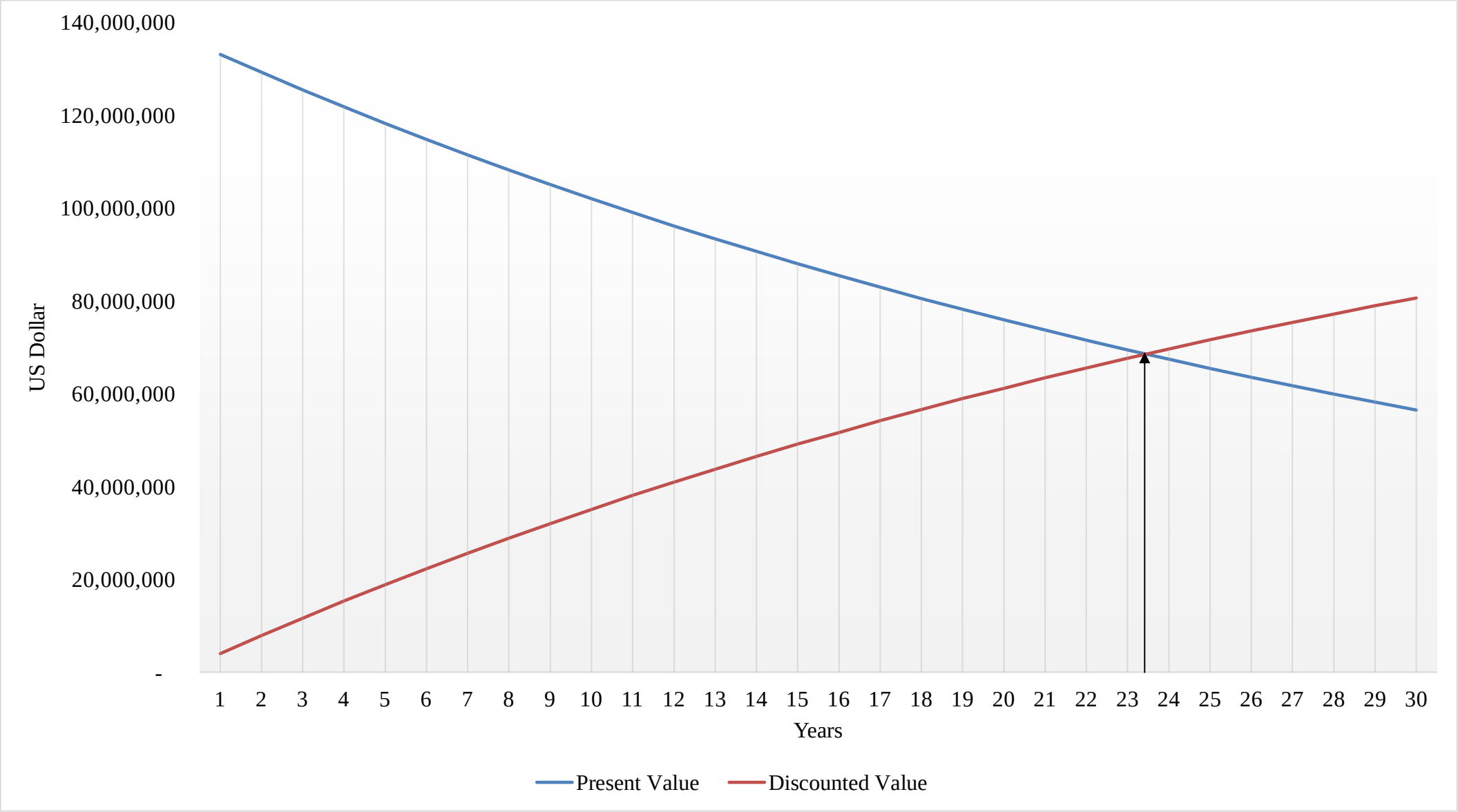


Figure 7.4-2: Internal rate of return chart for NASA N3-X

To find out the amount of time needed for the cost of investment to be covered Payback period (PP) method applied. From the IRR and NPV shows that PP does not need more than 17 years of calculation and that is the assumption of estimation. Moreover, the calculated discounted PP with a rate of 3% needs 24.5 years. Table 7.4-6 shows the data used for TeDP from year 0 until year 30.

Table 7.4-6: Payback period for NASA N3-X

Payback Period (\$)			
Investment	Year 0	...	Year 30
Cash Flows	2,342,042,900	137,043,934.9	137,043,934.9

Figure 7.4-3 presents the chart of PP that shows the time needed to cover the investment cost in year 17 and Figure 7.4-4 present the chart of discounted PP.

Calculating the exact PP as the following:

$$PP = (\$2,342,042,900) / (\$137,043,934.9) = 17 \text{ Years} = 229 \text{ Month}$$

From the calculation, Investment in NASA N3-X TeDP needs 229 months to cover the cost. Seventeen years of the project running life, represent 56.6% of the assumed operating life cycle of the project that makes it accepted in financial decisions. Last economic assessment to apply for TeDP project visibility from finances performance sideways is the economic add value. This method will specify the economic contribution that TeDP will add. To apply EAV need to find the investment cost per year, NASA N3-X need to have to run the project. Table 7.4-7 shows the investment cost needed for the project per year; this includes fuel, maintenance, crew, and operation costs.

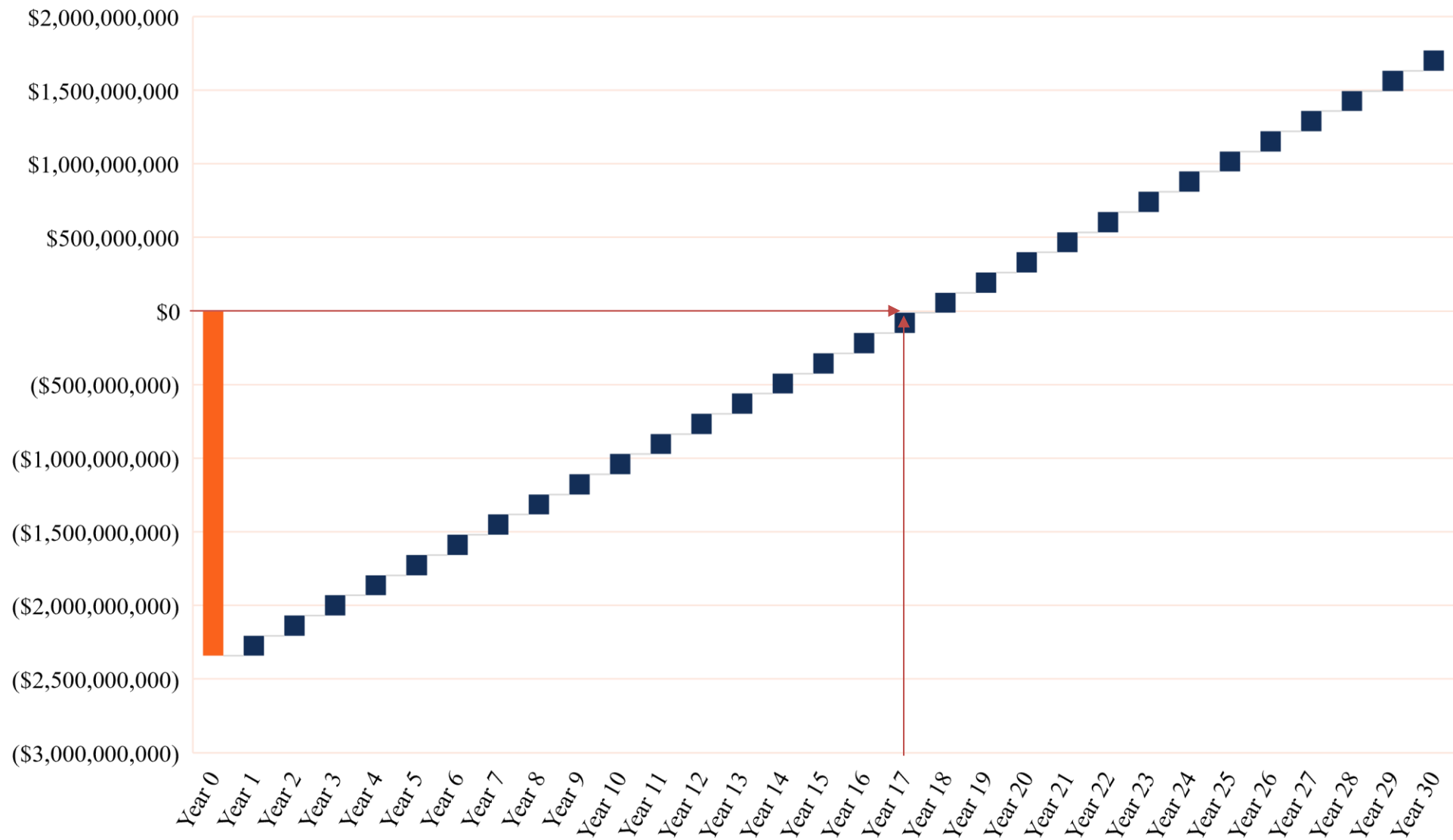


Figure 7.4-3: Undiscounted Payback Period chart for NASA N3-X

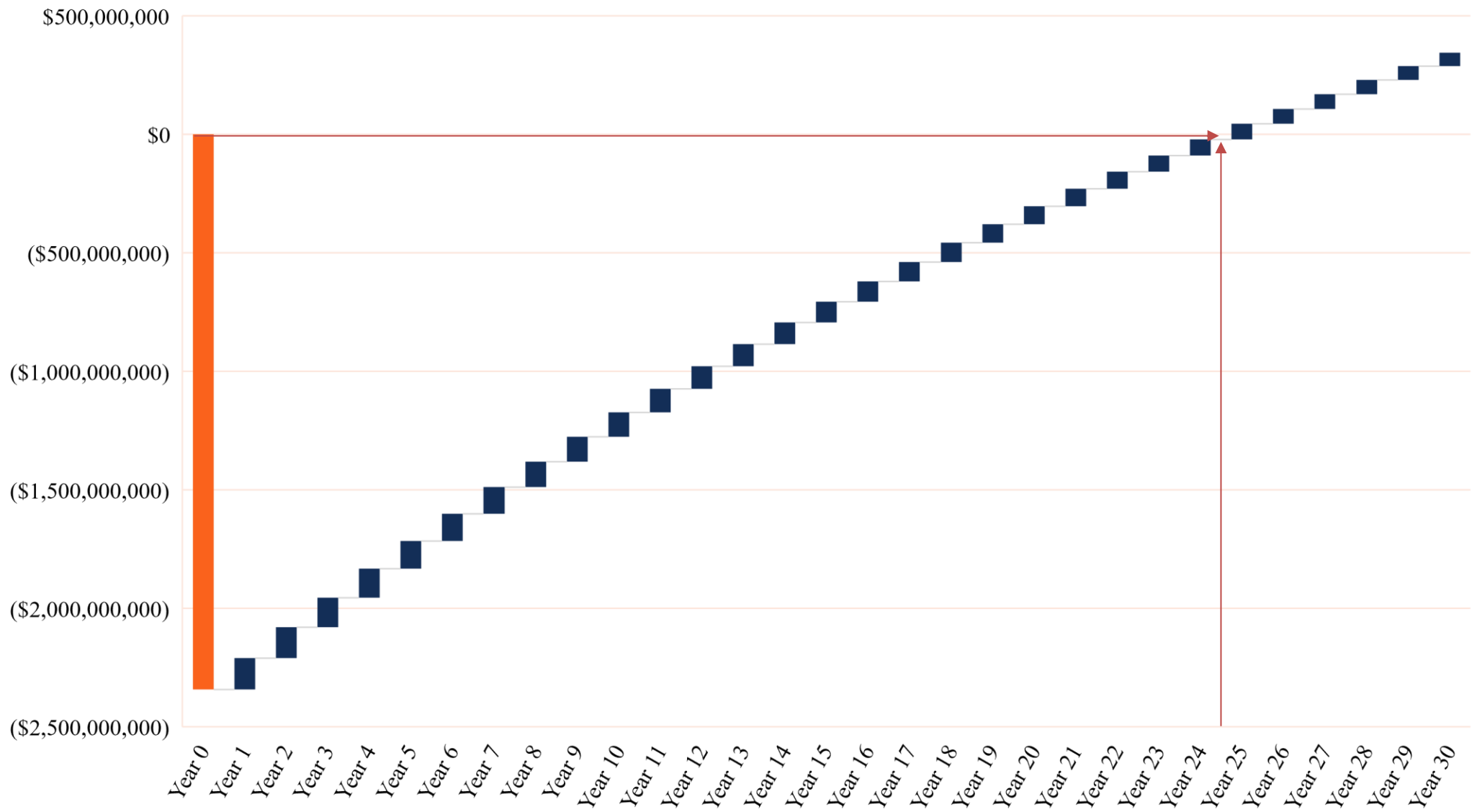


Figure 7.4-4: Discounted Payback Period chart for NASA N3-X

Table 7.4-7: Investment cost for NASA N3-X [110,189]

Investment cost \$/year	
Fuel and maintenance cost	63,466,510.25
Crew cost	5,104,671.0
Operation costs	2,000,000.0
Total	70,571,181.25

The assumptions taking into account for EAV calculation are as follows:

- Assumption of tax rate on ticket as income = 7.5% [190].
- WACC from 7-8% [110].
- Assumption of WACC is to have it 7.0% for the first year and it increases 0.5% annually.

EAV was calculated for 30 years; the PP is less than this period. Table 7.4-8 shows this value and the results taken from TeDP to economic. Net operating profit after tax calculated as the following:

$$NOPAT = 137,043,934.9 \times (1-0.075) = 126,765,639.8 \text{ USD}$$

Table 7.4-8: Economic add value for NASA N3-X

EVA Calculation			
Years	2019	2020-2024	2024-2029
Capital invested (beginning of year)	\$2,412,614,081	\$70,571,181.25	\$70,571,181.25
WACC	7.00%	7.50%	8.00%
Finance Charge	\$168,882,985.67	\$5,292,838.59	\$5,645,694.50
NOPAT	\$126,765,639.80	\$126,765,639.80	\$126,765,639.80
Finance Charge	\$168,882,985.67	\$5,292,838.59	\$5,645,694.50
Economic Value Added	(\$42,117,345.87)	\$121,472,801.21	\$121,119,945.30

7.4.2 Results of the Environmental Assessment

After found out the economic visibility for TeDP, the need for environmental impacts assessment become critical, especially with future regulation for clean sky air. With the same case study used in the economic assessment NASA N3-X TeDP used for the environmental assessment. The assumption for NASA N3-X to be fuelled by hydrogen as it proposed by NASA. The analysis then used is the input-output method as these methods reflect on environmental accounting can be connected to the economic

assessment. As simple, this method finds the input and output of the tested system. Table 7.4-9 represents the application of this method on TeDP.

Table 7.4-9: NASA N3-X Input-Output model

Input-Output analysis model		
Input →	Gas Turbine	→ Output
Hydrogen (H ₂)		Oxides of Nitrogen (NO _x)

After specifying the output air polluted gas, there is a need to size the amount of gas generated. Table 7.4-10 explores the exact amount of output gases for TeDP fuelled by hydrogen. Moreover, table 7.4-11 estimate the perceived noise emission from TeDP system.

Table 7.4-10: NASA N3-X emission sizing [191]

TurboElectric Propulsion Emission sizing	
Type of emission	Amount (g/KN)
CO	~ 0
CO ₂	~ 0
NO _x	17.6
Total emissions	17.6

Table 7.4-11: NASA N3-X effective perceived noise [22,191]

Turboelectric aircraft Effective perceived noise	
Lowest Noise level	32 dB
Highest Noise level	64 dB
Average noise prediction	48 dB

According to the International Civil Aviation Organization (ICAO), there is no penalty for the range of NO_x TeDP emission initially for the 30 years of operation. Furthermore, the effective perceived noise from TeDP is still bellow of the noise penalty. As a result of this environmental assessment, TeDP is accepted as environment-friendly at least for the 30 years onwards.

7.5 Chapter Summary

This entire assignment is based on an analysis of turboelectric distributed propulsion, zooming, in particular, on its economic and environmental effects. The analysis reveals that TeDP can be effective in aircraft because of its ability to pass the financial and environmental risk assessments outlined herein. The analysis also conveys that the application of TeDP has certain economic and environmental impacts, each of which

should be analysed by the concerned departments and management before utilising the services of TeDP. Ultimately, any investments in this project yield be a win-win relationship for both investors and aviation organizations. The following chapter 8 will focus on improving TeDP.

CHAPTER 8

TECHNO-ECONOMIC AND ENVIRONMENTAL KEY PERFORMANCE INDICATORS FOR TURBOELECTRIC DISTRIBUTION PROPULSION

ABSTRACT

The advancement of electrifying transportation applications becomes a need for action to reduce environmental emissions. Several aviation organisations and governments release a target for 2050 vision. One of the promising technologies to enter the service is turboelectric distribution propulsion (TeDP) as studied in previous chapters. This chapter 8 aimed to explore and identify key elements for enhancing turboelectric power in transportation propulsion. An enhancement valuation method is proposed to overcome the three major challenges in the propulsion model, namely, the economic impacts and effects, and the environmental emission generated. This study is the first to investigate the key performance indicators (PIs) for classification and also conduct risk management. First, the result indicators (RIs) were determined, and the result PIs were then analysed. The key RIs for turboelectric distribution propulsion were then specified, along with the key PIs. Quantitative measurement applied with the case study model of TeDP to estimate the established KPIs. This study found that up to 8% of TeDP efficiency can be enhanced by applying the KPI method in the real-world. The results of this work can provide developers and researchers with effective potential impact areas and integrate turboelectric distribution propulsion.

8.1 Introduction

Protect the environment is the leading ambitious for the next 30 years challenge onward. The Advisory Council for Aeronautics Research in Europe (ACARE) establish 2050 flightpath vision to used technologies and revolutionary ideas to reduce the emission. The target is to reduce 75% (per passenger/kilometre) in CO₂, 90% in NO_x and 65% of acoustic noise. Moreover, the aircraft movement on the ground should be zero-emission

[25,192]. The futuristic emission strategic not only limited to the Europe area but even been configured universally as a requirement from the International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO) [181,182].

To reach ACARE, IATA and ICAO environmental visions, alternative solutions of aircraft power and propulsion technologies need to investigate and integrate. Facing the challenges of current limitations of recourses and technologies supported electrification systems along with the different electrification types turboelectric distinguished as combining system for mechanical and electrical advantages. The main challenge faced by any electrical system is energy conservations and electric feed. The just in time concept unravel weight, energy life cycle, capacity, size and cost drawbacks.

Turboelectric transmission systems are composed of electric generators and motors, which convert mechanical energy to electricity, and vice versa. Electric generators in a turbine (gas or steam) convert mechanical energy into electric energy, while electric motors convert electricity into mechanical energy to power drive shafts. Although such a system appears simple, several critical factors must be considered, particularly at the design stage, to ensure that future air traffic and aircraft system performance goals are met. The design of turboelectric propulsion systems such as these must be highly integrated [54,193].

Similar to any other means of mass transportation, commercial aviation emits CO₂ to the atmosphere. By 2016, the emissions of CO₂ from the aviation industry constituted almost 2.0–2.5% of the overall annual global CO₂ emissions [54,194]. In the United States, this percentage was approximately 23% [195]. Additionally, as commercial aviation is continuously growing, particularly in terms of cargo ton-miles and revenue-passenger miles, the corresponding emissions will also continue to increase. Research has indicated that over 90% of the emissions from the aviation industry originate from large aircraft (aeroplanes with at least 100 passengers, or single- and twin-aisle aeroplanes). Therefore, air-transportation technology research teams and agencies must consider the environmental factors and explore methods of redesigning propulsion systems to improve their efficiency. Based on the effects of size and gas emissions, technologies used in larger aircraft should receive more focus.

Previous research has outlined the notable systematic challenges of reducing CO₂ emissions from the aviation industry. Most of these challenges are associated with policies and economic factors. Considering the scope of this research (turboelectric system), these challenges are due to the intricate nature of aircraft systems. Most commercial aircraft encompass numerous distinct, judiciously integrated systems that are carefully controlled to ensure their safety and performance. The introduction of newer technologies requires meticulous system integration to ensure that the functionality of one system (or even that of the aircraft as a whole) is not adversely impacted by improving another system. Therefore, adding novel aircraft propulsion technologies into operational aircraft is an intricate engineering task. For instance, all essential electrical components (generators, motors, and electrical distribution systems) in a turboelectric propulsion system are associated with significant heat dissipation. Therefore, a robust thermal system must be implemented to effectively manage the dissipated heat, which is expected to affect the performance of the aircraft. Even during the development of such systems, thorough and comprehensive certification procedures should be followed, because safety is a critical aspect of the aviation industry and must always be guaranteed [54].

Several public and private organisations are developing policies, standards, and novel technologies to develop an efficient turboelectric system that will aid in significantly reducing carbon emission. Such research could improve the economic aspect of aviation systems, as cargo and passengers could be transported over the same distances while consuming less fuel [54]. Some of these organisations include the U.S. Departments of Energy, Defence, Commerce, and Agriculture; the Environmental Protection Agency; the Federal Aviation Administration; the National Aeronautics and Space Administration (NASA); academia; and engine and aircraft manufacturers.

The introduction of electrical components has provided unparalleled flexibility to turboelectric propulsion systems, particularly ineffective with fan propulsors coupled to the power-generation turbine(s). This flexibility has resulted in reduced fuel burn, noise, and lower emissions [196].

However, the introduction of these aforementioned electrical components comes at a cost. The addition of these components would increase weight and occasionally impact the efficiency of the system, which may threaten the proposed benefits. Therefore, break-

even analysis is required to assess the performance of the electrical power system in turboelectric transmission in order to achieve a net benefit at the level it is deployed. Several key results or functional and performance indicators (PIs) or parameters must be defined to conduct this analysis. There are four related levels of results to analysis then break-even analysis will achieve. The objective of this research is to define key performance indicators (KPIs) for turboelectric in transportation that needs to detect results indicators (RIs), performance indicators (PIs) and key results indicators (KRIs) [197]. Figure 8.1-1 represents the core relation for KPI to the analysis threads.

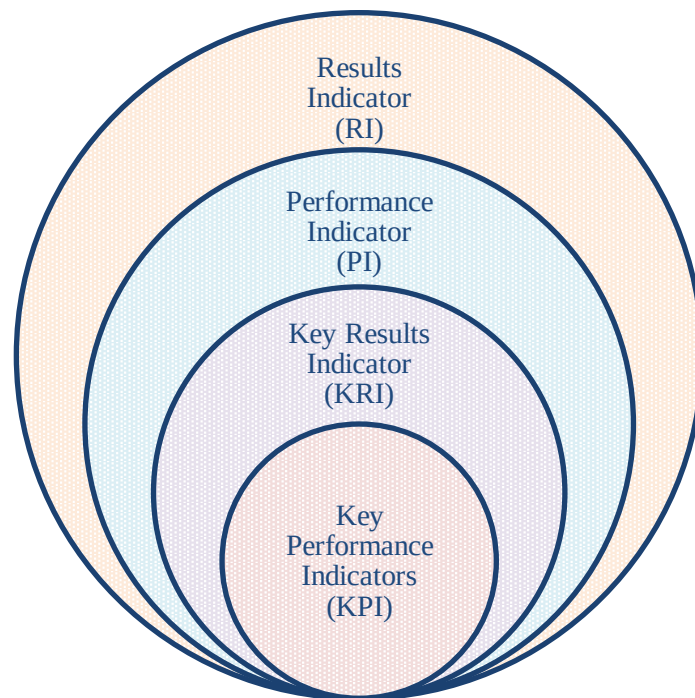


Figure 8.1-1: Key indicators hierarchy

This study comprehensively discusses some of the key techno-economic and environmental functions and performance indicators (PIs) of a turboelectric transmission system. After outlining the CO₂ emissions from commercial aviation, a turboelectric system is proposed to reduce these emissions and the complexities in the design and integration of aircraft systems. Some of the basic considerations in aircraft-propulsion integration and technology needs are discussed, and key results, performance parameters, and performance indicators are presented. The energy and propulsion technologies are the focus of this discussion, aiming to minimise global greenhouse gas emissions, particularly from commercial aviation. The entire system of energy and propulsion

technologies, from storage devices (such as batteries, alternative fuels, or jet fuel) to propulsion power generation (such as motors and/or gas turbines), is considered.

This chapter is structured as the following order respectively. Explain, discussion and implementation of RIs on turboelectric systems. Next, introduce the PIs reflections from the turboelectric approach. Then analyse the keys found from RIs affect the technical, economic and environmental aspects gains from turboelectric. After that analyse with the same aspects KRIs outcomes to get needed KPIs. Quantitative measurement of the KPIs outcomes done behind to estimate the quantity of each key. Finally, a recommendation and conclusion add to integrate turboelectric and overcome the limitations for the future area of research.

8.2 Results Indicators (RIs)

The design of a turboelectric system or any other electric system must meet the expectations of all the stakeholders of an aircraft, including customers, owners, environmental agencies, and governments. The expectations of these groups towards such technologies are outlined in this section as the results indicators (RIs) of turboelectric systems. These RIs could be divided into technical indicators, environmental indicators and economic indicators, as illustrated in Figure 8.2-1 as a result for each sector.

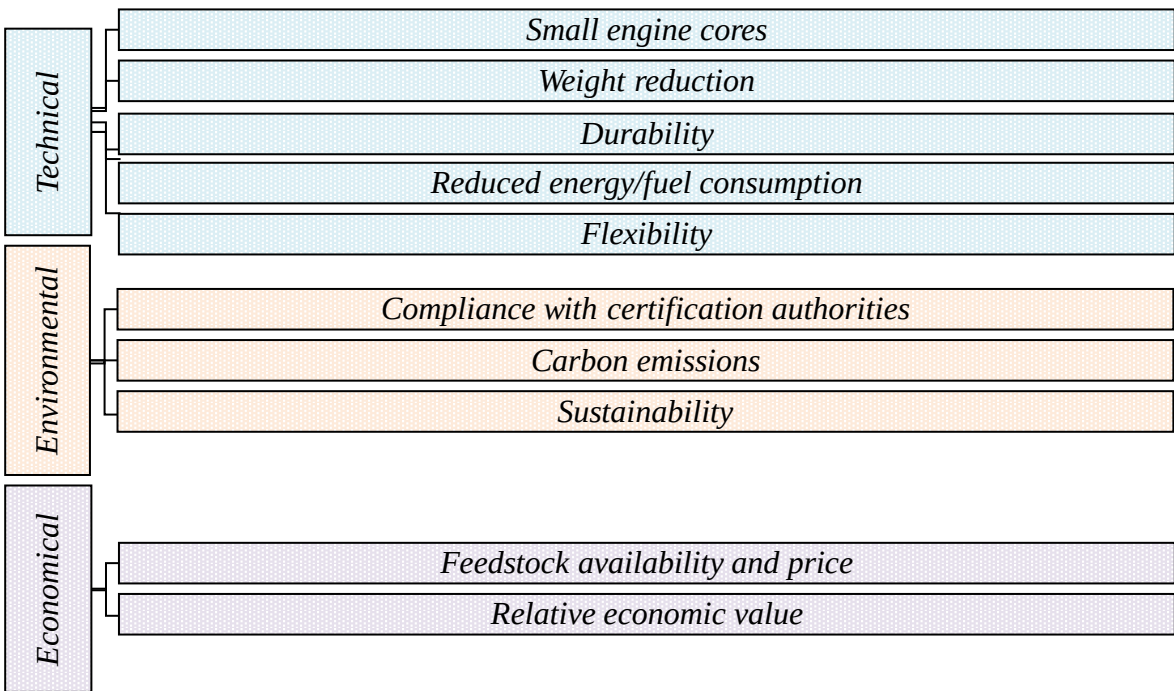


Figure 8.2-1: Turboelectric results indicators (TRIs)

From the literature, found that there are nine indicators to analyse effects on the total efficiency of the turboelectric system. These indicators were categorised based on the techno-economic environmental risk analysis (TERA) methodology to meet the method standards [3,110,198,199]. The framework based on three steps to apply: problem defines, data collection and risk analysis. Each part of TERA described with its indicators as the following:

a) Technical indicators:

This part represents the technical data found after defining the problem of each indicator and weight it as a risk to be analysed.

- *Small engine cores:*

Small engine cores are one of the RIs of a turboelectric propulsion system that is mainly assessed by certification agencies [34,67,200]. In this case, the cores of the resulting system must be relatively small to avoid weight and size issues that are likely to impact the system's efficiency. Great care must be taken to ensure that efforts to reduce core sizes must not cause a decline in performance factors, such as aircraft efficiency [201].

- *Weight reduction:*

Weight reduction is another crucial element of the turboelectric indicators. The materials selected for the components of a turboelectric system must ensure that the resulting design weighs less than the previous design [67,199,202,203]. Turboelectric total weight consists of seven elements: gas turbine engine, electric generator, superconducting bus, cryogenic inverter, motors, propulsive fans and cryocooler. The highest weight in the electric system is the electric generator with an estimation of 689.46 Kg per single generator [204]. In the case of the gas turbine (GT) embed with the generator, the total engines and generators' weight will be 16300.92 kg per aircraft with the assumption of 7461 kg per GT for twin engines and generators aircraft [205].

- *System parts durability:*

It is difficult to sustain the fuel-conversion efficiency when parts of the propulsion system age at a considerable rate. Therefore, research must be conducted into finding materials that do not age rapidly and/or methods of fabricating components in a way that fosters anti-ageing capabilities [206–209].

- *Reduced energy/fuel consumption:*

As stated above, if the turboelectric system is designed to be efficient, then fuel consumption would be reduced. Every aircraft owner/operator would like their aircraft to be cheaper to operate and maintain. One aspect leading to high operation costs is fuel consumption [47,210,211]. Therefore, the propulsion system must be designed with minimal fuel consumption.

- *Flexibility:*

Turboelectric system has a flexible integration depending on the aircraft size and power delivery. This includes the electric configuration and vehicle architecture [212,213]. Moreover, the flexibility could customise the emission weight and reduce costs based on the available technologies and regulations [214–218].

b) Environmental indicators:

This part represents the environmental data found after defining the problems of each indicator and weight it as a risk to be analysed.

- *Compliance with certification authorities:*

Aircraft environment safety is a critical factor. Therefore, the design of any of its components must be subjected to thorough assessment and test–retest procedures to ensure optimal performance. One of the most critical RIs is compliance with all environmental certification authorities. Some agencies tasked with certification tests include the U.K. Civil Aviation Authority, U.S. Federal Aviation Administration, and the European Aviation Safety Agency [47,105,115]. Therefore, every turboelectric

technology must be subjected to scrutiny by experts from these agencies to ensure that it fully conforms to all operational aspects of the aircraft.

- *Carbon emissions:*

As outlined in Section 8.1, by 2016, the commercial aviation industry contributed to over 2% of the overall annual global CO₂ emissions. Therefore, every aircraft system or component, particularly those involved in propulsion, must be improved to reduce this percentage, as the impacts of these emissions are experienced globally [33,40,115]. Climate change has been the key outcome of greenhouse emissions, which has impacted the global economy and society. Furthermore, environmental agencies have developed expensive programs. Therefore, carbon emission is a critical RI of turboelectric systems, as its outcome directly impacts financial aspects.

- *Sustainability:*

Sustainability is one of the crucial economic factors that could determine whether the turboelectric system is economically viable [65,84,105,219]. That is, while the focus is on alternative jet fuels, the sustainability of the source of these alternative fuels must be considered [220]. Whether there would be other impacts associated with the utilisation of such a fuel source, such as environmental and economic effects, should be explored in a feasibility study of sustainable alternative jet fuels (SAJFs). In most cases, government incentives are required to make such ventures profitable [221]. When the alternative fuel can be utilised for a long time with little or no impacts, it can be said that sustainability has been achieved.

c) *Economic indicators:*

This part represents the economic data found after defining the problem of each indicator and weight it as a risk to be analysed.

- *Feedstock availability and price:*

From an economic perspective, feedstock must be not only sustainable but also cost-effective. Several processes have already demonstrated that SAJF can be generated in the form of drop-in fuels [54]. However, these processes are technically challenging, and overcoming such challenges would ensure the economic competitiveness of SAJF produced on large scales. This is a crucial RI of the turboelectric system. System operation using low-cost feedstock would significantly reduce operational costs [54,222,223]. As such, this RI affects the operational outcomes of the entire system.

- *Relative economic value:*

The proposed turboelectric system must offer significant relative economic value. A balanced technological investment portfolio is required when designing turboelectric systems that would aid in ensuring that any type of economic uncertainty associated with changes in certain factors, such as fuel prices, would not negatively affect the sustained decrease in emissions from the industry [54,110].

8.3 Performance Indicators (PIs)

As mentioned above, electrical systems include essential components, such as electrical distribution systems, generators, and motors. Therefore, these main components are the focus of electric-propulsion research. This section outlines several key actions and events that can achieve the desired RIs outlined in Section 8.2. Figure 8.3-1 follows to illustrate the three aspects of the techno-economic environmental risk assessment TERA analysis method used to determine the performance indicators for the turboelectric system.

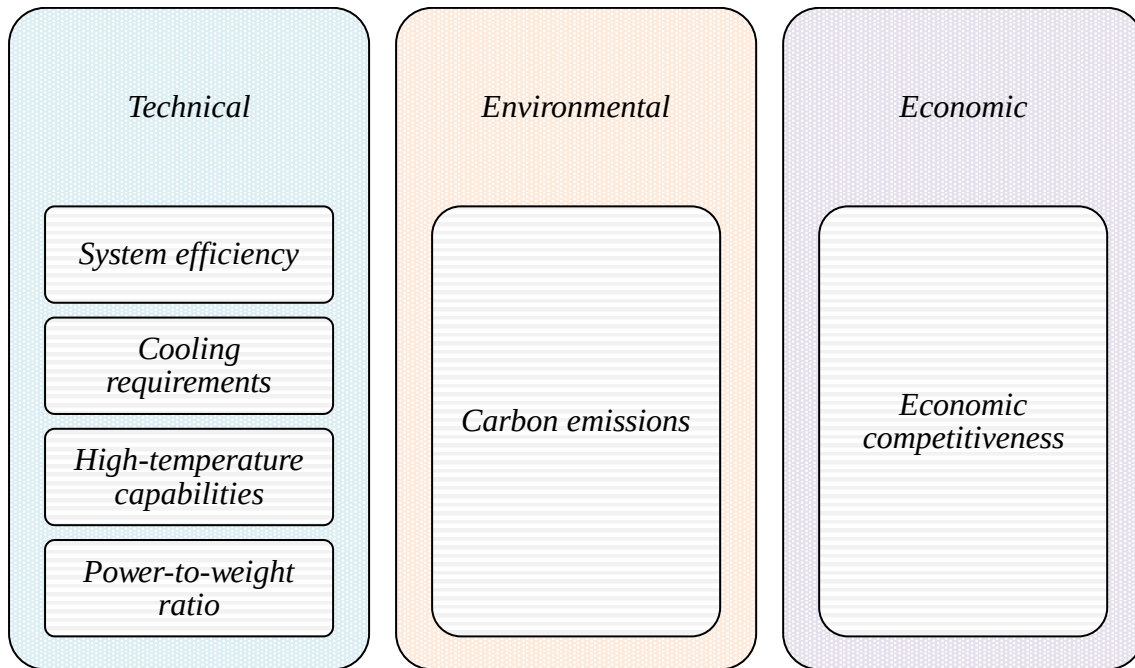


Figure 8.3-1: Turboelectric performance indicators (TPIs)

The performance parameters for turboelectric system data discussed as the following:

a) Technical indicators:

- *System's efficiency:*

One of the key PIs (KPIs) of any system is its efficiency, particularly from the perspective of performance. Ensuring efficiency is one of the main objectives of any newer technology intended for use in turboelectric systems. Therefore, efficiency in several aspects of the propulsion system is desired. The first is the propulsive efficiency of the system, which is the propulsive power as a function of the generation rate of propulsive, kinetic energy [196,224]. That is the efficiency of the fuel to be converted to kinetic energy in the propellant of an aircraft that replaces the losses occurring as a result of gravity or aerodynamic drag, or to accelerate the aircraft [225], or the fraction of mechanical energy utilised in propelling the aircraft. The propulsive efficiency of the system can be enhanced by boundary layer ingestion (BLI), which ensures that lower velocity flow is ingested by the system's propulsor near the airframe, leading to the re-energising of the wake and significantly decreasing the drag [196,226].

The other aspect of efficiency is the thermodynamic performance of the propulsion system, which is the quantity of work output as a function of the heat dissipated by the system. In the turboelectric system of an aircraft, this type of efficiency is attributed to the materials selected in the design of the system components [201].

- *Cooling requirements:*

As mentioned above, significant amounts of heat are dissipated from a turboelectric system. Therefore, it is essential to ensure that the required cooling systems are as straightforward as possible while still efficiently executing the desired function. The cost of the required cooling mechanism must be reduced without impacting any of the functionalities of the system as a whole. The turboelectric system must execute its propulsion functions without requiring another complex heat-dissipation system. There, the cooling requirements of the turboelectric propulsion system are a vital indicator of its performance [34,39,99,227].

- *High-temperature capabilities:*

A turboelectric propulsion system converts energy. As such, it could generate immense amounts of heat. Therefore, all of the system's components or materials utilised in their design must be able to withstand such immense temperatures. Such components are expected to accurately and precisely perform their functions, even at such high temperatures [101,228,229]. Therefore, research must also be conducted to develop measures that ensure that the system's performance is not negatively impacted by temperature.

- *Power-to-weight ratio:*

This is another PI determined by the materials selected for designing the turboelectric propulsion system and is the velocity of the aircraft multiplied by its thrust per unit mass. The power-to-weight ratio is a good measure of the propulsion system as a whole [221].

b) Environmental indicators: *Carbon emissions*

Carbon emissions are also an indicator of how well the turboelectric system performs its propulsion function. A critical PI that agencies will be interested in is the emissions of the propulsion system. This can be improved through numerous methods, including material selection and ensuring that thorough research and test–retest procedures are performed on the potential materials so that only the suitable materials are utilised. This may involve materials that do not undergo significant reactions leading to CO₂ emissions, or those that will have a lesser impact on the overall weight of the resulting system. Reduced weight, and hence reduced drag on the aircraft would reduce the energy required to fly an aircraft. Other possible ways of reducing CO₂ emissions include, but are not limited to, the enhancement of the propulsion system's efficiency, i.e., the conversion of fuel into thrust, and the reduction of the carbon intensity of the required energy, which reduces carbon emissions from electricity sources such as generators and batteries [19].

c) Economic indicators/*competitiveness*:

Commercial aviation is one of the most competitive industries. Although this is due to several factors, one of the key drivers is a fuel-burn reduction, which directly impacts CO₂ emissions [54]. Cost is fundamental in the development of a turboelectric system, as it directly affects key factors, such as the costs associated with a given aircraft. Therefore, the overall impact on the competitiveness of the aircraft is one of the crucial considerations when developing a turboelectric system. Designers must be able to explain how economically competitive the proposed design will be in relation to the existing designs. Therefore, economic competitiveness can only be considered a PI when the new system helps the aircraft gain a competitive advantage in the industry.

8.4 Key Results Indicators (KRIs)

The previous sections explained the measurement of the results from the turboelectric systems in the form of RIs. In this section, the key factors associated with those indicators are highlighted. Reliability, redundancy, and independent power, as well as speed control, are some of the key RIs (KRIs) for a turboelectric aircraft.

Initially, several electric aircraft-drive configurations require independent power and speed control for each fan propulsor. This requirement provides room for crucial configurations that were almost impossible to achieve in older aircraft. Such configurations include noise-minimisation strategies, the capability of providing high-velocity wing blowing with a regulated thrust, regulation of yaw via differential thrust, flight regimes that optimise operation, and decoupling of the turbine and fan speeds.

In the case of reliability and redundancy requirements, the system must meet the safety standards currently seen in the prevailing aircraft. The primary standard is a fail-safe requirement, in which catastrophic effects are never allowed to occur due to any given single-point failure at the aircraft level. Furthermore, the levels of oversizing and redundancy required to provide support for safety- and flight-critical loads during off-nominal failure cases determine the overall maximum, volume, and weight capacities of airborne power systems [196].

8.5 Key Performance Indicators (KPIs)

This section highlights some of the chief actions and activities denoted as KPIs that are crucial to the success of turboelectric systems. First, regarding the electric drive of a

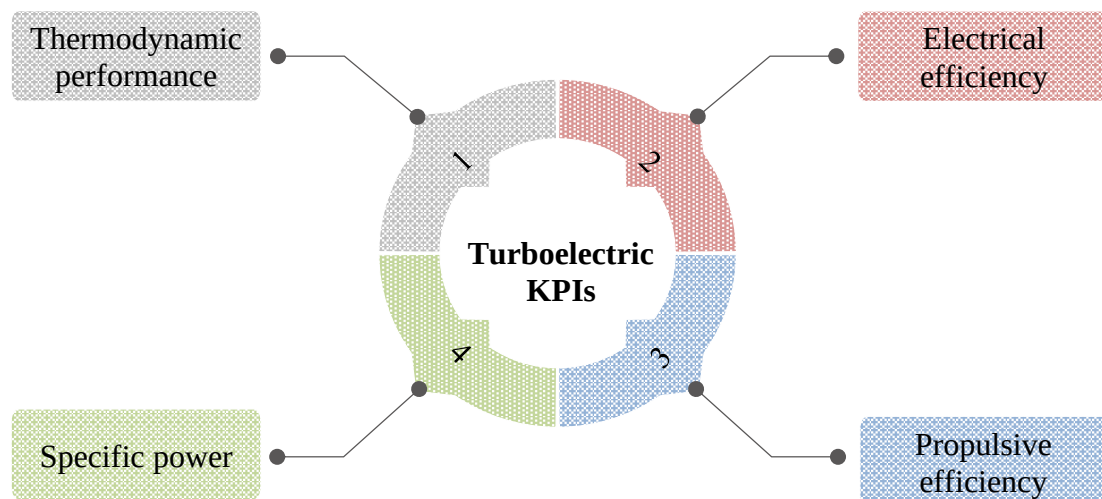


Figure 8.5-1: Turboelectric KPIs (TKPIs)

turboelectric system, two chief performance parameters are efficiency (usually denoted as η_{ED}) and specific power (denoted as Sp_{ED}). These two quantities to determine the performance levels of any aircraft. Overall, the KPIs for any turboelectric system can be described in terms of system efficiency, energy consumption, and design masses [230]. As stated previously, efficiency is a ratio of the input power of a system to the output power. In this case, efficiency can be considered in terms of the system's thermodynamic performance and propulsive efficiency, as discussed above. The specific power is defined as the ratio of the overall mass of the system to its rated power. This KPI is a function of the thermodynamic performance, electrical efficiency, propulsive efficiency and specific electrical drive power. This suggests that the KPI directly affects the weight of the electric drive of the system. Therefore, it is essential to select a size for the electric drive that ensures maximum electrical power, particularly during take-off. In the following Figure 8.5-1 represent these KPIs results for this research.

8.6 Quantitative Measurement

To determine the current and prospective improvements required, measures of the quantities of the identified KPIs should be used. Quantity data were used based on the available published data for turboelectric distributed propulsion (TeDP) and simulated using the Cranfield University in-house tool (TurboMatch). The case study used in the quantitate measurement was modelled as Cranfield TeDP with the name of "CTeDP-3". This model inspired from the joint development by Airbus Group Innovations, Rolls Royce, and Cranfield University for the E-thrust concept [71]. It consists of two turboshaft engines (35 MW per engine), four electric generators (16 MW per generator) and 16 motor fans (4 MW per motor). The following Figure 8.6-1 illustrates the structure of the CTeDP-3 case study model.

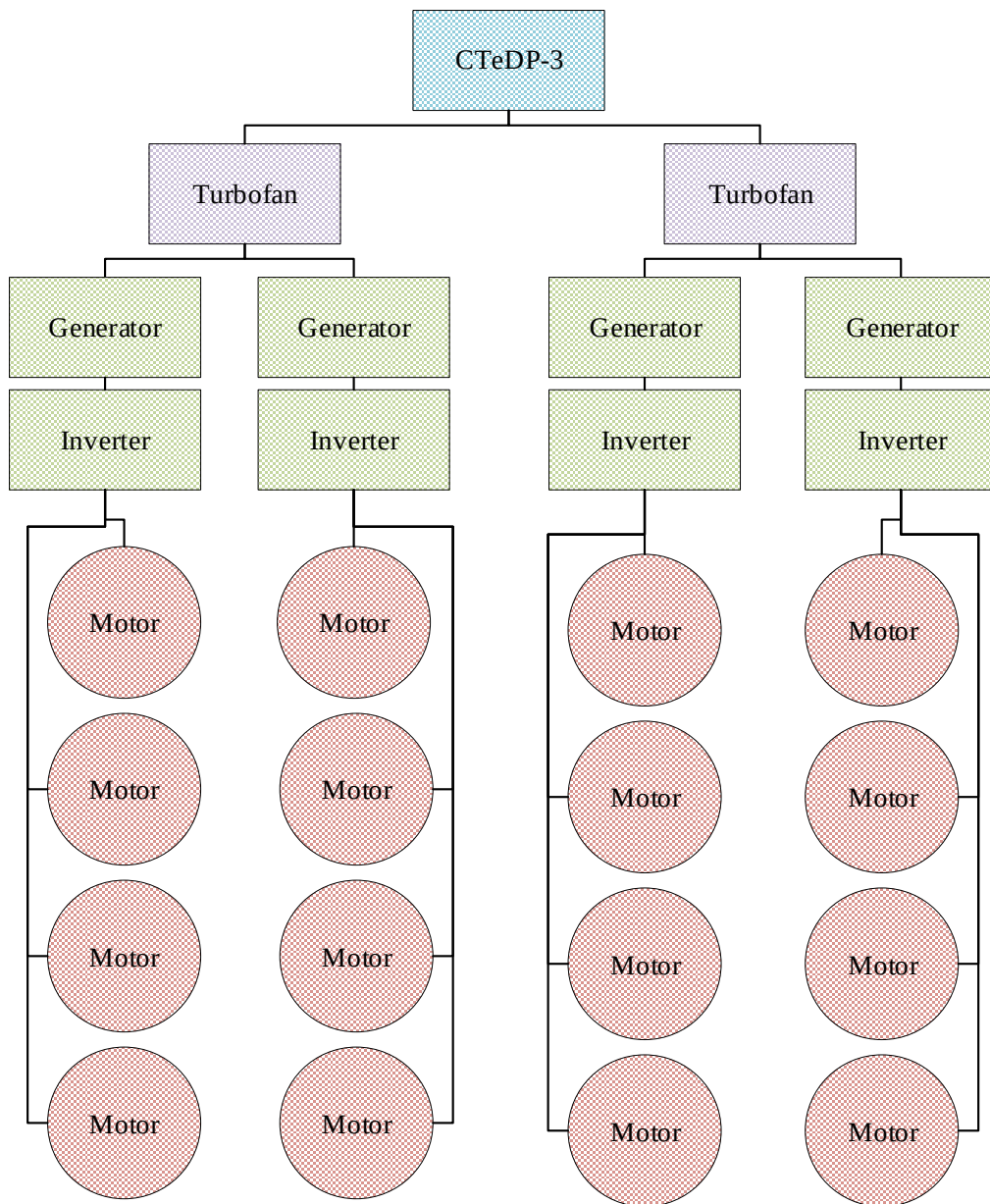


Figure 8.6-1: CTeDP-3 case study model structure

The simulation assumptions for the turbofan were fuelled by hydrogen, one spool, and off-design. Moreover, assume the power needed from each shaft is 32 MW for the two generators and the rest of the 3MW used for aircraft electricity. The engine characteristic and results represent as follows and table 8.6-1:

Shaft Power	= 35	MW
Net Thrust	= 43515.08	N/kg/sec
Fuel Flow	= 0.8518	kg/sec
Specific fuel consumption	= 0.0243	g/MJ

Table 8.6-1: Case study turbofan results

Station	Mass flow (kg/sec)	Total pressure (Atmospheres)	Total temperature (K)
Intake	130.0	1.0	288.15
Compressor	130.0	0.99	288.15
Burner	130.0	24.75	778.61
Turbine	130.852	23.51	1400.00
Nozzle	130.852	1.28	761.01
Performance	130.852	1.28	761.01

The performance plot for the turboshaft is illustrated in the following Figure 8.6-2.

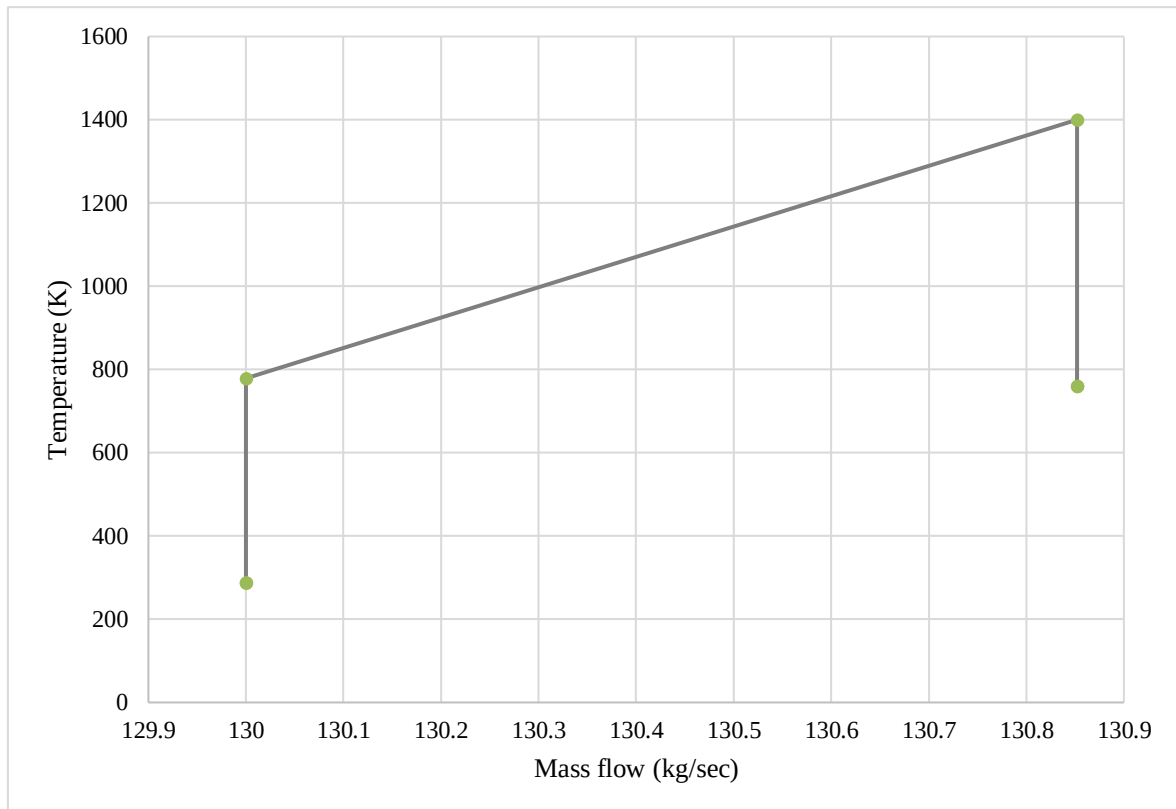


Figure 8.6-2: Plot the performance

The quantitative measurement for the electrical grid KPI study required the efficiency of each component of the electrical grid. The assumption of each component was made based on the calculated values in the published work [34] as the following table 8.6-2.

Table 8.6-2: Case study Cranfield TeDP model results

	Component	Assumed efficiency per component	Components total efficiency
CTeDP-3 model	electric generators	99.7%	98.8%
	inverters	98.8%	95.2%
	eclectic motors	99.5%	92.2%
	high temperature superconductors	99.0%	99.0%
	Total electrical grid efficiency		85.85%

Propulsive efficiency supposed in this case study is the propulsive power delivered by the motors divided by the shaft power input to the propulsor [54]. Where the specific power efficiency presumed to equal to the thermal efficiency, the results of the KPI model are presented in Table 8.6-3, along with the prospective performance of the KPIs.

Table 8.6-3: Quantitative KPI results for TeDP

KPI	Calculated efficiency	Projected target efficiency
Thermodynamic performance	34.23%	39.2%
Electrical efficiency	85.85%	93.8%
Propulsive efficiency	91.42%	94.4%
Specific power	34.23%	39.2%
Total TeDP system	26.86%	34.7%

8.7 Results Discussion and Future Trends

The outcome of this study can be discussed to evaluate the indicators to analysis the performance target. Results from the model of TeDP shows that the lowest level of efficiency is the thermodynamic performance. This is because of the standard gas turbine efficiency to be between 30-40%. Increase the efficiency means to modify gas turbine design or model. Also, the thermodynamic efficacy decreased by 1.31% from changing kerosene to hydrogen fuel regarding the fuel properties. The targeted efficiency was specified to the highest in component literature. The next KPI to discuss is electrical efficiency with the calculated efficiency of 85.85%. Regularly the electrical efficiency is higher than the mechanical efficiency; however, the integration in mechatronics result in

reducing the electrical efficiency. Moreover, the implementation of a number of motors and generators within the system result in part of efficiency reduction.

Propulsive efficiency in TeDP is high as the losses been waved as possible from the advantage of integration electric. Improving its efficiency limited in the design side and propulsive distribution. The final result of KPI efficiency measurement is the specific power, and by assumption, it is the same as the thermodynamic efficiency. Only the affection of mass flow for the total efficiency included, and it was neglected as a result will be almost the same. Figure 8.7-1 illustrates each KPI found for TeDP and the corresponding error margin. This indicates that changing the specific power or thermodynamic efficiency could improve the total system power by 3.9%. This would positively affect the electric efficiency as the power will spread throughout the electric grid with stable voltage, high electric current, and fewer elements in the system. However, the enhancement of electrical efficiency will increase system productivity by 2.4%. This would then improve propulsion efficiency and specific power. These outcomes would reflect on economic and environmental performance in optimistic and validate the KPI cycle.

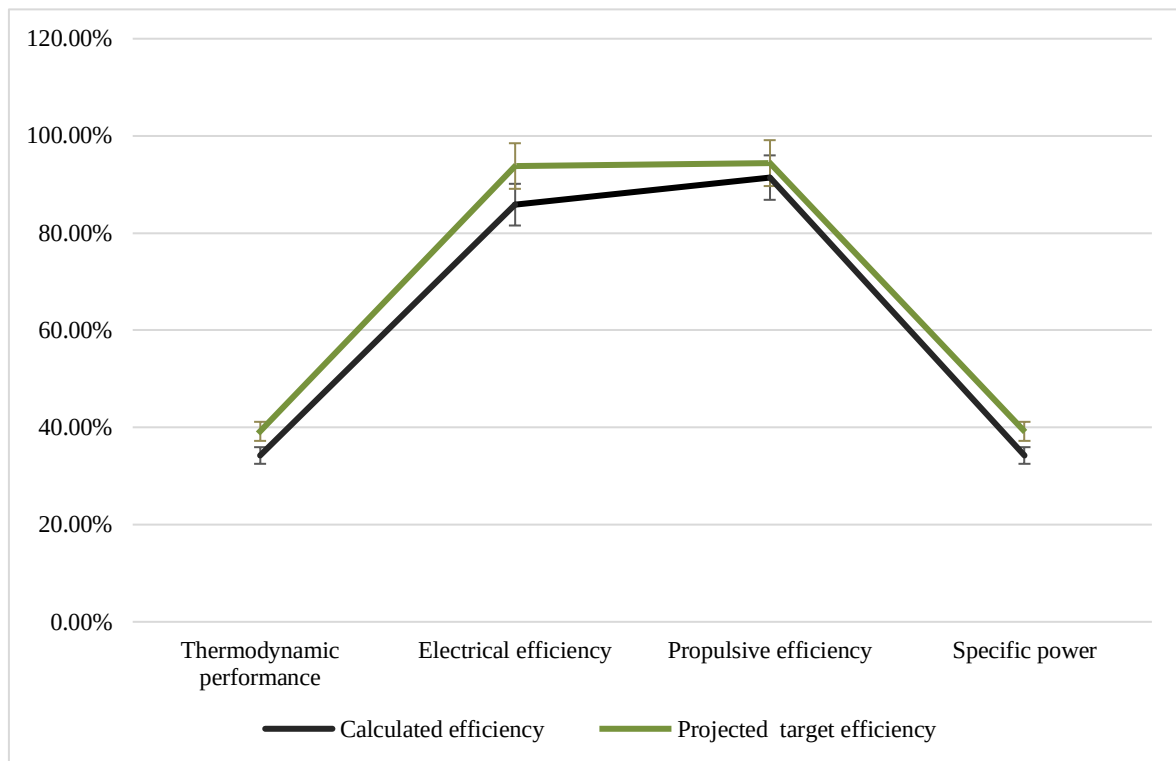


Figure 8.7-1: Turboelectric performance indicators

The achievements of this study indicate the need to study the electrical grid and investigate the opportunities to decrease the number of electric components and increase efficiency. Also, to investigate to model a specific gas turbine engine designed for TeDP to achieve higher efficiency. As advantages, this study shows implementing the TeDP system in a short future needs to focus on thermodynamic efficiency as primary KPI. This will increase the usability of transformation from the legacy system. The drawbacks were implementing the hydrogen fuel to reduce the efficacy of the system. It was not considered as KPI because the fuel and mass flow is a part of the thermodynamic and specific power term.

As a conclusion from the previous figure, electrical efficiency has the most extensive scope of investigation and development to integrate the turboelectric system. This includes the enhancement of electric generators and motors in the prime stage then the auxiliary systems. Thermodynamic performance and specific power would also assist in the integration of turboelectric if combined as representing 58% of the performance indicates. Moreover, the integration of turboelectric could be more substantial based on the technologies that exist during the time.

The limitation of this study lies in evaluating one type of gas turbine engine, fuel, and model. Additional limits consist of assessing the implementation of HTS for the electrical systems and compare it with different alternatives. Future research work suggestions for TeDP to study the integration of gearbox in TeDP and find an alternative model to represent the electrical parts. Moreover, considering the weight ratio will be a plus for the application.

8.8 Chapter Summary

This study aimed to discuss some of the indicators that determine the performance and results of the turboelectric propulsion system. Carbon emissions were identified as one of the key issues associated with commercial aircraft. Therefore, turboelectric systems must be designed to resolve this issue. The RIs of an aircraft include reduced fuel/energy consumption, compliance to certification agencies, reduced carbon emissions, reduced core, increased system component durability, sustainability, feedstock availability and prices, and relative economic value. The PIs identified included the system's efficiency, carbon emissions, cooling requirements, power-to-weight ratio, high-temperature

capabilities, and economic competitiveness. From these broad categories, the key RIs identified were reliability, redundancy, independent power, and speed control, and the KPIs include efficiency and specific power. The following last chapter in the research will conclude the conduction of TERA aspects in TeDP.

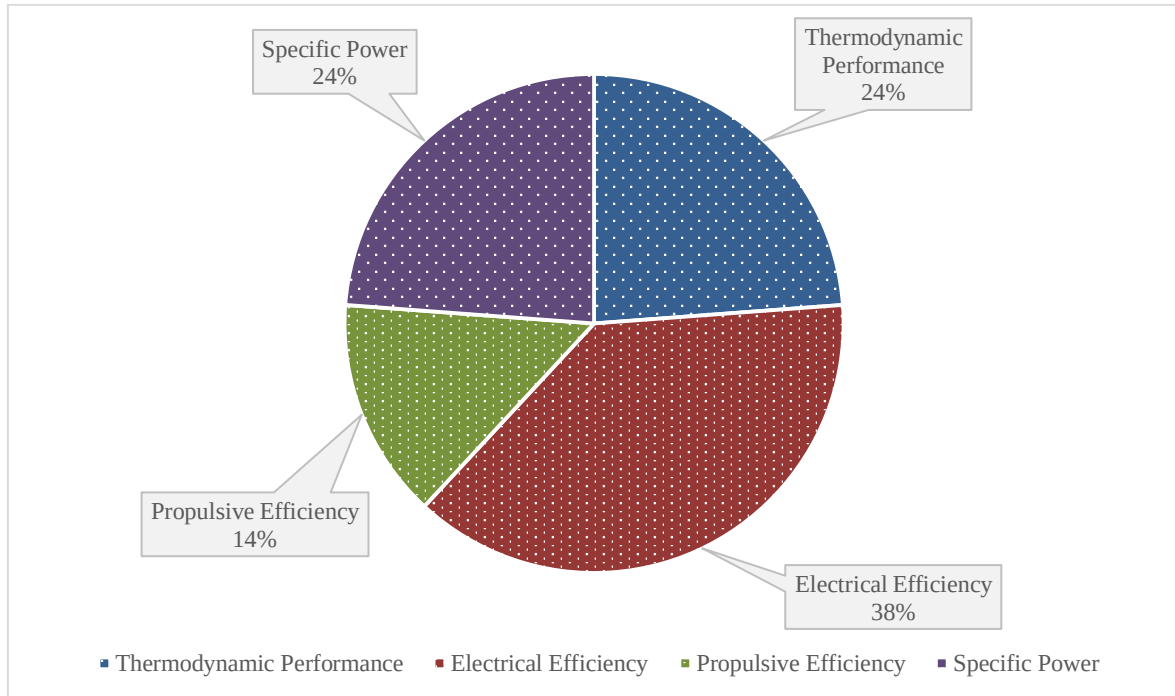


Figure 8.8-1: Enhancement of the turboelectric performance indicators

Figure 8.8-1 shows each KPI identified and the percentage required to meet the prospective performance. The electrical efficiency has the most significant improvement value and receives the most research and development, as it covers 38% of the current efficiency. Propulsive efficiency has received the least attention in TeDP improvement, but the importance of enhancing the electrical efficiency of generators and motors should not be neglected. Apply TeDP KPIs as a result of this study in the real-world will increase the total efficiency of up to 8%. This enhancement not only affects the technical aspects but also reflected on economic and environmental attitudes.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the project work for TeDP numerical modelling. It covers the summaries from each chapter (manuscript) and the closing remarks for the project. Moreover, this chapter comprises the intellectual contribution of the project work and research. The potential effects of TeDP are also included in this chapter, and recommendations are presented for the future development of a similar project.

Air traffic has significantly increased since the beginning of aviation commercialisation. The trend is more likely to remain the same or even to increase for the next 20 years due to the continued growth of the aviation industry worldwide. It is apparent, however, that the upsurge in the growth rate of the aviation sector poses severe environmental issues that continue to necessitate discussions on environmental assessment. The effects of the increasing growth in the aviation sector include an increase in fuel consumption, noise, field length, and emission of gaseous substances into the atmosphere [138].

One of the engineering challenges is a techno-economic environmental risk analysis (TERA) technique that combines mathematical models to simulate and optimise the performance of a set of technologies. It is undeniable, however, that the aviation industry is becoming environmentally aware. It is evident that the technical progress today is working towards improving aviation sustainability, especially on matters concerning environmental conservation.

Numerical modelling for the turbo-electric techno-economic environmental analysis can help in achieving some of the goals of the aviation stakeholders for environmental safety. [231] The numerical modelling system has significant benefits in terms of intellectual contributions. Numerical modelling also has a potential effect on the effectiveness of the aviation sector in solving various environmental conservation challenges society presently faces. It is undeniable, however, that the sector should consider some key recommendations as the stakeholders work towards achieving further growth and environmental awareness.

This chapter focuses on addressing these intellectual contributions, potential effects, and the recommendations for future work on the turbo-electric techno-economic environmental analysis system.

9.1 Manuscript Conclusions

This research consists of seven stand-alone manuscript chapters within the research area of TeDP. Thus, the conclusion summaries for each chapter are discussed as follows:

- *Chapter 1*

This chapter discusses the background of the implementation of TeDP in aircraft, concluding that a need exists and environmental organisations have called for a critical solution for airline emissions. Moreover, the aviation industry and organisations have faced technical and economic challenges for the resolution of the current situation. However, plans are needed to reach the next 20 years of targets due to the lack of contributions to fill the knowledge and tool gaps.

- *Chapter 2*

This chapter consists of the literature review on TeDP in civil aviation with alternative models and technologies. The study of the history, present, and future of TeDP facilitated the evaluation of the technology compared with other eco-friendly alternative propulsion technologies. Moreover, the conceptual design proposed by previous researchers for future implementation was found along with its constraints. Finally, the numerical modelling tools available in research and education to assess TeDP were studied, which show the lack and the limitation of tools for developing and modelling futuristic propulsion systems, especially for mechatronics.

- *Chapter 3*

From the overview of the existing tools and methods to assess TeDP, the limitations in developing such a tool were assessed. That is why this chapter presents a novel method and model to assess TeDP within the TERA methodology. The conclusion of this manuscript shows that, for the initial stage of mechatronic modelling and development, the complexity is not

desirable. Nevertheless, for the future development of accurate results, multifaceted parameters for the relation of transferral between mechanical and electrical power should be added.

- *Chapter 4*

To build a numerical model required in software engineering to create an integrated developing environment for TeDP, this chapter builds the notation integration essentials. It covers several modelling methods and then studies the state automata mechanism design for propulsion parts. The conclusion is that the TeDP system is integrable and extendable for specific power consumption. In addition, this model reflects the current state of available technology and the gridding for auxiliary parts that could disappear in the future development of primary parts.

- *Chapter 5*

This chapter introduces the available software that would help in the development and integration and the new software extension to transform the methods and models into a real tool. Moreover, it includes the analysis and validation of each part of the propulsion system. These indicate that a stand-alone extension tool is needed to differentiate power types, carriers, and consumptions.

- *Chapter 6*

The performance tools and optimisation extension show the validity in the case study results. This leads to uncertainty in the quantitative analysis regarding the different methods to apply to ensure integration optimisation. As a result, several optimisation options exist for NASA's conceptual design of N3-X in diverse aircraft conditions.

- *Chapter 7*

As a part of the research to cover TERA methodology, this chapter explores the economic part with the novel assimilation of EAV for TeDP, including the traditional methods used in finance assessment. The second part of the

environment assessment involving any penalties or regulation from TeDP was not neglected. Thus, TeDP is economical and environmentally friendly.

- *Chapter 8:*

After the assistance of TeDP, key performance indicators for future development in research and industry were the focus as well as the project efficiency outcomes for implicit key indicators with data visualisation. The outcome from the study is four key indicators to advance the thermodynamic performance, electricity efficiency, propulsive efficiency, and specific power.

9.2 Intellectual Contribution

Numerical modelling for the turboelectric analysis has contributed to the intellectual research and development of future distributed propulsion. These intellectual contributions could be discussed as follow:

- *The numerical model for the turboelectric techno-economic system can enhance the accuracy of the model in improving engine performance.*

First, numerical modelling for the turbo-electric techno-economic environmental analysis enhances insight about the performance of engines. This project used the numerical propulsion system simulator (TurboMatch & GridMatch) tools to estimate the performance of the electrical components and gas turbine engines. The total performance depends on several components of the engine system and propulsion model configuration, whereas the total efficiency of all components determines the level of efficiency of the gas turbine engines, electric generators, electric motors, and electric buss. This aims to improve environmental safety and engine efficiency. The research for the TeDP model was to assess different components of the engine system. The numerical model can make the assessment process more productive by enabling researchers and developers from other aviation organisations to conduct accurate assessments. The process of numerical modelling using turbo-electric techno-economic methodology can enable us to understand more about the scope of operation, including the environmental conditions within which an aircraft model can

operate. In that regard, it can enable us to develop a compatible novel technical model for different aircraft models. The intellectual contribution of the numerical modelling process, therefore, is that it can enhance efficiency in a techno-economic environmental analysis.

- *Numerical modelling can enable a logical combination of the new technologies applied in contemporary aviation systems.*

The two ICAO and NASA entail an emission goal of developing a conceptual aircraft model, such as the N3-X aircraft, that uses as acoustic emission reduction for the cruise efficient short take-off and landing (CESTOL) system as a baseline.[211] The recommendations recently promoted the need to use new technology in reducing pollution and acoustic emissions to save the world from their side effects. The proposed system model for use in that aircraft is the TeDP. The creation of new technical systems is quite expensive and time-consuming. Using techno-economic environmental analysis, it is essential to develop systems that are both efficient and affordable to enhance the economic benefits that the airlines are seeing. The intellectual capability of the industry should be the central aspect of that improvement.

- *The numerical modelling process for the turbo-electric techno-economic environmental analysis can enhance the efficiency of the models.*

In particular, the case study in this project, N3-X, has 16 electrical fans in its TeDP system that depends on various superconducting motors as their sources of power. From the assessment, N3-X systems use fewer electric fans with better optimisation management, which could provide the same propulsive power. Using numerical modelling enables inventing a strategy through which the same power and speed can be achieved with an economically viable model that is also environmentally friendly.

- *The numerical modelling process for the turboelectric techno-economic environmental analysis can enhance design optimisation.*

The implementation of quantitative risk analysis, such as the Monto Carlo and Latin hypercube methods, can minimise the threat of a potential error estimation of the component parameters during the delineation and optimisation of a power grid. It can also improve the precision in the estimation of the arrangement of electrical components and the relation with a gas turbine. In the integration of numerical modelling, the expansion in research can logically develop a suitable framework, which can minimise the risk of ad-hoc judgement that can hurt the delineation of analysis input. Using linear parameter bounds plus stochastic algorithms can help in the development of a robust solution while performing a constant theoretical design. It is evident that most commercial gas turbine performance tools use secant techniques with a Broyden update. In particular, this approach should be the correct choice for the industry. It is therefore evident that a numerical modelling process can enable the selection of the best tools for design optimisation to enhance efficiency, including the techno-economic environmental assessment. Improved efficiency translates into higher performance and a reduction of the risks of failure.

- *Numerical modelling can define the critical functions of a turboelectric system.*

As a result, the numerical modelling process can have significant intellectual contributions to the process of developing turbo-electric systems. A reverse-Brayton cycle cryocooler (RBCC) is one of the most viable options that is used in various aerospace applications.[146] It is the most efficient and cost-effective option for small power scales. It exhibits a high range of reliability and effectiveness with extensive maintenance-free operations. A numerical modelling process can enhance the understanding of the scope of operation of the RBCC and the ability of researchers to understand the critical performance components. [146] Through the numerical modelling process, the researchers and industry can gain significant intellectual aspects from which they can address diverse perspectives concerning the diverse aircraft models.

- *Numerical modelling can also aid in the fast detection of statistical errors in a turboelectric system.*

During uncertainty quantification, a numerical modelling process typically has several benefits that can make accurate predictions and develop relevant solutions for different technical challenges. In turbo-electric systems, this project occasionally makes some assumptions owing to unavoidable circumstances in the development and operations of the models. It is always important to account for any assumptions made and the associated uncertainties to develop comprehensive and reliable reports concerning the development of the turbo-electric systems. The systems should be efficient and productive to make the aircrafts financially viable. Numerical modelling is suitable for making accurate predictions during uncertainty computation [91]. It can, therefore, enhance the integration of logic in the calculation of uncertainties in the turbo-electric systems and enhance the turbo-economic environment assessment. Ideally, the stakeholders involved in the computation of such uncertainties have a suitable chance through which they can make a relevant decision when determining the measures of uncertainties in the system. The intellectual contributions in that context entail the facilitation of the accurate computation of uncertainties in turbo-electric aviation systems. The benefits of numerical modelling during the computation of uncertainties include the fact that they can enhance the efficiency and accuracy level. It is apparent that, during uncertainty quantification, the sources of the various uncertainties can provide an accurate prediction. Correct predictions of the sources of uncertainties are relevant because they can enable working with accurately acquired figures. The modelling of the TeDP systems enhanced the logic of balancing the power input and power transmission fluctuations throughout the aircraft system. For example, the intellectual contributions in that context include the fact that the necessary level of temperature for cryocooling power is successfully predicted.

9.3 Potential Impact

A numerical modelling process can enable estimating not only performance and cost but also emissions from the aircraft. Numerical modelling could aid in reducing environmental aviation pollution. Dealing with different engine systems and different components is a complex task that necessitates a numerical modelling procedure. The process, therefore, prepares engineers to monitor the amount of emissions that the aircraft engine system can generate over time and on a particular journey. It not only prevents environmental pollution in the aviation industry but can also minimise the duration of exposure to emissions. Prevent emissions from the very first instance could be prepared by calculating the number of emissions expected from a particular engine system and the ways to minimise them in different weather conditions. The advantage of the numerical modelling process is developing suitable models through which the proper scope of operation of the engine system and the minimisation of environmental pollution are balanced. One of the primary goals is to use hydrogen fuel to prevent environmental pollution from the aviation sector. As initially indicated, the aviation sector continues to become more environmentally aware over time. In this regard, all the endeavours of developing an engine system today must factor into the aspects of environmental pollution and prevention measures.

NASA goes a long way in achieving the objectives of ensuring sustainable aviation practices worldwide. The organisation plans to achieve clean aviation systems over time. As a result, in its N3-X concepts, the organisation proposed an improvement in the different aircraft models to minimise pollution. In that conceptual goal, NASA proposed the modification of the Boeing 737-800 aircraft model by fixing a type of engine that can minimise emissions. The proposed engine for the aircraft model is the General Electric CFM56-7B engine, which can meet the N3-X goal. An engine like the General Electric CFM56-7B is proposed for the Boeing 737-800 model and can reduce the power of engine combustion by about 33%. As a result, it can minimise the number of oxides of nitrogen generated by about 60%. The main effect, therefore, of the numerical modelling for turbo-electric systems is to enable achieving the predetermined environmental protection goals. Achieving NASA's goals is a great accomplishment because the organisation has

committed itself to prevent environmental pollution from the very beginning, which is from the perspective of changing aircraft engine models.

This has a significant effect on achieving greater aviation efficiency. Improvement in aviation efficiency is a more significant step ahead because it can enable airlines to serve their clients well. Improvement in aviation efficiency for the Boeing 737-800 model after the engine system modification is evident following the reduction in the airfield length required. The efficiency is evident and becomes a significant benefit for airlines, which incur considerable costs from inefficient aviation systems. The process of modifying the Boeing 737-800 aircraft model began with the modification of the CFM56-7B turbofan. In the process, they began by fixing an ultra-high bypass ratio (UHB) propulsion system. A novel noise reduction system could also be fixed. They modified parts of the aircraft in bits, and the transition into a more efficient engine system can begin with changing a turbofan or an aircraft model.

Numerical modelling also has an effect on the costs of constructing and maintaining aircraft. It is evident that, upon the improvement of the engine system, the efficiency will improve, the amount of taxiing time will reduce, and the take-off airfield length will reduce. The reduction in the take-off airfield length for airlines minimises the cost incurred during the construction of the vast physical space for an airline. As a result, the airline can use the remaining space for other purposes, such as building parking or an inspection system for passengers. Meanwhile, apart from enabling the creation of more space for the construction of other essential factors within the airline, the numerical modelling process can also create more opportunities for the airline to consider better management of the space available for the benefit of the clients. Every airline focuses on providing the most attractive services to clients as a marketing method in the competitive industry. As a result, numerical modelling substantially improves the efficiency of aviation systems. It covers a broad set of subsections of the industry because it improves aircraft efficiency, reduces pollution, and minimises the costs of operation alongside the cost of construction and maintenance of an airline space.

Numerical modelling can also necessitate the airlines to invest in a change to adopt new aircraft models over time. As a result, it becomes necessary for most airlines to invest in acquiring new aircraft models that are suitable for the contemporary era. The engine

modification processes can be expensive. It will take a long time before an airline fully achieves the transition into a novel technology in engine systems. It is evident, however, that the aviation sector is changing with time. Carriers can begin to develop programmes that align with the changes achieved through numerical modelling. Although numerical modelling is a more technical process that can involve the modification of different parts of the propulsion system, its effect is notable from the external environment. It can affect not only the environmental influence of aviation but also the cost, required skills, and predictable modifications arising from an aviation system.

9.4 TERA Conclusion

As a conclusion for the three parts of TERA methodology, which are the technical, economic and environmental, this study results in positive outcomes for a turboelectric upgrade in future propulsion. In the technical aspect, turboelectric can be improved up to 2% with the existing technologies and could reach 5% with the material limitation enhancements. The economic study for 30 year shows the low risk in investing in developing, integrating and operating turboelectric. The economic challenge lies in the cost of manufacturing the electric motors that need to be noticed in future studies. The last term in the TERA is the environmental impacts for turboelectric. This aspect still green in the level of emission as the future fuel projected to be Hydrogen. For that reason, the assumption of the research used Hydrogen fuel, and the result shows almost zero-emission for TeDP. To conclude, the three aspects of the TERA methodology shows low risk could have in TeDP systems.

9.5 Recommendation for Future Work

Future research and development in TeDP should focus on the technical enhancement of electrical parts, such as the motor and generator, to study the opportunity to increase the efficiency and minimise cost. Some other recommendations for future work in numerical modelling in the turboelectric techno-economic environment assessment from various points of view include the following:

- *Technical recommendations*

The technical part of TeDP is related to design and model integration. This would lead to an increase in the efficiency and power for all parts of the system. The improvement needs to be in the redesign of the electric generator, electric motor, and other electric parts, such as the rectifier and inverter. There are two challenges for the improvement of the generator and motor: the high cost and the temperature on the TeDP system. A suggestion for future work is focused on the material science of manufacturing the generator and motor. The second suggestion is to use nanotechnology in building these primary components in turbo-electric systems. In addition, it is recommended to study the implementation of nanotechnology for the electric grid within the TeDP system. For the gas-turbine side, the recommendation is to compare different fuel configurations and types to find the most efficient power source and even to study the reflection of the total efficiency and power with different types of hydrogen fuels.

- *Numerical recommendations*

Numerical analysis entails techniques to aid in the quantitative and qualitative determination of the financial viability that mixes numerical modelling and design to support the economic evaluation process of an aircraft system. Future research should, therefore, focus on examining the different ways through which numerical modelling can facilitate a successful transition into a more environmentally friendly aviation industry worldwide. The current findings point out some of the economic effects numerical modelling can have on the maintenance of TeDP. Consequently, future research should explore the economic effects of numerical modelling because the cost minimisation benefits can attract several airlines to invest in new models. In addition, computational fluid dynamics (CFD) could be interesting to study the thermal management and transportation of the TeDP system. The risks of hydrogen tanks and heat limitations should also be explored. The effect of numerical

modelling is significant because it extends to different aspects of aviation systems.

- *Environmental recommendations*

Although the aviation sector is becoming environmentally aware, the stakeholders should take several steps to achieve a complete environmental protection path. In this regard, future research should focus on novel gas turbine engines that have built-in electric generation designs that different airlines and different aircraft manufacturers can adopt to achieve full compliance with the applicable standards of environmental safety. This improvement should include the most critical components in the system, including the turbine and compressor. These critical components are points of high sensitivity relative to the necessary levels of technical progress in terms of specific mass.

- *Economical recommendations*

Future research should assess the possibility of developing globally acceptable standards for airlines to invest in the transformation of engines to minimise emissions and improve efficiency. The development of standards should be an informed process through which different stakeholders can gain an understanding concerning the expected achievements. Research on numerical modelling can help enable stakeholders to make accurate forecasts when developing a plan for change. Change is systematic and occurs in bits until the stakeholders responsible achieve a thoroughly environmentally friendly system.

9.6 Closing Remarks

Numerical modelling in the turbo-electric techno-economic environment assessment is important because it empowers stakeholders intellectually to advance the aviation sector towards a more environmentally friendly and economically viable system. Numerical modelling always enabled reaping significant benefits from the work of developing efficient TeDP systems. Accuracy in uncertainty quantification is one of the greatest

achievements attained through numerical modelling. It also achieved higher precision standards when making predictions and in system cycle optimisation. The benefits of numerical modelling in turbo-electric systems go beyond simple engine modifications because the TeDP can also reap significant benefits from the changes. Numerical modelling can enable carriers to save more space by reducing the take-off airfield length and reducing the amount of fuel expenditure. The use of numerical modelling has significant effects on the improvement of performance and productivity in aircraft. It can lead to the development of efficient engine systems that reduce the need for extensive airfield lengths. In this regard, airlines can use the remaining airfield to construct additional critical services, such as maintenance services. It is therefore prudent to recommend that the industry should adopt new technology developed through numerical modelling to enhance their productivity and growth in TeDP.

9.7 Manuscript Outcomes

As an outcome from the research, prepared and submitted articles for publication as follows:

- M. Alrashed, T. Nikolaidis, P. Pilidis, and S. Jafari, “Turboelectric Uncertainty Quantification and Error Estimation in Numerical Modelling,” *Applied Sciences*, vol. 10, no. 5, p. 1805, Mar. 2020 [Online]. Available: <http://dx.doi.org/10.3390/app10051805>.
- M. Alrashed, T. Nikolaidis, P. Pilidis, W. Alrashed and S. Jafari, “Economical and Environmental Viability Assessment of NASA’s Turboelectric Distribution Propulsion”, *Energy Report*, Submitted.
- M. Alrashed, T. Nikolaidis, P. Pilidis, W. Alrashed and S. Jafari, “Key Performance Indicators for Turboelectric Distributed Propulsion”, *International Journal of Productivity and Performance Management*, Submitted.
- M. Alrashed, T. Nikolaidis, P. Pilidis and S. Jafari, “GridMatch: turboelectric modelling and simulation tool to assess power and propulsion performance”, *IEEE Access*, Submitted.
- M. Alrashed, T. Nikolaidis, P. Pilidis and S. Jafari, “Performance System Simulation of Turboelectric Distribution Power in Civilian Aircraft: A Systematic Review and Meta-analysis”, *Engineering*, Submitted.

- Mosab Alrashed, Theoklis Nikolaidis, Pericles Pilidis and Soheil Jafari, “Method to assess turboelectric distributed propulsion: techno-economic and environmental aspects”, *Method X*, Paper under revision process.
- Mosab Alrashed, Theoklis Nikolaidis, Pericles Pilidis and Soheil Jafari, “Modelling Notation of More Electric to Turbo Electric Propulsion”, in *Journal of Systems and Software*, Paper under revision process.

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