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UNIVERSIDADE Ð COIMBRA

Constâncio António Pinto

Dynamic Modelling for Reliability Analysis of Power Supply Systems in a Large European Hospital by Petri Nets, Fuzzy Inference System, Stochastic or Markov Chains

Doctoral Thesis in Mechanical Engineering, Advanced Production Systems supervised by Professor Doctor José Manuel Torres Farinha (principal supervisor), Professor Doctor Cristovão Silva (co-supervisor) and Professor Doctor Humberto Manuel de Matos Jorge (co-supervisor), presented to the Department of Mechanical Engineering, Faculty of Science and Technology at University of Coimbra Portugal.

March 2022

Faculty of Science and Technology

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COIMBRA

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DECLARATION

I certify that this Thesis entitled "Dynamic Modelling for Reliability Analysis of Power Supply Systems in a Large European Hospital by Petri Nets, Fuzzy Inference System, Stochastic or Markov Chains" was written by me and describes my research work supervised by supervisors unless otherwise stated. Previous researchers have not submitted this work for a degree or other professional qualification.

On behalf of the researcher:

Constâncio António Pinto

Majoring in mechanical engineering

Faculty of Science and Technology

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DEDICATION

For my beloved family: my wife Christiane, my children Graciela, Tobias and little David, who supported this work with love and dedication as a mutual family.

ABSTRACT

The hospital's electricity supply infrastructure, to function correctly, needs to be appropriately maintained to ensure its reliability to achieve maximum availability. The main achievement of this research is the use of Petri Nets (PN) to determine the most critical and sensitive tools in assets. Uses Fuzzy Inference System (FIS) can analyze and determine the percentage of reliability, asset availability, and stochastic versus fuzzy, to investigate assets carefully without "Historical Data Maintenance". It can support the electric power system's operation and maintenance by taking a case study in a large Hospital in Europe. This study aims to identify and analyze possible system failures and propose solutions to improve the reliability and maintenance of operations to maximize the electric power system's availability and reliability. It is necessary to develop a maintenance diagnosis and planning methodology for evaluating several components of the energy supply system. We use dynamic modelling based on the Petri Nets System Block Diagram to analyze and simulate discrete system events and visualize their operating processes and functions. We propose a new design for the electric power system to increase its reliability based on the research results. It can contribute to an idea or design that is more reliable and available for the asset being studied and uses that method for other assets in the future.

Keywords: Reliability; Availability; Maintainability; Petri Nets; Fuzzy Inference System; Stochastic/Markov Chains and Dynamic Modelling.

RESUMO

A infraestrutura de fornecimento de energia elétrica de um hospital, para funcionar corretamente, precisa ser mantida adequadamente para garantir a sua fiabilidade e conseguir a sua máxima disponibilidade. A vertente mais relevante de inovação da presente tese relaciona-se com o uso de Redes de Petri (PN – Petri Nets) para identificar os módulos mais críticos e sensíveis em ativos físicos. O Sistema de Inferência Fuzzy (FIS - Fuzzy Inference System) permite analisar e determinar a fiabilidade e disponibilidade de ativos físicos, na vertente estocástica e Fuzzy, permitindo estudar em detalhe ativos mesmo sem "Dados Históricos de Manutenção", tendo como caso de estudo um grande Hospital na Europa. Esta tese tem como objetivo identificar e analisar possíveis falhas do sistema elétrico e propor soluções para melhorar a fiabilidade e manutenção das operações para maximizar a disponibilidade e fiabilidade do sistema elétrico de potência. Foi desenvolvida uma metodologia de diagnóstico e planeamento de manutenção para avaliação de diversos componentes do sistema de fornecimento de energia elétrica. Foi usada modelação dinâmica baseada na Rede de Petri do Diagrama de Blocos do Sistema, para analisar e simular eventos discretos do sistema e visualizar os seus processos operacionais e funcionais. Com base nos resultados da investigação foi proposto um novo projeto para o sistema elétrico de potência, visando aumentar a sua fiabilidade. Em última instância, visa contribuir para uma ideia de projeto mais fiável e com maior disponibilidade do ativo em estudo, bem como, no futuro, permitir usar o mesmo método para outros ativos.

Palavras-chave: Fiabilidade; Disponibilidade; Manutibilidade; Redes de Petri; Sistema de Inferência Fuzzy; Cadeias Estocásticas/Markov e Modelação Dinâmica.

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LIST OF ABBREVIATION/ACRONYMS

AFBD	- Asset Functional Block Diagram
AHA	- American Hospital Association
AHBD	- Asset Hierarchy Block Diagram
AHP	- Analytic hierarchy process
ANFIS	- Adaptive Network Fuzzy Inference System
APFD	- Asset Process Flow Diagram
ATP	- Automatic Train Protection
ATS	- Automatic Transfer Switch
BCHP	- Building Cooling, Heating and Power
CBM	- Condition Based Maintenance
CBRAM	- Computer-Based Risk Analysis Model
CFPN	- Continuous Fuzzy Petri Net
CM	- Corrective Maintenance
COG	- Centroid of Gravity
CPNTools	- Coloured Petri Nets Tools
CTC	- Centralized Traffic Control
DESs	- Discrete Event Systems
ECSPN	- Extended Coloured Stochastic Petri Nets
EEN	- External Electric Network
EMP	- Main Electric Power
EPSS	- Emergency Power Supply System
FBD	- Functional Block Diagram
FFMEA	- Fuzzy Failure Modes and Effects Analysis
FIPN	- Fuzzy Inference Petri Nets

FIS - Fuzzy Inference System

FMEA - Failure Modes and Effects Analysis

FMECA - Failure Mode Effect and Criticality Analysis

FPN - Fuzzy Petri Nets

FPN-R - Fuzzy Petri Nets based rescheduling model

FTPN - Fuzzy Time Petri Nets

Gensets - Generator Sets

GPFM - Generalized Proportional Failure Rate Model

GSPN - Generalized Stochastic Petri Net

HCPN - Hierarchical Coloured Petri Net

HLFPN -High-Level Fuzzy Petri Net

HPV - Human Papillomavirus

IEEE - Institute of Electrical and Electronics Engineers

LVDB - Low Voltage Distribution Board

MATLAB - Matrix Laboratory

MSI - Maintenance Significant Items

MTBF - Mean Time Between Failure

MTTR - Mean Time to Repair

O&M - Operation and Maintenance

OEE - Overall Equipment Effectiveness

OFS - Operator Functional State

OSHA - Occupational Health and Safety Administration

PdM - Predictive Maintenance

PFD - Process Flow Diagram

PHCN - Power Holding Company of Nigeria

PM	- Preventive Maintenance
PN	- Petri Nets.
PQ	- Power Quality
PS	- Power Supply
PSO	- Particle Swarm Optimization
PT	- Power Transformer
RAMS	- Reliability Availability Maintainability and Safety
RBM	- Risk Based Maintenance
RCA	- Root Cause Analysis
RCM	- Reliability Centred Maintenance
RM	- Reactive Maintenance
RMS	- Reliability Maintainability Supportability
RTF	- Run to Failure
SCBM	- Sustainable Conditions Based Maintenance
SCORM	- Sharable Content Object Reference Model
SinFPN	- Synchronized Fuzzy Petri Nets
SPN	- Stochastic Petri Nets
STPNs	- Stochastic Time Petri Nets
TBM	- Time Based Maintenance
TFPN	-Time Fuzzy Petri Nets
TPM	- Total Productive Maintenance
TPN	- Time Petri Nets
UPS	- Uninterrupted Power Supply.

CHAPTER 1. INTRODUCTION

1.1 Framework

The electric power system plays a strategic function in a major European hospital. Therefore, the managers must have an extreme duty to keep electrical power installations running continuously; if a failure occurs, it may cause dangerous problems for the hospital's activities in the context of its operation. Therefore, the electrical installation system must be designed to keep the system running with maximum availability in the most reliable way. Because of the risky management of this type of physical asset, its maintenance and reliability are strategic. This research aims to improve the reliability and availability of this system using Petri Nets, Fuzzy Inference System (FIS) and Stochastic Time Petri Nets (STPN) to simulate and improve existing systems with a new and more reliable project using CPNTools and MATLAB as simulation tools.

1.2 Research Limitations

This thesis was developed walking a very difficult way, as is described next:

- When I came to Coimbra, the first challenge was the Portuguese language, namely doing the exams and reports of the Curricular Units of the first year of the doctoral program;
- Overcoming this challenge, sometime after starting the research it appeared the Covid-19 pandemic;
- For familiar reasons, it was necessary to move to Germany until the end of the thesis, which corresponded to a big limitation on the research development;

- However this limitation, all difficulties were overcome, and the thesis was finished;
- The next step is to return to my Country, Timor-Leste, to help improve it in the fields of my competencies.

1.3 Research Questions

The objective of this research is to answer the following questions:

- First, which are the system's most sensitive and critical components?
- Second, what is the average reliability of the installed system?
- Third, what are each asset component's contributions related to its operational context?

1.4 Papers published

The results of this research have been successfully published three times in the international scientific journal indexed by Scopus, with the following links:

(1) https://www.wseas.org/multimedia/journals/control/2021/a045103-965.pdf

(2) https://www.mdpi.com/2076-3417/11/6/2604

(3) https://www.mdpi.com/1996-1073/15/3/1024

(4) And it was also presented on:

14th National Congress of Maintenance and 5th Maintenance Meeting of Portuguese Official Language (2017).

1.5 Thesis structure

The structure of this thesis is as follows: the First chapter corresponds to the Introduction; the Second chapter presents the State-of-Art - the maintenance concept, the maintenance for electrical safety system in hospitals, preventive maintenance (PM), corrective maintenance (CM), the reactive maintenance (RM), the run to failure (RTF) maintenance, the predictive maintenance (PDM), the total productive maintenance (TPM), the reliability, availability and maintainability system, the reliability centered maintenance (RCM), the risk-based maintenance (RBM), the condition based maintenance (CBM), the generators, UPS and ATS, as part of the electrical emergency system in hospitals, the Petri nets systems, the fuzzy inference system (FIS), the stochastic time Petri nets (STPNS) and Markov chains, the CPNTools software simulator description; the Third chapter presents the Electrical System of a Large European Hospital - the description of an extensive European Hospital profile, the modelling of the hospital's electrical system using block diagrams, the group of generators, automatic transfer switch and UPS; the Fourth chapter describes the Dynamic Modelling of the Hospital's Electrical System Using Petri Nets, FIS and Stochastic or Markov Chain - the modelling of the hospital electrical system by Petri nets simulator CPNTools, the modelling the hospital electrical system by block diagrams, the modelling and analyzing with fuzzy inference system, the fuzzy logic designer, the membership function editor, the rules of the editor of software, the rules viewer, the surface viewer, the synthesis of FIS, the modelling with Markov chains and stochastic matrixes processes analyzing, the stochastic versus fuzzy process; the Fifth chapter discusses solutions and the results; the Sixth chapter presents the conclusions.

CHAPTER 2. STATE OF THE ART

2.1 The Maintenance Concept

Maintenance is an essential factor for the sustainability of the asset's operating functions and, consequently, its availability and reliability. Maintenance is also a way to mitigate the damages to assets; therefore, the people in charge must be competent in their professional fields. Based on the following citations, this thesis is based on existing norms and relevant research papers relating to maintenance to support new ideas pertinent to further improvement. American Hospital Association (AHA) (1980) mentions that "proper maintenance of the power system is essential to its safety and reliability. The designer can incorporate certain features into the system to make maintenance safer and more comfortable and to make it possible to perform routine maintenance and inspection without dropping essential hospital load". Anderson & Neri (1990) report that "maintenance deals with the specific procedures, tasks, instructions, personnel qualification, equipment and resources needed to satisfy the system maintainability requirement within an actual environment use". According to August (1999), "Maintenance (as defined by 10CFR50.65) aggregates the functions required to preserve or restore safety, reliability, and availability of plant structures, systems, and components". According to the Department of the Army (TM 5-698-2, 2003), "Maintenance is defined as those activities and actions that directly retain the proper operation of an item or restore that operation when it is interrupted by failure or some other anomaly - within the context of RCM, the proper operation of an item means that it can perform its intended function". Farinha (2018) also referred to "the norm NP EN 13306 Maintenance Terminology, maintenance is the combination of all technical, administrative and management actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function". Gulati (2009) states that "Maintenance is concerned with keeping an asset in right working conditions, so that the asset may be used to its full productive capacity. The maintenance function includes both upkeep and repairs". Moubray (1997) states that "Maintenance's role is to ensure that physical assets continue to do what their users want to do". Wang (2012) says that "Maintenance is a function that operates in parallel to production and can significantly impact the capacity of the production and quality of the products produced and, therefore, it deserves continuous improvement". Adekitan *et al.* (2018) report that "maintenance is a critical and vital operational component that determines vehicle performance and service longevity". Dewi *et al.* (2020) report that "maintenance of electrical components in the green building has a more significant correlation or relationship to increase safety performance based on research results than health performance, comfort and convenience". Fatimah and Amin (2019) report that "the implementation of continuity of optimal hospital building maintenance is expected to reduce the incidence of heavier damage and to minimise the cost of existing repair, ensuring the readiness of supporting facilities for the implementation of health services to the public in the hospital". Indriani *et al.* (2020) report that "the development of a green building electrical components maintenance guideline in a web-based information system has shown its capability on improving maintenance work, achieving building reliability requirements". Afzali *et al.* (2019) report that "one of the most important ways to improve the reliability of a distribution system is performing maintenance strategies; on the other hand, the studies of cost/benefit will lead to performing the important maintenance components". Hoseini *et al.* (2020) report that "to achieve reliable and optimised maintenance, the correlation between energy carriers should be considered".

It can consider that maintenance is a management tool to prevent failures in the physical assets, using both planned and non-planned interventions to maintain their valuable lives in charge of the maintenance engineers.

2.2 The Maintenance of Electrical Safety Systems in Hospitals

This thesis discusses the electrical power system maintenance and modelling that supplies a Big European Hospital electricity. Several relevant papers are considered to analyze the maintenance of the electrical system. AHA (1980) states that "the engineering and maintenance department is responsible for ensuring the safe, cost-effective operation and maintenance of hospital facilities and expensive equipment. Organizing this department into a well-disciplined team capable of supporting the hospital is a formidable task regardless of size". Farinha (2018) mentions that "another way of analysing the useful life proposed in (AHA, 1996), based on the knowledge of type parameters of most hospital equipment, which allows establishing the maximum limit of maintenance expenses from the ones it is more economical to replace the equipment than to repair it". Mwanza & Mbohwa (2015) states that "researchers set objectives which were to determine the different maintenance practices used to maintain the hospital's equipment, challenges of these maintenance practices and the effect of maintenance practices on health-care service delivery". Bagnara *et al*. (2010) state that "High-Reliability Organizations (HRO) are complex systems in which many accidents and adverse events that could occur within those systems or at the interfaces with other systems are avoided or prevented. Many organizations in high-risk industries have successfully implemented HRO approaches". Christiansen *et al*. (2015) state, "For the case of hospitals, however, information about the magnitude of electricity consumption caused by the vast amounts of medical equipment is still lacking. Not least, due to the strongly growing use of such electrically operated devices in an increasingly complex environment, electricity has become the major energy cost driver in modern hospitals". Christiansen *et al*. (2016) state that "the measurements presented here offer a more detailed look on the split of electrical energy consumption among some of the most prominent areas in hospital buildings". González *et al*. (2018) state, "The accurate identification of the final energy consumption in hospitals is a key task to determine potential savings and therefore to set appropriate design criteria". Morgenstern *et al*. (2016) "aim to explore how meaningful energy benchmarks reflecting good energy management and design can be constructed for hospital buildings, a category encompassing complex buildings with different setups and large variability between them". IEEE C2 (National Electrical Safety Code, 2007) "is the practical safeguarding of persons during the installation, operation, or maintenance of electric supply, communication lines and associated equipment. These rules contain the basic provisions necessary for the safety of employees and the public under the specified conditions". According to the AHA (1980), "safety requires adequate provision for the protection of life, property, and hospital services continuity. The importance is protecting against possible extensive equipment damage caused by electrical system breakdown". BenSaleh *et al*. (2010) mention that "as more automated hospitals, the more excellent protection against the lack of energy. Hospital systems are increasingly dependent on technology, well-designed emergency energy systems, and the ability to adapt to the changing environments". Jamshidi (2015) mentions that "Risk-Based Maintenance (RBM) is composed of two main components: (1) A comprehensive framework for prioritisation the critical medical devices; (2) A method for selecting the best maintenance strategy for each device". The WHO (World Health Organization) and Pan American Health Organization (2015) mention that promoting "the aims of 'hospitals safe from disasters' by ensuring that all new hospitals aware about the safety will provide them to function in disaster situations and implement mitigation measures to reinforce existing health facilities, particularly those providing primary healthcare”. Ikuzwe *et al*. (2020) mention that “the optimal lighting maintenance plan would save up to 59% of lighting energy consumption with acceptable maintenance costs”. Carnero & Gómez (2017) mention that “there are no models in the literature analysing the choice of the most suitable maintenance strategy to be applied in electric power distribution systems in Health Care Organizations”. Swain & De (2019) mention that “a distribution system connected with smart meters and communication network, capable of monitoring and controlling the individual DERs and loads from a remote location, that can be termed as a smart distribution system”. Chan *et al*. (2020) mention that “the safety concern and volume of Repair, Maintenance, Alteration and Addition (RMAA) works that have significantly increased in recent years; RMAA works include a variety of work trades. Electrical and Mechanical (E&M) works are regarded as the most hazardous trades with numerous complex activities”. Kallambettu & Viswanathan (2018) mention that “the functional safety standard IEC 61511 (IEC, 2016) is applied to the Safety Instrumented System (SIS) protection layers to avoid the undesired events or reduce the likelihood of the events or impacts due to failures in the process, process equipment, or its control system including human interactions”. García-Sanz-Calcedo *et al*. (2017) mention that “the aims to analyse the impact of maintenance management on the energy consumption of a hospital in Extremadura (Spain) and to look for existing relationships between the time spent on maintenance operations and the energy consumption of the building”. García-Sanz-Calcedo *et al*. (2019) mention that “improving energy efficiency in healthcare buildings is a major challenge in this sector of engineering; however, the energy consumption indicator commonly used in public hospitals (kWh per bed) does not take into account the healthcare activity carried out in these buildings". Ismail *et al.* (2020) present "a data-driven method for LM using load characteristics and specifications, according to the type of user, time, and location (load behaviour) studies in arranging the loads to occur load balance to improve the load curve around the electrical network during the whole day". Yousefli *et al.* (2020) mention that "the complex, uncertain, and dynamic nature of the maintenance management environment is a source of concern to facility managers in hospitals due to the unexpected failure of building components, the daily arrival of maintenance orders, and schedule changes; in such circumstances, centralised systems become far-fetched because of their top-down approach, which lacks a feedback mechanism and ignores new information; therefore, to address any change, centralised systems have to be reformulated, making it impractical, short-sighted, and problematic to adopt them in hospitals". Yuan (2020) mentions that "the process of continuous development of electrical automation technology, power companies implement state maintenance of relay protection equipment to avoid the drawbacks in traditional maintenance methods to achieve the purpose of extending the service life of relay protection equipment". Fatimah & Amin (2019) mention that "the implementation of continuity of optimal hospital building maintenance is expected to reduce the incidence of heavier damage and minimise the cost of existing repair and to ensure the readiness of supporting facilities for the implementation of health services to the public in the hospital".

2.3 Preventive Maintenance (PM)

As the name implies, in preventive maintenance, the users must carry out their maintenance to avoid damage or interruptions in the assets, complying with the manufacturers' recommendations, the installation commissioning, and the rules of the conventions and the applicable regulations; its mission is to control or manage the Time-Based Maintenance and Condition-Based Maintenance of the assets, like the following citations: Amaral (2016) mentions that “maintenance carried out according to predetermined criteria, to reduce the probability of a good's failure or the degradation of a service rendered”. American Hospital Association (AHA, 1980) mentions that “specific minor and repetitive work becomes cumbersome if Working Orders write for each assignment”. Anderson & Neri (1990) mention that “Preventive Maintenance is performed to retain a system in a satisfactory in operational condition by inspection, and subsequent repair or replacement, and by scheduled overhaul, lubrication, calibration, etc.". According to August (1999), “Preventive Maintenance is the traditional term for scheduled maintenance (10CRF50.65). Predictive, periodic, and planned maintenance actions are taken before failure to maintain Structures, Systems and Components within design operating conditions by controlling degradation or failure.” According to Bloom (2006), “Preventive maintenance is the strategy designed to prevent an unwanted consequence of failure. This strategy could be directed at preventing failures at the component level, or it could be designed for preventing failures directly at the plant level”. Farinha (2018) states that “preventive maintenance carried out at predetermined intervals or according to prescribed criteria to reduce the likelihood of damage or degradation of the operation of an asset”. Gulati (2009) points out that “Maintenance Preventive (PM) a maintenance strategy based on inspection, component replacement, and overhauling at a fixed interval, regardless of its condition at the time. Usually, scheduled inspections are performed to assess the condition of an asset”. Levitt (2003) mentions that “PM is a series of tasks performed at a frequency dictated by the passage of time, the amount of production (cases of beer made), machine hours, mileage, or condition (differential pressure across a filter) that either: Extend the life of an asset; Detect that an asset has had critical wear and is about to fail or break down". According to Nakajima (1989), "Preventive Maintenance is the periodic inspection to detect a condition that might cause breakdowns, production stoppages, or detrimental loss of function combined with maintenance to eliminate, control, or reverse such conditions in their early stages; in other words, preventive maintenance is the rapid detection and treatment of equipment abnormalities before they cause defects or losses". Smith & Hinchcliffe (2004) refer that "Preventive maintenance is the performance of inspection and/or servicing tasks that have been preplanned (i.e., scheduled) for accomplishment at specific points in time to retain the functional capabilities of operating equipment or systems". Wireman (1998) mentions that the "PM program is the key to any successful asset management process. The PM program decreases the amount of reactive maintenance to a level low enough that the other initiatives in the asset management process can be useful".

2.4 Corrective Maintenance (CM)

Amaral (2016) refers that "corrective maintenance performed after failure. If the intention of the corrective intervention is definitive, the intervention is called "curative". Anderson & Neri (1990) mention that "Corrective Maintenance is performed to restore an item to a satisfactory condition after failure or after its performance has degraded below that which was specified". According to August (1999), "Corrective Maintenance is a combination of condition-directed, condition-based no-scheduled maintenance but has never been differentiated". According to Bloom (2006), "Corrective maintenance is an integral part of the bigger picture of a preventive maintenance program". Farinha

(2018) states that “corrective maintenance is carried out after the detection of a fault and intended to restore an asset to a state in which it can perform a required function”. Gulati (2009) refers to “the repair actions initiated resulting from observed or measured in an asset after or before the functional failure”. Smith and Hinchcliffe (2004) refer that “Corrective maintenance is the performance of unplanned (i.e., unexpected) maintenance tasks to restore the functional capabilities of failed or malfunctioning equipment or systems”.

Corrective Maintenance is carried out after failure, when damage and disruptions occur improperly, based on operational time and the conditions in which the assets work. Thus, users can correct problems as requested, such as replacing existing materials with better materials or redesigning appropriate forms to ensure users' satisfaction or makers of the assets themselves in a mutually beneficial way.

2.5 Reactive Maintenance (RM)

Gulati (2009) refers to “the activity carried out to fix an asset in response to failure or breakdown. When it is performed in emergency mode, it may cost 3-5 times more”.

A highly undesirable action is reactive care when the user carries out the asset that does not pay attention to the element of care or, in other words, the damaged assets are just about to act; it can also be said to be late acting, and the assets have been damaged.

2.6 Run To Failure (RTF) Maintenance

August (1999) states, “Run to Failure is a misnomer, a term intended to summarize the no scheduled maintenance aspect of many planned maintenance tasks. Misleading because virtually none of these tasks result in functional failure". According to Bloom (2006), "Corrective maintenance is an integral part of the bigger picture of a preventive maintenance program". Gulati (2009) refers to a "management strategy that permits a specific failure mode to occur without any attempts to prevent it. A deliberate decision based on economic effectiveness". Smith and Hinchcliffe (2004) refer that, "as the name implies, we make a deliberate decision to allow equipment to operate until it fails. No preventive maintenance of any kind is ever performed. Rather, the maintenance action occurs after the failure has occurred".

Run To Failure (RTF) is a definition that addresses goods that cannot be repaired but are maintained so that their usefulness reaches the time specified by the manufacturer, such as light bulbs, filters, gaskets, etc.

2.7 Predictive Maintenance (PdM)

American Hospital Association (AHA, 1980) also mentions that "predictive maintenance, scheduled maintenance repairs, project repairs, programmed repairs, and budgeted repairs are descriptive titles for the same function. This function is concerned with repairs rather than maintenance". According to August (1999), "Predictive Maintenance to diagnose a condition and predict future maintenance requirements. They are gradually being supplanted by conditions directed. On-condition terminology". Farinha (2011) designates "it as the conditional maintenance carried out according to the extrapolated forecasts of the analysis and evaluation of significant parameters of the degradation of the good". According to Bloom (2006), "Predictive maintenance (PdM) is a subset of condition-directed maintenance. It includes using mostly non-intrusive technologies to monitor equipment for precursors to failure. Predictive maintenance techniques are used to determine the condition of the equipment so that incipient failures can be detected and required overhaul or replacement that can be scheduled to preclude the occurrence of a functional failure". Levitt (2003) mentions that "PdM is the proclamation or declaration in an advanced base on observation to preserve (something) from failure or sustain it against danger". Wireman (1998) mentions that "once the operational involvement has freed the maintenance and engineering resources, they should refocus on the predictive technologies that apply to the assets. For example, rotating equipment is a natural fit for vibration analysis, electrical equipment for thermography, and so forth".

Predictive maintenance permits predicting an asset's maintenance, namely what must be done in the future about the things that might occur. It needs reasonable anticipation, especially regarding failure.

2.8 Total Productive Maintenance (TPM)

Cabral (2006) states, "TPM actively cultivates maintenance of improvement and moves the centre of gravity of the preventive maintenance a bit more towards the side of machine operators". Farinha (2018) states, "TPM can be considered a system for maintaining and improving the integrity of production and quality systems through equipment and employees that add business value for an organization". Nakajima (1982) refers that "Total Productive Maintenance (TPM), often defined as productive maintenance implemented by all employees, is based on the principle that equipment improvement must involve everyone in the organization, from line operators to top management". Wireman (1998) mentions that "TPM is an operational philosophy that everyone in the company understands, in some way, and their job performance impacts the performance of the assets. For instance, operations must understand the equipment's real capacity and not run it beyond design specifications, creating unnecessary breakdowns”.

Total Productive Maintenance involves all entities that work on the asset responsible for the maintenance issue because it has rights, responsibilities and ownership rights on the assets.

2.9 Reliability, Availability, Maintainability and Safety

Every asset corresponds to Reliability, Availability, Maintainability and Safety (RAMS). Therefore, the users need a more profound understanding to maintain the functionality of the assets to produce optimally. A more comprehensive mathematical analysis is required to implement a better Reliability, Availability and Maintainability System (RAMS). All decisions and activities that will carry out are more accurate to satisfy the asset’s users. Therefore, in the science of Reliability, Availability and Maintainability systems, a graph is the "Bathtub Curve", as shown in Figure 2.1.

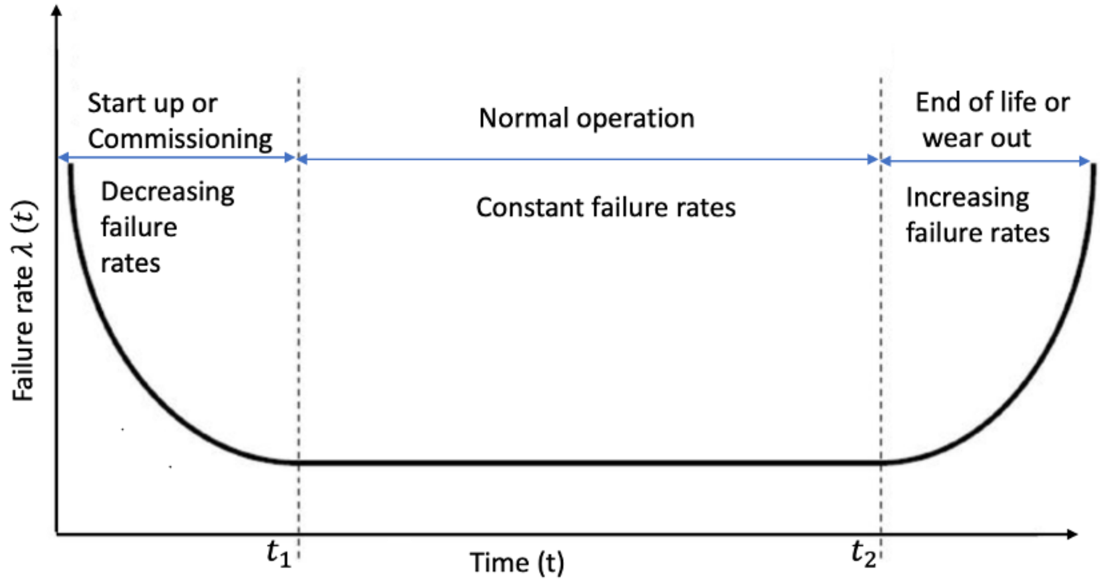


Figure 2.1 *The reliability of the "Bathtub Curve"*

The graph shown in Figure 2.1 has three parts:

- Infant mortality or decreasing failure rate, known as early failures;
- Useful life with a constant failure rate or random failures;
- Wear-out or increasing failure rates or wear-out failures.

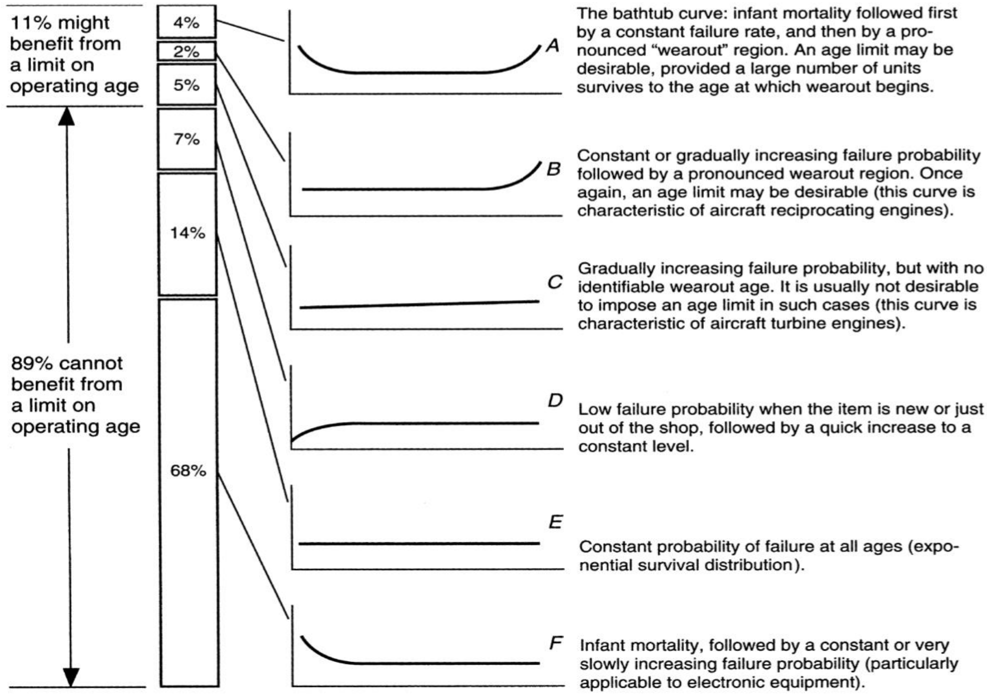


Figure 2.2 *Age-reliability patterns for nonstructural equipment (Smith, 2004)*

The device's failure generally follows the bathtub curve shape in Figure 2.1, but not all devices fail according to the bathtub curve shape, as shown in Figure 2.2.

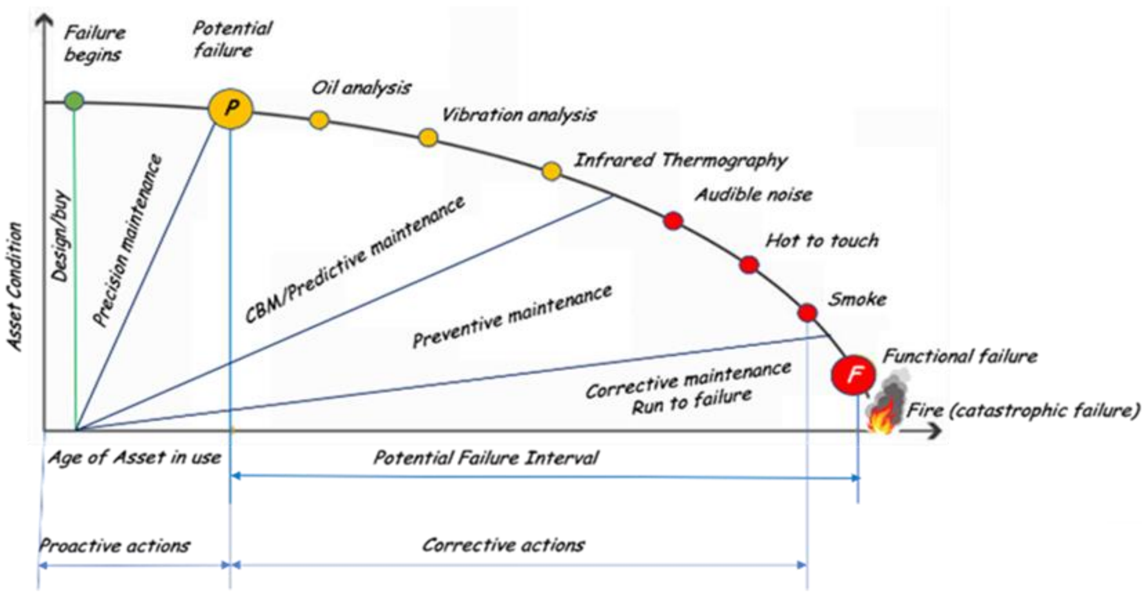


Figure 2.3 *The Potential Failure Curve (Smith, 2004)*

Figure 2.3 shows how assets start falling until the end of disaster failure; it can see data about the graphical behaviour that, when beginning asset installation or commissioning, it can be said that, to start the various types of failures, the nature of handling also varies; however, special attention needs to be paid to the point of Potential Failure to avoid fatal accidents. It is necessary to keep in mind the meaning of potential failure. According to Moubray (1997), “a potential failure is an identifiable condition that indicates that a functional failure is either about to occur or occur”. Smith (2004) mentions that “failure is the inability of a piece of equipment, a system, or a plant to meet its expected performance”. Sifonte & Picknell (2017) mention that “failure: is the termination of an item's ability to perform its required function to the desired standard”. From this graphical understanding, we derive some statistical formulas to ensure statements of reliability and availability become real numbers to be implemented by the wishes of the asset users. Therefore, the following formulas are essential to understanding the science of reliability, availability and maintainability techniques.

Reliability, in terms of a useful life system, can be described by Formula (1):

$$R(t) = e^{(-\lambda t)} \qquad (1)$$

Where,

R*(t)* is the Reliability, i.e., the probability of the system still working since starting its mission

t is the mission time, in hours, cycles, miles, etc.

e is the natural logarithm = 2.71828

λ (lambda) is a constant failure rate = 1/MTBF (Mean Time Between Failures)

$$MTBF = \frac{Operating\ Time}{Number\ of\ Failures} = \frac{\sum_{i=0}^{n} TBF_i}{n} \quad (2)$$

$$MTTR = \frac{Total\ Repair\ Time}{Number\ of\ Failures} = \frac{\sum_{i=0}^{n} TTR_i}{n} \quad (3)$$

Where,

MTBF = Mean Time Between Failure

MTTR = Mean Time to Repair.

The Availability is evaluated according to Formula (4):

$$A = \frac{Uptime}{Uptime+Downtime} = \frac{MTBF}{MTBF+MTTR} \quad (4)$$

We have patterns like λ (failure rate) and μ (repair rate) related to those formulas.

The failure rate is given by Formula (5):

$$\lambda = \frac{1}{MTBF} \quad (5)$$

And the repair rate is given by Formula (6):

$$\mu = \frac{1}{MTTR} \quad (6)$$

Although the above formulas are already available, it is not enough because each asset or equipment is installed in series or parallel depending on the design according to its requirements.

A Reliability Block Diagram in the Series system is shown in Figure 2.4.

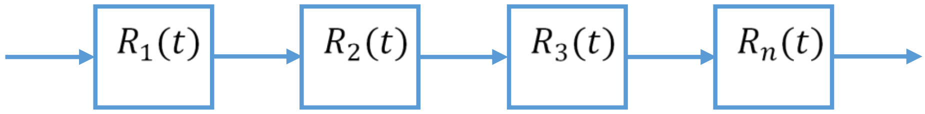


Figure 2.4 *Block Diagram in Series system*

Where:

$$R_{system(t)} = R_1(t) \times R_2(t) \times R_3(t) \ldots \times R_n(t) \quad (7)$$

If the components have exponential failure probabilities with the corresponding failure rates, $\lambda 1$, $\lambda 2$, $\lambda 3$, and so on, then the system Reliability is given by Formula (8):

$$R_{system} = e^{-\lambda_1 t} \times e^{-\lambda_2 t} \times e^{-\lambda_3 t} \times \ldots \times e^{-\lambda_n t} = e^{-(\lambda_1+\lambda_2+\lambda_3+\cdots+\lambda_n)t} \quad (8)$$

The sum ($\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_n$) is constant. It is the composite failure rate of the series system.

From the system failure rate l, the Mean Time Between Failures of the system can be calculated by Formula (9):

$$\mathrm{MTBF}system = \frac{1}{\lambda} \quad (9)$$

A Reliability Block Diagram in a Parallel system is shown in Figure 2.5.

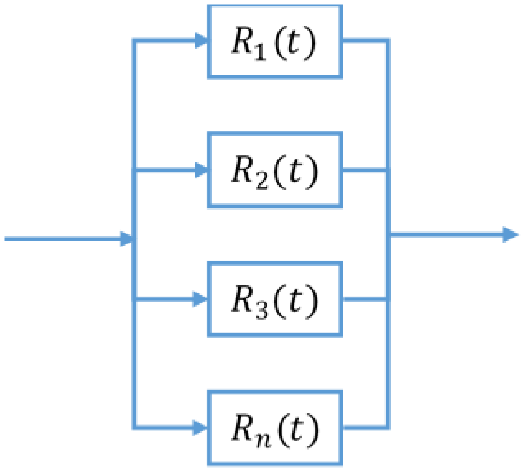


Figure 2.5 *Block Diagram in Parallel system*

Where,

R $_{system}$ = $1 - (1 - R_1(t)\ (1 - R_2(t)\ (1 - R_3(t)\ (1 - R_n(t)$ (10)

Or

R $_{system}$ = $R_1(t) + R_2(t)\ + R_3(t) + R_n(t) - R_1(t) \times R_2(t)\ \times R_3(t) \times R_n(t)$ (11)

Or

R $_{system}$ = $e^{-(\lambda 1)t} + e^{-(\lambda 2)t} + e^{-(\lambda 3)t} + e^{-(\lambda n)t} - e^{-(\lambda 1+\lambda 2+\lambda 3+\lambda n)t}$ (12)

Maintenance, reliability, and availability are essential tools to prevent failures, damages, and delays in the production processes and services in terms of time, costs, and systems' performance. The quality management effort for internal and external customer satisfaction, guided by the international norms and world conventions, takes advantage of the research relating to hospital physical assets to support new ideas relevant to further improvement, as the following authors described. According to Anderson and Neri (1990), "Reliability is the probability that a hardware item will satisfy its performance requirements for a specified time interval under operational conditions. Availability is the probability of a hardware system or component item being in service when required. Maintainability is defined as the probability that a hardware item will be retained in, or restored to a specified operating condition, within allowable time limits, using available test equipment, facilities, personnel, spare parts and prescribed procedures". According to Smith (2005), "Reliability is the probability that an item will perform a required function, under stated conditions, for a stated period. Maintainability is the probability that the failed item will be restored to operational effectiveness within a given period when prescribed procedures perform the repair action. Availability is the proportion of time that an item is capable of operating to specification within a large time interval". According to Gulati and Smith (2009), "Reliability, as defined in the military standardMIL-STD-721C, is the probability that an item will perform its intended function for a specific interval under stated conditions. Maintainability is the measure of an item or asset's ability to be retained in or restored to a specific condition when maintenance is performed by a person having specified skill levels, using prescribed procedures and resources at each stage of maintenance and repair. Availability is a function of reliability and maintainability of the asset". According to Smith and Hinchcliffe (2004), "Reliability is the probability that a device will satisfactorily perform a specified function for a specified period under given operating conditions. Availability is a measure of percentage (or fraction) of time that a plant is capable of producing its end product at some specified acceptable level". According to August (1999), "Availability is the period that a unit is available to be dispatched for generation, whether it is or not. Expressed as a fraction of calendar time. Maintainability is the capacity to maintain equipment. The design considers maintenance to provide access, turnaround, tools, and other support requirements of facilities maintenance. Reliability is the ratio of successful missions to total trials". American Hospital Association (AHA, 1980) mentions that "hospital activities are continuous and highly integrated, requiring the highest degree of service continuity. Other types of activities can tolerate momentary or even short-time outages without difficulty. Service reliability depends on adequate, modern system equipment, properly installed and maintained, and correctly chosen power system circuit arrangements". Aksu & Turan (2006) state that "a reliability methodology applicable to a pod propulsion system has been developed. The quantitative reliability assessment has been carried out for a generic pod propulsion system, consisting of two rotating pod units that provide steering and thrust and two fixed pod units that provide thrust only. Failure Mode and Effects (FMEA) has been utilized in the developed methodology". Ali *et al.* (2019) state that "to develop a safety and profitable process, uncertainty quantification is necessary for reliability, availability, and maintainability analysis. Aries Velásquez *et al.* (2019) state "a reliability model based on information available in the maintenance system – driven framework using both classical and Bayesian methodologies". Buss *et al.* (2019) state, "Analysis of the majority of road accidents demonstrates that the weakest part of human-machine Driver Automobile Road Environment system limiting its efficiency and reliability is a human. To provide necessary reliability and safety, the driver of any vehicle has to be cautious". Calixto (2016) states that "reliability, availability, and maintainability (RAM) analysis is the basis of complex system performance analysis. The analysis steps, such as scope definition, lifetime data analysis, modelling, simulation, critical analysis, sensitivity analysis, and conclusions, will be discussed to demonstrate such methodologies". Çekyay & Özekici (2015) state that "analyse system reliability, mean time to failure, and steady-state availability as a function of the component failure rates. Our primary objective is providing explicit expressions for these performance measures and obtain various characterizations on their mathematical structures". Chen & Mehrabani (2019) state that "the reliability analysis is then employed to evaluate optimum inspection and maintenance solutions using a multi-objective optimization method". Corvaro *et al.* (2017) state that "the complex of RAM factors constitutes a strategic approach for integrating reliability, availability and maintainability, by using methods, tools and engineering techniques (Mean Time to Failure, Equipment down Time and System Availability values) to identify and quantify equipment and system failures that prevent the achievement of the productive objectives". Ebeling (2010) refers that, "Reliability is defined to be the probability that a component or system will perform a required function for a given period when used under state operating conditions"; "Maintainability is defined to be a probability that a failed component or system will be restored or repaired to a specified condition within a period when maintenance is performed by prescribed procedures and Availability is defined as the probability that a component or system is performing its required function at a given point in time when used under state operation condition". Ekisheva & Gugel (2015) state, "The North American Electric Reliability Corporation uses transmission equipment inventory and outage data to analyse outage trends to assist in identifying significant reliability risks to the Bulk Power System". Eti *et al*. (2007) state that, "Reliability, availability, maintainability and supportability, as well as the risk analysis, have become significant issues in the power industries. Significant causes of customer dissatisfaction often result from unexpected failures, which have led to unanticipated costs in the Afam thermal power-station". Feng *et al*. (2011) state that "many problems have existed in synthesis design of Reliability, Maintainability, Supportability (RMS) and performance, such as RMS design activities are numerous and optional, variable feedback branches can satisfy same RMS requirement, some iteration among RMS and Performance activities is necessary, and many uncertainties exist in the design process". Hairong Sun *et al*. (2003) state that "the availability of the fault management server does not need to be 99.999% to guarantee a 99.999% system availability, as long as the fail-safe ratio (the probability that the failure of the fault management server does not bring down the system) and the fault coverage ratio (the probability that the failure in the system can be detected and recovered by the fault management server) is sufficiently high". Jiang *et al*. (2012) state that "Reliability and availability have always been essential characteristics of systems, but become even more critical and complex issues on networks. Due to the high complexity of accurate calculation methods, simulation methods for network reliability and availability evaluation have been a popular area of research and received significant attention". Lee *et al*. (2019) state that "when using conventional fault trees, the reliability of a system with dynamic characteristics cannot be evaluated accurately because the fault trees consider the reliability of a specific operating configuration of the system". Liang *et al*. (2015) state, "Mission reliability and inherent availability are important reliability parameters of a warship; these parameters do involve not only factors of reliability, but also those of maintainability. Therefore, extensively used reliability allocation methods cannot address the reliability allocation of warships". Postnikov *et al*. (2018) state that "the use of two reliability indices (probability of failure-free operation and availability factor) to determine the reliability parameters of components resolves a system conflict of the reserve, which consists of the contradiction that arises with increasing reliability of emergency supply of by adding redundant elements that in the same time reduce the reliability of rated (expected) level supply due to the increasing number of components that can fail". Rajpal *et al*. (2006) state that, "Neural network approach has been used in the present study to analyse the reliability, availability and maintainability of a complex repairable system. A general model has been proposed, and the technique has been illustrated through a specific application, namely a helicopter transportation facility". Ritchie & Brouwer (2018) state that "alternative uses multiple fuel cell systems, each supporting a small number of servers to eliminate backup power equipment providing that the fuel cell design has sufficient reliability and availability. Potential system designs are explored for the entire data centre and individual fuel cells. Reliability block Diagram analysis of the fuel cell systems was accomplished to understand the systems' reliability without repair or redundant technologies". Roubos *et al*. (2018) state that "the extent to which a reliability problem is time-variant affects the present value of future failure costs and the associated reliability optimum. Therefore, a method was developed to determine the influence of time-independent variables on the development of failure probability over time". Safie *et al*. (2014) state, "Reliability and Maintenance are exceptionally critical to building safe, reliable, and cost-effective systems. The challenges of today's unmanned and manned space flight programs demand the most efficient use of our technical knowledge base to develop cost-effective and affordable systems". Shan *et al*. (2017) state that "the dynamic reliability evaluation is more accurate and realistic than the conventional reliability approach with assumptions. During the heating season, both reliability and availability possess ladder growth patterns as outside temperature increases, which is significantly different from the traditional reliability evaluation of heating networks as the traditional reliability indices are irrelevant to the outside temperature and keep constant during the whole heating season, which can't reflect the changeability of reliability and availability". Shen *et al*. (2019) mention that "to describe the system performance, system availabilities including immediate availability and limiting average availability, and some time distributions of interest are important indexes. Then, the problem of optimal maintenance policy is formulated by considering constraints of availability and operating times". Sikos & Klemeš (2010) state that "the proposed methodology focuses on Heat Exchanger Network (HEN) maintenance through the influence of availability and reliability rather than the optimization of cleaning schedules only. It has been shown that the failure analysis can predict heat exchanger bundle replacement times, leading to significant savings,". Sinha *et al*. (2019) state, “proposing a unified model to predict the worst-case achievable reliability/availability of the hardware-software combined system at early design phases. The proposed model identifies system functions from the requirements specification document”. Song & Wang (2013) state, “a comprehensive review of reliability assessment and improvement of power electronic systems from three levels: 1) metrics and methodologies of reliability assessment of existing system; 2) reliability improvement of an existing system using algorithmic solutions without change of the hardware; and 3) reliability-oriented design solutions that are based on the fault-tolerant operation of the overall systems”. Sutton (2015) states that “Reliability, Availability and Maintainability programs are an integral part of any risk management system. Techniques possess many similarities to those used for safety”. Tian *et al*. (2012) state that “based on the principles of reliability and maintainability, a type of gunfire control system was taken as the research object. The method of combining the system composition character with the system reliability index allocation model was used to realize system reliability”. Wang *et al*. (2013) state, “Failure of a component in Building, Cooling, Heating and Power (BCHP) system may fail a sub-system or of the whole system. The reliability and availability analysis of the BCHP system helps the designer decide the redundancy in equipment failure. The authors present the redundant design of BCHP system and its operation mode”. Wang *et al*. (2018) refer to “An approximation model proposed to deal with kinematic reliability problems of steering mechanisms. Compared to available reliability methods in the literature, results have demonstrated high accuracy of the proposed method for various kinematic reliability problems”. Yang & Tsao (2019) state that “provided the reliability and availability analysis of a repairable system with standbys, working vacations, and retrial of failed components. The matrix-analytic method was used to compute steady-state availability”. Yu *et al*. (2007) refer that “in a multi-component system, the failure of one component can reduce the system reliability in two aspects: loss of the reliability contribution of this failed component, and the reconfiguration of the system, e.g., the redistribution of the system loading. The system reconfiguration can be triggered by the component failures and by adding redundancies". Zafiropoulos & Dialynas (2005) state that "reliability assurance activities are becoming an essential part of electronic devices' design. The authors present a reliability analysis methodology consisting of a reliability prediction methodology and a subsequent fuzzy FMECA methodology". Zanotti *et al.* (2017) state that "integrating a Reliability and Maintainability (RAM) Scrum Team as part of the Agile product development can help deliver reliable and maintainable hardware quicker and at a lower cost providing a competitive advantage. In summary, it helps to enable a transformational change". Zio *et al.* (2019) refer to "reliability engineering in the modern civil aviation industry, and the related engineering activities and methods. They consider reliability in a broad sense, referring to other system characteristics that are related to it, like availability, maintainability, safety and durability". Maruyama *et al.* (2018) mention that "Availability is an important factor in fusion reactor remote-handling systems. There are several specific characteristics in availability for remote-handling systems in fusion reactor applications". Qiu et al. (2017) mention that "availability and optimal maintenance policies are considered for a competing-risk system subject to multiple failure modes. Inspection-based maintenance policies are adopted. The authors derive the analytical results on the immediate availability and steady-state availability for maintained competing-risk systems". Martin *et al.* (2016) mention that "Operation and Maintenance (O&M) costs are estimated to account for 14% to 30% of total Offshore Wind Farm (OWF) project lifecycle expenditure according to a range of studies. In this respect, identifying factors affecting operational costs and availability is vital for wind farm operators to make the most profitable decisions". Antosz & Ratnayake (2019) mention that "The forecasting of intermittent demand for spare parts is a challenge, as it is not always possible to avoid random unforeseen breakdowns, which reduce availability and increase the unreliability of manufacturing systems". Perez-Gonzalez & Finan (2018) mention that "the problem of scheduling jobs on a single machine with cyclical machine availability periods. In this problem, the scheduling horizon is composed of periods where the machine is available, followed by other periods where no operation can be performed". Jin *et al*. (2010) mention that "One of the most important challenges to overcome is how to balance maintenance of the system and the global system availability. In this paper, a novel mechanism is proposed, the Cobweb Guardian, which provides solutions not only to reduce the effects of maintenance but to remove the effects of dependencies on system availability due to deployment dependencies, invocation dependencies, and environment dependencies". Van *et al*. (2012) mention that "to construct an optimal maintenance planning with a given availability constraint under limited repairmen. Thanks to the rolling horizon spirit, the maintenance planning can be updated to consider short-term information that could be changed with time". Gunadi (2015) "proposes a qualitative system dynamics model to elucidate complex feedback relationships between e-government website maintenance, staff management, and organizational collaboration which eventually influence or are influenced by the dynamic level of website availability". Choi & Chang (2016) state that "the concept of subsea production systems with a seabed storage tank provides an alternative to conventional floating facilities and performs the reliability, maintainability and availability study for the seabed storage tank". According to Smith & Hinchcliffe (2004), "Reliability is the probability that a device will satisfactorily perform a specified function for a specified period under given operating conditions. Availability is a measure of the percentage (or fraction) of time that a plant is capable of producing its end product at some specified acceptable level". Shen *et al*. (2019) mentioned that "to describe the system performance, system availabilities including immediate availability and limiting average availability, and some time distributions of interest are important indexes. Then, the problem of optimal maintenance policy is formulated by considering constraints of availability and operating times". Do *et al*. (2015) proposed and showed "how to optimize a dynamic maintenance decision rule on a rolling horizon? The heuristic optimization scheme for the maintenance decision is developed by implementing two algorithms (genetic algorithm and MULTI FIT) to find optimal maintenance planning under both availability and limited repairmen constraints".

From the dynamics of various opinions regarding reliability, availability, and maintenance, it is essential to pay close attention to these variables to ensure the production industry's successor service satisfies customers.

2.10 Reliability Centred Maintenance (RCM)

Anderson & Neri (1990) state that "RCM is based on the premise that more efficient lifetime maintenance and logistic support programs can be developed using a well-disciplined decision logic analysis process that focuses on the consequences of failure and the actual preventive maintenance tasks". August (1999) "defines RCM as follows: it is a maintenance perspective in the operational context - understanding plant goals, needs and equipment (e.g., how to meet the equipment, age and failures) and, then, develop a strategy to optimize results in the context of your goals". August (2005) "notes that RCM is a process of developing maintenance plans, a risk management process, providing a specialized support system that identifies different ways in which the equipment can fail, and the implementation symptoms fail, not a technology-specific maintenance method or a service method that encompasses both". Bloom (2006) states that "RCM has the following definition: "A set of tasks generated from a systematic evaluation, is used to develop or optimize a maintenance program. RCM incorporates the decision logic to determine the safety and operational consequences of failures and identifies the mechanisms responsible for those failures". Carretero *et al*. (2003) state that "the problem of applying RCM to large scale railway infrastructure networks to achieve an efficient and useful maintenance concept. Railways use nowadays very traditional Preventive Maintenance (PM) techniques, relying mostly on 'blind' periodic inspection and the 'know-how' of maintenance staff". Crocker and Kumar (2000) refer that "Reliability Centred Maintenance (RCM) is a procedure carried out as part of the Logistic Support Analysis (LSA) process described in the US Department of Defence Military Standards (Mil-Std 2173)". Dehghanian *et al*. (2013) "uses a comprehensive three-stage algorithm to present the essential prerequisites, implementation steps, and post-analysis of the RCM procedure. This two-paper set brings new facts to light in the identification of system-critical components. They show that reliability indices and their variations effectively contribute to the component criticalities". The Department of the Army, TM 5-698-2 (2003), states that "while the RCM focuses on identifying preventive maintenance actions, corrective actions identified by a standard. That is, when no effective or enforceable preventive action for a particular item, that item is doomed to failure (assuming security is not in question)". Deshpande and Modak (2002) refer, "the reliability centred maintenance offers the most systematic and efficient process to address an overall programmatic approach to the optimization of plant and equipment maintenance". Eisinger & Rakowsky (2001) refer that, "the discussion above and especially the analysis of the illustrative are detection and extinguishing system clearly show that probabilistic RCM is superior to traditional "YES/ NO" decision making".

Farinha (2011) mentions that “RCM has become a new paradigm in maintenance activity. It corresponds to an industrial management approach focused on identifying and establishing maintenance improvement and capital investment policies, leading to risk management of Type equation here, equipment failures more effectively”. Gulati (2009) refers to “RCM as a systematic, disciplined process to establish the appropriate maintenance strategies for an asset/system in its operational context, to ensure the safety, the fulfilment of the mission and function of the system”. Gupta & Mishra (2018) refer, “Identifying critical components and their prioritization for implementation of maintenance is an important task in the industry. It is also one of the essential steps of RCM”. Hansen (2012) says that “RCM is a process used to determine, systematically and scientifically, what can be done to give confidence so that the environmental organization continues to function and does what the users want to do”. Heo *et al*. (2014) refer to “an RCM model, based on a component state model and an impact model, to find the optimal maintenance strategy for various kinds of ageing the components in a transmission system”. Igba *et al*. (2013) refer that, “RCM is a way of capturing the potential causes of downtime and poor performance by preventing failures and having a proactive approach to Operations and Maintenance (O&M”. Melani *et al*. (2018) state that “evolution from the consolidated RCM models is something that quite a few experts have been pointing out for quite some time now. Various authors are frequently considering adding different techniques in an RCM analysis to increase its efficiency and quality”. Mkandawire *et al*. (2015) refer that “it is usually challenging to assess the effectiveness of the RCM at its inception, when data is inadequate or when it is implemented on a large population of assets, especially when most of them are small in size as in the distribution systems”. Mokashi *et al*. (2002) refer that, “There is appreciation amongst both classification societies and equipment suppliers of the principles of RCM in the maritime industry”.

Moubray (1991) states that "RCM is a process to determine what must be done to ensure that any physical asset continuous to do what its users want in its operational context. The RCM process entails asking seven questions about that asset or system under review, as follows:

What are the asset's functions and associated performance standards in its present operating context?

In what ways does it fail to fulfil its functional failures?

What are the causes of each functional failure?

What happens when each failure occurs?

In what way does each failure matter?

What can be done to predict or prevent each failure?

What should be done if a suitable proactive task cannot be found?".

As Mourbay (1991) says, "the following RCM tables should be taken into account:

Function, Functional Failure, Failure Mode and Effect Analysis;

RCM Decision Worksheet or Logic Tree Analysis;

A check sheet for high-frequency maintenance Schedules".

Navarro *et al*. (2019) state that "in the context of a Reliability-Based Maintenance optimization on both life cycle costs and life cycle environmental impacts. Maintenance optimization results in significant reductions of life cycle impact if compared to the damage resulting from performing the maintenance actions when the end of the structure's service life is reached". Nowlan & Heap (1978) report that "Reliability Centred Maintenance terminology is related to the maintenance plan to be implemented. This fundamental principle of RCM is like a logical decision to think about the questions that often arise to know the nature of equipment failures, namely:

How did failures happen?

What is the consequence of failure?

Can preventive maintenance be applied for prevention?"

Rahmati *et al.* (2018) state that "RCM takes benefit of stochastic Condition Based Maintenance (CBM) approach that works based on the offensive stochastic scheme of machines during their process time". Regan (2012) states that "the concept of Reliability Centred Maintenance lends itself to a process used to develop proactive maintenance for an asset, but RCM can also be used to formulate dozens of solutions that go well beyond maintenance". Rausand (1998) reports that "RCM is a technique for the development of a PM program. Based on the assumption that the equipment's inherent reliability is a design and build quality function. An effective PM program will ensure that the inherent reliability is realized". Sainz & Sebastián (2013) refer that "the maintenance tasks would be achieving a good condition state of the equipment through the good implementation of RCM, added to the FMECA and Root Cause Analysis (RCA) techniques, the mathematical modelling, Condition Monitoring Systems (CMS) and measuring results through Overall Equipment Effectiveness (OEE), it makes possible to find and eliminate the causes of failures and anomalies, trying to achieve zero failure and the maximum operational readiness". Selvik & Aven (2011) state, "Reliability Centred Maintenance (RCM) is a well-established analytical method for preventive maintenance planning. As its name indicates, reliability is the main point of reference for planning. Still, the consequences of failures are also assessed". Siqueira (2006) refers that "based on the RCM structured approach, a set of information artefacts and probabilistic data are derived as necessary for the correct application of the methodology". Tang *et al.* (2017) refer that, "Identification of Maintenance Significant Items (MSI) is one of the key phases of the Reliability Centred Maintenance (RCM), which is a screening phase where the number of items for analysis is reduced". Jaarsveld & Dekker (2011) refer that, "in an attempt to overcome this problem, propose using the data gathered in RCM studies to determine shortage costs, discussing the benefits of this approach”. Vishnu & Regikumar (2016) refer that “RCM is a recently evolved maintenance strategy that incorporates all the advantages of traditional maintenance strategies. More precisely, RCM selects the most appropriate and tailor-made maintenance strategy for all the equipment in the plant-based on its criticality score and reliability parameters”. Wireman (1998) says that “RCM is an advanced method that only applies to preventive maintenance in which a prediction program is implemented. In this case, the Working Order system, usually referred to in the Anglo-Saxon literature by the Computer Maintenance Management System (CMMS), collects the equipment's faults under analysis”.

2.11 Risk-Based Maintenance (RBM)

Agrafiotis *et al*. (2018), “using data from completed RBM studies carried out in the last four years, the authors demonstrate that their implementation of RBM improves the efficiency and effectiveness of the clinical oversight process as measured on various quality, timeline, and cost dimensions”. Arunraj & Maiti (2007) refer that, “the concept of risk-based maintenance was developed to inspect the high-risk components, usually with high frequency and thoroughness and to maintain in a greater manner, to achieve tolerable risk criteria. Risk-based maintenance methodology provides a tool for maintenance planning and decision making to reduce the probability of failure of equipment and the consequences of failure”. Cullum *et al*. (2018) refer to the “Scheduling (RBM) framework as applied to ships and naval vessels and provides a critical analysis of Risk Assessment and Maintenance Scheduling techniques used”. Hameed & Khan (2014) refer that, “The framework proposed in their work estimates the risk-based shutdown interval for inspection and maintenance. It provides a tool for maintenance planning and decision making by considering the probability of the equipment or system for failure and the likely consequences that may follow". Hameed *et al*. (2016) refer that, "A risk-based shutdown inspection and maintenance helps to select the critical equipment and systems which cannot be inspected or maintained without taking the plant out of operation". Hu *et al*. (2009) state that "RBM strategy uses risk criteria to schedule maintenance to save capital and guarantee safety. However, it requires improvement since the effect of poor maintenance is not considered in maintenance planning". Jaderi *et al*. (2019) state that "Risk-Based Maintenance (RBM) is among the most advanced comprehensive risk assessment methodologies for the criticality analysis of assets. The study applies both traditional RBM and Fuzzy RBM (FRBM) methods for the risk analysis of petrochemical assets failure". Jamshidi *et al*. (2015) refer to "a new comprehensive risk-based prioritization framework for selecting the best maintenance strategy. The framework encompasses three steps. In the first step, a Fuzzy Failure Modes and Effects Analysis (FFMEA) method is applied by considering several risk assessment factors". Khan & Haddara (2003) refer that, "Risk assessment integrates reliability analysis with safety and environmental issues. Risk-Based Maintenance answers the six following questions in developing an optimum maintenance strategy:

What can cause the system to fail?

How can it cause the system to fail?

What would be the consequences if it fails?

How probable is the occurrence?

How can we prioritize inspection/maintenance actions?

What is the optimum frequency of inspection/maintenance tasks?

Such a maintenance planning approach is expected to provide a cost-effective maintenance program. It also minimizes the consequences (related to safety, economics, and the environment) of a system's outage/failure". Kiran *et al.* (2016) state, "Assessment of the risk of failure is equally important as reliability evaluation and plays an important role in improving plant availability. This work discusses the importance of evaluating reliability and risk of failure in planning a maintenance schedule and thereby improving the plant's availability". Krishnasamy *et al.* (2005) state that the "Risk-Based Maintenance (RBM) approach helps in designing an alternative strategy to minimize the risk resulting from breakdowns or failures. Adopting a risk-based maintenance strategy is essential in developing cost-effective maintenance policies". Kumar & Maiti (2012) refer that, "The maintenance policies considered are Corrective Maintenance (CM), Time Based Maintenance (TBM), Condition Based Maintenance (CBM) and Shutdown Maintenance (SM). For modelling, Fuzzy Analytic Network Process (FBD MATLAB) has been employed". Leoni *et al.* (2019) refer, "Risk-Based Maintenance (RBM) is a methodology to optimize maintenance schedules. Bayesian Network is applied to model the risk and the associated uncertainty. The developed method can assist the asset managers in working out the exact maintenance time for each component according to the risk level". Mancuso *et al.* (2016) "present a novel risk-based methodology for optimizing the inspections of large underground infrastructure networks in the presence of incomplete information about the network features and parameters". Mohamed & Saad (2016) refer that "a risk assessment model is proposed, which includes the likelihood of the risk and the consequences of failure. A new mathematical equation is proposed to assess the likelihood of risk and identify the optimum inspection interval". Moradkhani *et al.* (2015) refer that, "Modelling the dependence of component failure rate on the preventive maintenance (PM) expenditures is the core of risk-based maintenance management. This paper introduces the Generalized Proportional Failure Rate Model (GPFM) for this purpose". Pui *et al.* (2017) state that "Dynamic Risk-Based Maintenance

(RBM) methodology is a tool for scheduling maintenance plans based on an acceptable level of risk. It is applied to improve systems' safety and reliability, assisting in identifying and prioritizing critical components' maintenance". Rathnayaka *et al*. (2014) refer that the "risk-based integrated safety indexing approach is a systematic decision-making support tool to improve system safety with the application of inherent safety design options". Ratnayake & Antosz (2017) refer that "Risk-Based Maintenance (RBM) helps to deal with such issues. An important element of the RBM planning is assessing the consequences of action and prioritising maintenance tasks based on the risk of potential failures". Ratnayake & Chandima (2014) refer that, "An increased focus on Risk-Based Maintenance (RBM) optimization has been prompted in the offshore Oil and Gas (O&G) production and process industry due to the currently existing regulations and guidelines on preventing the Functional Failure Risk of rotating equipment and instrumentation. The RBM optimization approach prioritizes functions based on the potential risk of a given functional failure". Uchida *et al*. (2018) state, "Improvement of plant reliability based on RCM is going to be undertaken in Nuclear Power Plants (NPP). RCM is supported by three types of maintenance: Risk-Based Maintenance (RBM); Time Based Maintenance (TBM); and Condition Based Maintenance (CBM)". Wang *et al*. (2012) refer that, "A Risk-Based Maintenance (RBM) strategy is a useful tool to design a cost-effective maintenance schedule; its objective is to reduce overall risk in the operating facility. In risk assessment of a failure scenario, consequences often have three key features: personnel safety effect; environmental threat; and economic loss". Hameed *et al*. (2019) refer to "on equipment inspection and shutdown at optimized, risk-based maintenance intervals for a processing facility unit, considering the human errors that can introduce during these activities". Hu & Zhang (2014) refer that "considers the safety, maintenance benefits, as well as losses by downtime, and the rationality of maintenance costs, comprehensively to investigate the influence of different maintenance strategies on these variables". Bongiovanni *et al*. (2017) state that "a study conducted into the managerial practices implemented to mitigate the consequences of a major fire emergency and restore normal business operations at a large paediatric hospital promptly". Amicucci *et al.* (2010) state, "Among the proposed guidelines, other than normal referring, there are: 1) adoption of a monitoring system to improve the quality of the electrical parameters in the operating rooms; 2) institution of emergency procedures for the management of electrical faults; 3) the procedures for management fires in the operating rooms; 4) and maintenance interventions and inspections of medical devices to maintain minimum requirements of safety and performance". Hameed *et al*. (2014) presented a "study on equipment inspection and shutdown at optimized, risk-based maintenance intervals for a processing facility unit, considering the human errors introduced during these activities".

2.12 Condition-Based Maintenance (CBM)

Farinha (2011) designates "conditional maintenance as preventive maintenance based on monitoring the property's functioning and the significant parameters of that operation, integrating the resulting actions". Gulati (2009) states that "the maintenance tasks required based on the health of an asset are determined from non-invasive measurements of operation used for monitoring the equipment's condition. CBM allows preventive and corrective actions to be optimized by avoiding traditional calendar or run-time directed maintenance". Wang (2012) states that "the combination of Condition-Based Maintenance and a delay time-based model is a natural one to be considered. With condition monitoring, more information about the plant state is available. It can also aid the maintenance decisions as to what needs to be maintained at a PM time". Kumar *et al.*

(2018) refer to the “big data analytics framework in our study for estimating the uncertainty based on backward feature elimination and fuzzy unordered rule induction algorithm prediction errors, is an innovative contribution to the remaining life prediction field. The authors elaborate on the basic underlying structure of the CBM system defined by the transaction matrix and the threshold value of failure probability”. Mourtzis & Vlachou (2018) refer that, “It also demonstrates that such collected data can be used in an adaptive decision-making system, which includes a multi-criteria decision-making algorithm and a condition-based maintenance strategy aiming to improve factory performances compared to traditional approaches”. Zhu *et al.* (2017) refer to “a maintenance model for a single component that is part of a complex engineering system and has a monotonic, stochastic degradation process. A warning limit is given for this component, using a Condition-Based Maintenance (CBM) policy”. Yang *et al.* (2017) refer that, “Condition-based maintenance (CBM) is a key measure in preventing unexpected failures caused by internal-based deterioration and external environmental shocks. The study proposes a Condition-Based Maintenance policy for a single-unit system with two competing failure modes, i.e., degradation-based failure and shock-based failure”. Guillén *et al.* (2016) refer that, “To address the CBM management challenge, the authors propose a framework with a template to clarify the concepts and to structure and to document the knowledge generation for a given Condition-Based Maintenance solution”. Xu *et al.* (2018) refer that, “discretization technique can capture the degradation dependence between components and guarantee the accuracy of estimating component reliability. The condition-based threshold determined by the proposed model for replacement decision is system level”. Lam & Banjevic (2015) refer to “a decision policy for Condition-Based Maintenance that schedules inspections according to the current health of the system, optimized myopically over the next inspection interval. In traditional

Condition-Based Maintenance practices, regular inspections are considered a given requirement". Ayo-Imoru & Cilliers (2018) refer to, "Condition-Based Maintenance (CBM) involves undertaking maintenance activities based on the health of the system. CBM has found useful applications in many industries. The authors present a survey on the state of Condition-Based Maintenance in the nuclear industry". Hwang *et al*. (2018) refer that "it is necessary to undertake proactive maintenance in advance to avoid abnormal situations. Due to the emergence of Information Communication Technologies (ICT) and sensor technologies, it is possible to gather the health status data of important equipment and use this information for maintenance during the OEE period". Alaswad & Xiang (2017) state, "Condition-Based Maintenance (CBM) is a maintenance strategy that collects and assesses real-time information and recommends maintenance decisions based on the current condition of the system. In recent decades, research on CBM has been rapidly growing due to computer-based monitoring technologies' rapid development". Sampath *et al*. (2017) refer that, "To clearly understand the gas exchange process in coal seams, the process was overviewed at macro and microscopic level, considering two possible CBM storage mechanisms: 1) adsorption as the most probable mechanism and; 2) existence of methane as hydrates due to special reservoir conditions". Sakib & Wuest (2018) refer to that "to show scopes of Condition-Based Predictive Maintenance that is evolving in manufacturing. The use of methods has been validated through further analysis, compared with one another, and brings out the most advantages in Condition-Based Predictive maintenance". Noman *et al*. (2018) refer that "a methodology is proposed: first, collect the articles using Web of Science based on selected keywords from 1970 to December 31, 2017; next, determine the most influential journals, articles, keywords, authors, and institutions in CBM; then, the analysis of country has been performed to analyse CBM studies concerning its geographical distribution". Lu *et al*.

(2018) refer to "an opportunistic CBM optimization approach for Offshore Wind Turbines (OWT) in which economic dependence exists among the components that are subjected to Condition Monitoring". Kumar *et al.* (2018) refer that, "Vibration analysis is the most effective procedure to recognize the nature and degree of any issues in machines and components (i.e., bearings and gears) or any upkeep choices identified with the machine. Condition-Based Maintenance is the request-based upkeep to guarantee the machine accessibility by convenient maintenance activities and lessening breakdown upkeep". Voskuijl & Mark (2015) refer to that as "A new approach to the flight control system. The control system gains are scheduled based on the helicopter's operational history (condition). In combination with Condition-Based Maintenance, this methodology can lead to reduced maintenance costs and an increase in the helicopter's utilization rate". Azadeh *et al.* (2015) state, "Condition-Based Maintenance (CBM) is an increasingly applicable policy in the competitive marketplace as a means of improving equipment reliability and efficiency. Not only has maintained a close relationship with safety, but its costs also make it even more attractive issue for researchers". Basurko & Uriondo (2015) refer that, "Condition-Based Maintenance for Diesel engines has contributed to the reliability, energy-efficiency, and cost reduction". Rasmekomen & Parlikad (2016) refer to "an approach to optimize Condition-Based Maintenance (CBM) of multi-component systems where the state of certain components could affect the rate of degradation of other components, i.e., state-rate degradation interactions". Liu *et al.* (2017) refer that, "condition-based model can be widely applied for infrastructure systems which are subject to cumulative damage and exhibit a long-life cycle". Walter & Flapper (2017) refer to that "Condition-Based Maintenance policy for complex systems, based on the status (working, defective) of all components within a system, as well as the reliability block diagram of the system". Mérigaud & Ringwood (2016) refer that "it is preferable to select or develop CBM systems that can process and analyse data on-site with restricted computational power and send only limited, condensed information to the operator". Bousdekis *et al*. (2018) refer that "the proposed approach can significantly enable the transition of a manufacturing enterprise from sensing to proactive in alignment with the CBM framework. Currently, three decision methods have been incorporated in the system, covering a wide range of application scenarios". Cipollini *et al*. (2018) refer to a "Condition-Based Maintenance of a vessel, characterized by a combined Diesel-electric and gas propulsion plant. In particular, this analysis considers a scenario where the collection of vast amounts of labelled data containing the decaying state of the components is unfeasible". Sato *et al*. (2017) refer that "Condition-Based Maintenance is effective in improving availability by preventing failure occurrences, especially in the case where the lives of equipment or components are unstable because of varying operating and environmental conditions". Cipollini *et al*. (2018) refer, "CBM, providing evidence of the possible advantages in the experimental section with an indirect measurement of the potential savings". Morimoto *et al*. (2017) refer that, "with the advancement of sensor and network technologies, Condition-Based Maintenance (CBM) is applied to various industrial equipment. In particular, mechatronics systems are suitable for CBM because of the sensors equipped in the systems". Kerremans *et al*. (2018) state, "Simple process monitoring, by Principal Component Analysis and contribution methods, is applied to single and successive sensor failure simulations. The economic benefits of the proposed Condition-Based Maintenance approach demonstrated, even for cases in which the faulty sensor was not correctly identified". Cholette *et al*. (2019) refer that "boiler heat exchanger tubes erode over time, leading to costly leaks and capacity loss as damaged tubes are taken out of operation. These losses can be recovered by replacing the heat exchanger, albeit at significant capital cost". Chen *et al*. (2015) refer, "Condition-

Based Maintenance has been proven effective in reducing unexpected failures with minimum operational costs. The study considers an optimal condition-based replacement policy with optimal inspection interval when the degradation conforms to an inverse Gaussian process with random effects". Angius *et al*. (2016) refer that "CBM policy can significantly affect the time to completion of a lot. The work focused on production lines composed of two synchronous machines decoupled by a buffer: First, three baseline systems have been considered and analysed in detail; the analysis has put on the spotlight the sensitivity of optimal maintenance policies to small variations of the parameters; Secondly, a real industrial case characterized by multi-stage processing of parts in the aeronautics industry has been presented". Sato *et al*. (2017) refer that "describes the overview of the "Smart Maintenance Initiative" and demonstrates actual developments for track maintenance, such as high-frequency monitoring device and analysing methods and prospects, implementing Condition-Based Maintenance (CBM), which is one of the critical parts of the Smart Maintenance Initiative". Hoang *et al*. (2016) refer that "an extension of an existing CBM by integrating energy consumption in the optimization model is also investigated in the way to compare the new CBM approach with conventional (extended) one". Cheng *et al*. (2018) refer that "quality control and Condition-Based Maintenance for an imperfect production system subject to both reliability and quality degradations. The system produces a single type of product to meet the constant demand". Shin & Jun (2015) refer that "there is no doubt that the CBM approach will be one important tool to industries in the era of Big Data. Although the concept of CBM was introduced a few decades before, recently, the CBM approach has been highlighted by industries according to the development of emerging ICTs". Do *et al*. (2019) refer that "a Condition-Based Maintenance policy for a two-dependent component system is studied? Two kinds of dependency are investigated and integrated into the maintenance modelling: state dependence, whereby the degradation rate of each component depends not only on its state but on the state of the other component; and economic dependence, whereby setup cost and duration are shared when components are replaced simultaneously”. Peng & Houtum (2016) refer to “a new joint optimization model to determine the production lot-sizing and CBM policy. The average long-run cost rate, including the setup cost per lot, the inventory holding cost, the lost sales cost, and the predictive/corrective maintenance cost, is minimised by optimising the two decision variables related to the production lot-sizing and CBM policy”. Zandieh *et al.* (2017) refer that, “however, they might be unavailable due to preventive maintenance, basic maintenance, or unforeseen breakdowns in realistic situations. The authors simulate Condition-Based Maintenance (CBM) for flexible Job-shop Scheduling Problem (JSP) and consider the combination of Sigmoid function and Gaussian distribution to improve the CBM simulation”. Sénéchal (2018) refers that “Performance Indicators supporting decisions in the case of a Sustainable Conditions Based Maintenance (SCBM). This terminology is based on six classification criteria: performance dimensions; sustainability dimensions; decision levels; items on which PI is about; category of inputs required; and usefulness of the PI in SCBM”. Zhao *et al.* (2018) refer that “a delayed Condition-Based Maintenance (CBM) problem for systems under continuous monitoring is studied. The system is assumed to be affected by competing for degradation failures and fatal shocks”. Noman *et al.* (2018) refer that “a general study of CBM research has been introduced utilizing bibliometric methods. The results indicate that the research in this field experiences a high level of variability concerning nations, as there are several powerful nations in the CBM research field”. Wan Anping *et al.* (2018) refer that “a novel CBM prognostic method for gas turbines has been proposed and discussed. Based on the METS theory, this method can be considered a combination of model-based and data-driven approaches". de Jonge *et al*. (2017) refer that "results show that all factors can significantly affect the benefit of Condition-Based Maintenance over time-based maintenance. The obtained insights are useful for companies to assess the relative importance of the different factors in specific practical situations and to judge whether the relative benefit of CBM outweighs the additional costs, e.g. monitoring equipment and collecting, storing and analysing data". Niu *et al*. (2010) refer to "a novel Condition-Based Maintenance system that uses Reliability Centred Maintenance mechanism to optimize maintenance cost, and employs data fusion strategy for improving condition monitoring, health assessment, and prognostics". Boudhar *et al*. (2013) refer that "a Condition-Based Maintenance policy is adopted with three thresholds for order management, preventive maintenance management and corrective maintenance from which the machine is considered failed".

2.13 Generators, UPS and ATS, as part of the electrical emergency system in hospitals

AHA (1980) mentions that "electrical systems in hospitals are increasingly demanding, complex, and strategic. The partly due to the more critical need for the medical equipment used, whether for diagnosis, treatment, or aftercare. In any electrical system, the hospital engineer's primary concern and the design engineer is the power distribution system". Lei & Singh (2015) state, "The quantitative relationship between switching time and system-wide energy unavailability is studied. The study results indicate the impact of protection system failures on system-wide reliability indices and signify the importance of accelerating line switching process". Grajales-Espinal *et al*. (2016) state that "the fault location method considers the phase and sequence network parameters and voltage and current measurements at the main substation and the distributed generators, in pre-fault and fault steady states". Lopes *et al.* (2007) state that, "an overview of the key issues concerning the integration of distributed generation into electric power systems that are of most interest to the stakeholders (power system planners and operators, policymakers and regulators, Distributed Generation developers and customers) in the electrical energy supply industry today". Salman & Stewart (2015) state that "the case study considered showed the importance of evaluating system reliability, component importance as well as targeted hardening of distribution systems. Showing that hardening components or lines that have a greater impact on system reliability could be cost-effective in some cases". Bertling *et al.* (2005) "proposes a method for comparing the effect of different maintenance strategies on system reliability and cost. This method relates reliability theory with the experience gained from statistics and practical knowledge of component failures and maintenance measures". Volkanovski *et al.* (2009) present "a new method for power system reliability analysis using the developed fault tree analysis. The method is based on fault trees generated for each load point of the power system. The fault trees are related to disruption of energy delivery from generators to the specific load points". Heylen *et al.* (2016) state that "evolutions in the power system challenge how power system reliability managed. In particular, currently used reliability criteria, typically the deterministic N-1 criterion, are increasingly inadequate". Moreno-Munoz *et al.* (2011) state that "Uninterruptible Power Supply (UPS), particularly when configured in distributed Direct Current (DC) mode, can become an Energy-Efficient (EE) solution in high-tech buildings, especially when integrated with complimentary Power Quality (PQ) measures". Anderson & Bezuidenhoudt (1996) state that "the purpose of these rules is the practical safeguarding of persons during the installation, operation, or maintenance of electric supply and communication lines and associated equipment". Zheng *et al*. (2012) refer to "the impact of automatic switches on the reliability of power distribution systems. Based on the studied system's topology characteristics, the reliability model developed to implement the Monte Carlo simulation". Moreno-Munoz *et al*. (2010) state, "Distributed Generation (DG), particularly when configured in Combined Heat and Power mode, can become a powerful reliability solution in highlight automated factories, especially when integrated with complimentary Power Quality (PQ) measures". Zhan *et al*. (2008) present "the design considerations and architecture for an intelligent network UPS system with back-up Proton Exchange Membrane Fuel Cells (PEMFC) and a battery power source. A UPS hybrid system architecture is developed and includes a PEMFC generating system and its data-acquisition devices, an AC–DC rectifier, AC–DC charger, DC–AC inverter, DC-DC converter and associated intelligent network controllers". Froger *et al*. (2016) state that "the reliability of the power plants and transmission lines in the electricity industry is crucial for meeting demand. Consequently, timely maintenance plays a major role in reducing breakdowns and avoiding expensive production shutdowns". National Electrical Safety Code, New York, NY (IEEE, 2006) refer that "they do not cover installations in electric supply stations except as required by Rule 162A. Note 1: Part 4 contains the approach distances and work rules required of supply and communication employers and their employees working on or near supply and communication lines and equipment. Note 2: The approach distances to energized parts and other requirements applicable to the activities of utility or non-utility construction personnel and others near existing supply lines governed by the Occupational Health and Safety Administration (OSHA), federal, state, or local statutes or regulations". Jiang & Singh (2011) state that "develops new models and concepts for incorporating the effect of protection system failures into power system reliability evaluation. The two types of protection failures, i.e., undesired-tripping mode and fail-to-operate mode, and their impact on reliability modelling discussed". Sittithumwat *et al*. (2004) state that "maintenance of distribution systems plays a central, although often overlooked, role in determining both the reliability and cost of supply. In previous work, an approach was developed that optimizes the effectiveness of distribution protective devices". López *et al*. (2016) state that "a Mixed-Integer Second-Order Conic Programming model to solve the reconfiguration problem of electrical distribution systems, considering the simultaneous minimization of total active power losses and improvement of customer-oriented reliability indices". Sauer *et al.* (2012) refer that, "Information about the energy-related behaviour of UPS units is scarce. In the research, we estimate and analyse UPS units' installed capacity and assess their power consumption, losses, and impact on the power quality in the electrical system. The analysis performed through energy efficiency and power quality measurements performed on UPS units commonly available in Brazil". Zhang *et al*. (2016) state, "By intruding on the substations and control centre of the supervisory control and data acquisition system, trip commands can send to intelligent electronic devices that control the power system breakers. Reliability of the power system can be impacted through the cyberattacks". Liu & Singh (2010) state, "In power system reliability evaluation, usually component failures are assumed independent, and reliability indices are calculated using methods based on the multiplication rule of probabilities. But, in some cases, when the effects of fluctuating weather are considered, the previous assumption is invalid". Elloso & Cruz (2017) state that "different risk factors and epidemiological patterns in different communities; thus government programs must be utilized to educate people on safety and proper handling of electricity. Education, enforcement and training should be stressed as the primary weapons to combat this problem". Giannoukos & Min (2013), "based on mathematical and electrical modelling of living tissues and their electrical bioimpedance, and being impedance complex, dynamic, depends on frequency and changes with time, the equivalent electrical circuit of a tissue in the Fricke-Morse and Debye model, as well as the electrical safety checks for medical devices and the standards for medical equipment and how to measure leakage currents, are presented in the authors' work". Addabbo *et al*. (2016) state that "the main energy provider is most of the times supported by local Uninterruptable Power Supply devices (UPS) which should, therefore, have a higher order of magnitude in terms of exploitability and reliability concerning the hardware they are locally supporting". Moreno-Munoz *et al*. (2011) state, "Energy Smart Building aims to accelerate the uptake of Energy Efficiency (EE), healthy buildings that, by integrating smart technology and solutions, consume radically limited resources while enhancing the quality of life. It has demonstrated that the DC-UPS architecture offers a 5–15% power system efficiency improvement compared to that of the AC-UPS system, depending on the AC–DC front end implementation and the mix of loads". Aamir *et al*. (2016) refer that, "Uninterruptible Power Supplies (UPS) have reached a mature level by providing clean and uninterruptible power to the sensitive loads in all grid conditions. Generally, the UPS system provides regulated sinusoidal output voltage, with low Total Harmonics Distortion (THD) and high input power factor irrespective of the grid voltage changes. This thesis provides a comprehensive review of UPS topologies, circuit configurations, and different control techniques used in the UPS system". Adoghe & Odigwe (2009) refer that "an Automatic Transfer System (ATS) was developed to monitor the AC. The voltage comes from the Power Holding Company of Nigeria (PHCN) line for power failure conditions. Upon detecting an outage for a predetermined period, the standby generator starts; once it is up to speed, the load is transferred from the PHCN line to the local Generator". Wakudkar *et al*. (2018) refer that "automatic transfer switch helps transfer the load from various power sources to ensure continuous operation of the load - automatic transfer switch needed in developing countries where frequent power failure is a significant problem". Hsu *et al*. (2016) refer, "the effect of switching scheme on the performance of HPV and build an entire HyPV system for a field test. It found that for constant Af, the ATS switching frequency and battery charge/discharge cycles are sensitive to Af's setting value. Af with trapezoidal function, the cycles of ATS switching and battery charge/discharge are not sensitive in the Af setting". Choi & Hwang (2018) refer to "a novel method for estimation of driveline torque of wet type AT (Automatic transmission). The previous torque estimation methods in the clutch-to-clutch shift mechanism are mainly applicable to the single gear shift". AL-Hazemi *et al*. (2018) refer that "the proposed technique achieves power savings by leveraging a micro–Automatic Transfer Switch (micro-ATS) at the server end. The novelty of this work lies in the developed adaptive algorithm that continuously looks for opportunities to reduce the number of UPSs by offloading under-loaded UPSs to a neighbouring UPS whenever that neighbouring UPS can handle the extra load".

2.14 The Petri Nets Systems

According to Wang (1998), "Petri Nets can be identified as bipartite directed graphs consisting of three basic objects: places, transitions, and directional arcs, which connect places to transitions and transitions to places. In the graphical representation, the place is represented by round or oval circles, where tokens deposit or pass by only as needed; transitions are represented by bars or boxes where they can be fired to move the tokens to another place (transitions because the tokens cannot be deposited there, pass). Transitions can represent Petri Nets in their simplest form and entry and exit locations. This primary network can be used to represent various aspects of the system being modelled. To study the system's dynamic behaviour being modelled, in terms of conditions and changes, each location has the potential to store none or a positive number of tokens, represented by minor solid points. The presence or absence in a place can indicate whether a condition associated with this place is true or false.

A Petri Net can be defined as follows: it consists of 5-tuples N = (P, T, 1, 0, Mo), where,

P = {P1, P2, ..., Pm} is a limited set of places;

T = {t1, t2, ..., tn} is a limited set of transitions, $P \cup T \neq \emptyset$, and $P \cap T = \emptyset$;

I (P, T) → N is an Input function that defines an arc directed from a Place to a Transition, where N is a set of negative integers;

O (T, P) → N is the Output function that defines the arc directed from Transition to Place; and

Mo: P → N is the initial marking.

Marking is the assignment of tokens to places of the Petri Net. Tokens are primitive concepts for Petri Nets (such as places and transitions). Tokens are assigned to and can be thought to be located in Petri Net sites. The number and position of tokens may change during the implementation of the Petri network. The token is used to determine the execution of the Petri Network.

The simulation example refers to Figure 2.6, where we have:

P = {p1, p2, ..., p7};

T = {t1, t2, ..., t5};

I (t1, p1) = 2, I (t1, pi) = 0 for i = 2, 3, ..., 7;

$I(t2, p2) = 1$, $I(t2, p7) = 1$, $I(t2, pi) = 0$ for $i = 1, 3, 4, 5, 6$;

$O(t1, p2) = 1$, $O(t1, p3) = 2$, $O(t1, pi) = 0$ for $i = 1, 4, 5, 6, 7$;

$O(t2, p4) = 1$, $O(t2, pi) = 0$ for $i = 1, 2, 3, 5, 6, 7$;

$Mo = (2\ 0\ 0\ 0\ 0\ 0\ 1)^{T}$”

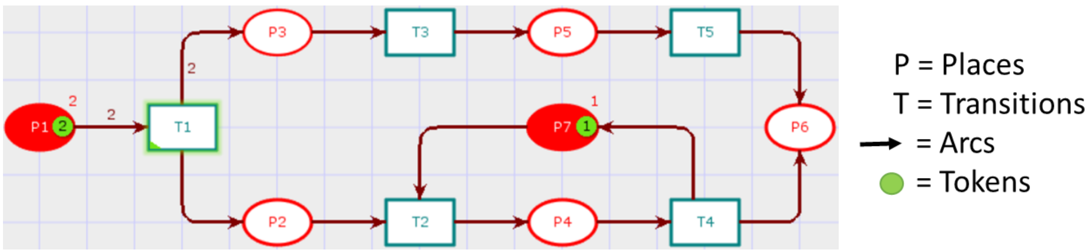


Figure 2.6 *Petri Nets simulation circuit as an example, using CPNTools software*

Based on Petri Nets, the authors use this approach to evaluate an electrical system in a large hospital that supports its daily activities. This critical asset requires excellent maintenance to avoid failures, disrupting the hospital activities considered very risky. Therefore, maintenance plays an important role; it requires special expertise to know the historical data of failures in the hospital's complex electrical circuit. But, if the historical data is unavailable because the operators neglected to collect it, or there is no information system to manage them, it is not easy to do the maintenance work. Due to historical data and unavailability of technical work drawings, it is difficult to conduct a research and convincing investigation. This difficulty comes to solving it using a potent tool, Petri Nets. Petri Nets can easily navigate the electrical system circuit with circuits and simulations because it uses a token flow representing an electric current. Places as items or components and transitions as an operating system or components that supply tokens to flow from part to part to identify and categorize successive instruments that are more critical, less critical, and subsequent. Performance evaluation plays an important role in planning, designing, and operating dynamic discrete event systems. Petri Nets is a modelling tool that provides graphical representations of dynamic and complex systems based on a strong mathematical basis and is disseminated both by the publication of many research results published in the last decade and by various performance domains such as communication networks, production systems, automation, traffic, logistics, the order of care, fault Diagnosis and, in general, all discrete event systems. According to Wang (1998), "Petri Nets, named after Carl Adam Petri, defined a general-purpose mathematical tool for describing relations between conditions and events. Petri Nets have resulted in considerable research because they can be used to model properties, such as process synchronization, asynchronous events, sequential operations, concurrent operations, and conflicts or resource sharing". Sheng and Prescott (2017) state, "To aid fleet managers in making cannibalization related decisions present a Hierarchical Coloured Petri Net (HCPN) model of a fleet operation and maintenance process which considers mission-oriented operation, multiple level maintenance, multiple cannibalization policies maintenance scheduling and spare inventory management". Eisenberger & Fink (2017) state, "Petri Nets are such a mathematical tool that has been applied for maintenance modelling and simulations of different applications. Several types of Petri Nets with different properties have been introduced". Shang & Bérenguer (2015) state that "to assess the effects of delayed repairs on maintenance performance and take them into account for track maintenance decision, especially for the Condition-Based Maintenance. The authors propose a Coloured Petri Net (CPN) model to evaluate the delayed maintenance based on track condition for the given repair delays". Ding *et al.* (2006) state that "an algorithm to compute markings to determine reachable states for a discrete-FTPN model. It provides us with a way of implementing this model of a fuzzy timed system. Performance can be obtained based on the reachability graph. The authors also studied a continuous-FTPN model". Rochdi & Driss (1999) describe that "developed and used a new algorithm and its corresponding software (PETRARBRE) that can easily enumerate minimal cut-sets of coherent fault trees. This algorithm uses the Petri net model of the fault tree. It takes full advantage of Petri Nets properties". Volovoi (2004) states, "The new framework compared with existing Petri-Net approaches and other system reliability modelling techniques such as reliability block Diagrams and Fault Trees. The relative differences are emphasized and illustrated with several examples, including modelling load sharing, imperfect repair of pooled items, multiphase missions, and damage-tolerant maintenance". Long *et al*. (2016) state that "Extended Coloured Stochastic Petri Nets (ECSPN) used for modelling the production systems in Industry 4.0 and their availability, for supporting the analysis and optimization of availability as well of the supporting resources. Three models of ECSPN are built and simulated using the software REALIST to model interactions and self-organization. Finally, the modelling results are explained". Li *et al*. (2015) state that "an approach developed for diagnosability analysis of Discrete Event Systems (DESs) modelled by Labelled Petri Nets. The approach, which extends from the on-the-fly and incremental diagnosis technique, aims at improving the efficiency of diagnosability analysis by generating as less state space as possible". Baresi & Pezz`e (2005) state, "The approach defines interpreters using two sets of rules: the first set specifies the correspondences between the elements of the diagram notation and those of the semantic domain (Petri Nets); the second set transforms events and states of the semantic domain into visual annotations on the elements of the diagram notation". Chew *et al*. (2008) state that "PNs provide an effective, easily understood and compelling way of predicting the reliability of a system or platform. The PN technique extends to phased missions, where complexities of modelling such as component failure rate dependencies, different distributions and repairable systems are easily included". Garg (2012) mentions that the "Petri Nets tool is applied to represent the asynchronous and concurrent processing of the order instead of the fault tree analysis". Leigh & Dunnett (2014) mention that "the study has aimed to develop a model using Petri Nets to determine the feasibility of adopting this technique to model the maintenance processes efficiently". Ren *et al*. (2014) mention that "if a Petri Nets are required to model processes that have a random (or pseudorandom) nature and, if this randomness follows a specific pattern such as a statistical distribution, the transitions can sample their switching times from this distribution". Baidada *et al*. (2019) mention that "this approach consists of generating and collecting the corresponding traces of different cases, filtering and analysing them using Colored Petri Nets to extract a high-level sequence diagram finally". Xie *et al*. (2016) mention that "a novel energy consumption model based on Generalised Stochastic Petri Nets is proposed, and an analysis method is also presented; furthermore, the model was successfully applied to a turning machine tool". Kabir & Papadopoulos (2019) mention that "Petri Nets are another formal graphical and mathematical tool capable of modelling and analysing the dynamic behaviour of systems. They are also increasingly used for system safety, reliability and risk evaluation". Caterino *et al*. (2018) present "a new assessment method, also adapted to a specific risk, such as the mechanical one, using as assessment tools the check-list and Petri Nets". Zhou & Reniers (2020) mention that "Weighted Fuzzy Petri Nets (WFPN) with inhibitor arcs are proposed to model relationships between risk factors and risk assessment structure, considering veto factors". Fierro *et al*. (2020) mention "techniques that include Colored Petri Nets, which have been effectively tested in hierarchical modelling, analysis and control of distributed systems, characteristics suitable for the specification of a supply chain management system in an industry 4.0 scenario". Singh & Singh (2019) mention "a technique to make the performance analysis of safety-critical and control systems that helps to estimate the risk and the performability to ensure the system dependability requirements". Lei *et al*. (2006) state, "As the complexity of manufacturing systems keeps increasing; the maintenance decision making grows more difficult as well. Therefore, the performance evaluation of different maintenance policies or schedules has to rely on simulations. This paper has developed a modularized and flexible simulation package for manufacturing production systems using Stochastic Timed Petri-Nets (STPNs)". Sadou & Demmou (2009) state, "It presents a method for deriving feared scenarios (which might lead the system to a critical situation) in Petri nets. An ideal way to obtain scenarios in Petri nets is to generate the reachability graph. However, for complex systems, it leads to the state space explosion". Córdova & Cifuentes (2016) "present a method of assignment of defence lawyers to causes, using Petri Nets, decision trees and Monte Carlo method. It presents a simulation model of assignment applied to law activities, specifically to defender lawyers contracted by tender, using Petri Nets, Monte-Carlo and decision trees". Lefebvre *et al*. (2015) state, "Reliability analysis often based on stochastic discrete event models like stochastic Petri Nets. For complex dynamical systems with numerous components, the stochastic process's analytical expressions are tedious or even impossible to work out because of the combinatorial explosion with discrete models". Zaitsev & Shmeleva (2011) state, "A parametric Colored Petri net model of the switched Ethernet network with the tree-like topology was developed. The model's structure is the same for any given network. It contains a fixed number of nodes: the tree-like topology of a definite network given as the marking of dedicated places". Jensen *et al*. (2009) state, "Coloured Petri Nets (CPNs) is a language for the modelling and validation of systems in which concurrency, communication, and synchronization play a major role. Coloured Petri Nets is a discrete-event modelling language combining Petri Nets with the functional programming language Standard ML". Pashazadeh & Niyari (2014) state that "Coloured Petri Net is an extension of traditional Petri Net that it is a modelling capability that has grown dramatically. A developed model with Coloured Petri Net is suitable for verifying operational aspects and performance evaluation of information systems". Miyagi *et al*. (2002) state that "a systematic methodology for modelling and simulation of control strategies in Intelligent Buildings systems through a Petri Net approach. Demonstrate the introduced methodology; a case study was conducted, and satisfactory results have been observed in the control systems integration and performance". Sorensen and Janssens (2004) state, "The automatic generation of a discrete-event simulation model from the Petri Net model, was explained. Finally, some potential applications of the Petri Net were illustrated". Petri nets can also be used in a complementary way to the preceding, as is described by Solaiman *et al*. (2020) that proposed "a method to improve fault prognosis using Fuzzy Petri Nets (FPN), by adding internal and external changing conditions to the prognosis process; the authors introduce new kinds of certain factors that can be adapted with changed conditions on a bus of the reliability test system to show its differences from traditional FPN". Pinto *et al*. (2021) stated that "the importance of Petri Nets as a powerful tool in maintenance management, providing analysis and simulation of the systems to increase the reliability and availability of the individual assets and their operations". Farinha (2018) presents an "example using Petri Nets on an electrical circuit has followed: Below is the situation of an Emergency Generator that, as is known, starts operating when the external mains voltage from below a certain value about the nominal voltage. In the example, the value assumed for starting the Emergency Generator is 350 V. When the value of the voltage of the external electrical network from below this value, the

Generator starts, turning off when the value of the electrical network is above that. For this purpose, the following situations are assumed for the Emergency Generator: The Generator can be in two possible operational states: in standby and operation (generating electricity); two situations give rise to those states: mains voltage above 350 V (> 350 V) and below this value (<350 V); Other possible states, such as malfunction, are not considered. Figure 2.7 illustrates the state diagram and the Petri Nets for the preceding situations, respectively".

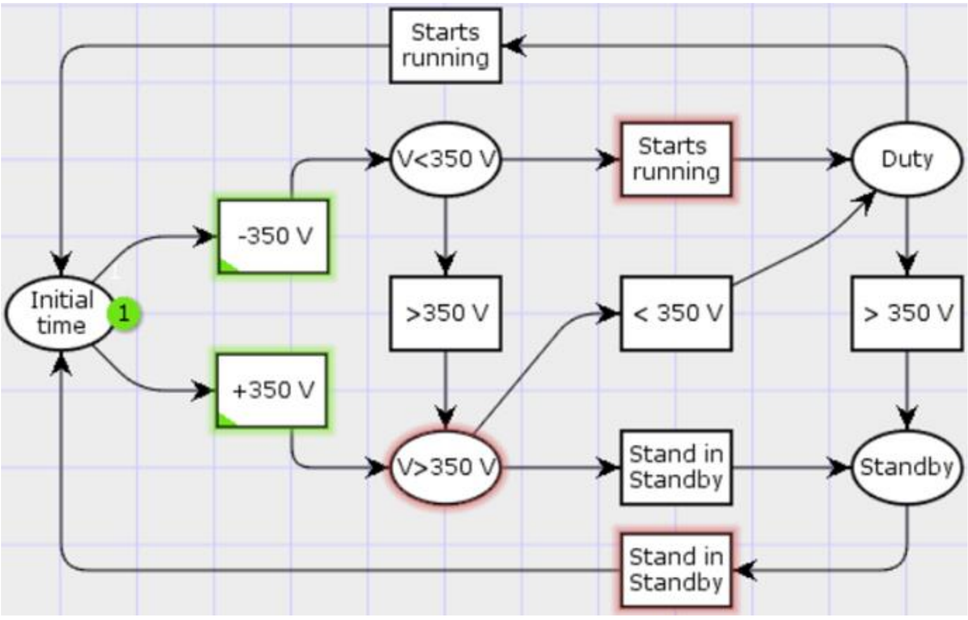


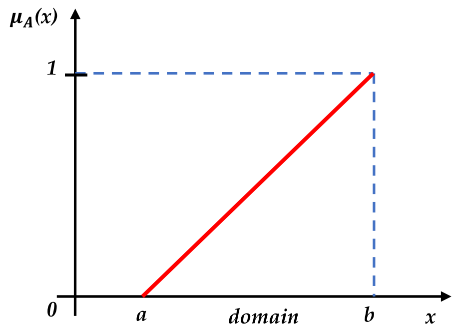
Figure 2.7 *Example of PN remains on standby, (green dot = token = electrical power)*

Among all opinions, the researchers say that fuzzy Petri Nets correspond to a very high potential tool to reveal complicated and unclear things inside the systems.

2.15 The Fuzzy Inference System (FIS)

Fuzzy Logic was created in 1965 by Lotfi A. Zadeh, a professor at the University of California at Berkeley. Fuzzy Logic is an analysis where the data is fuzzy or unclear; then, some ideas initiate science to solve fuzzy problems; the elements or formulas that are closely related to our research are as follows regarding the Membership Function:

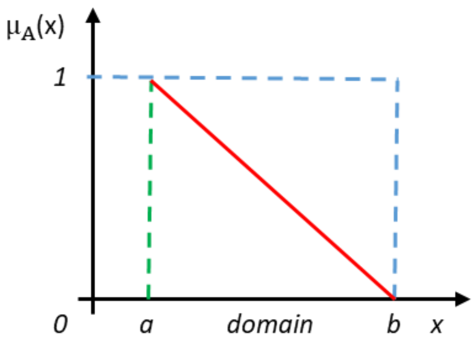
The membership function can be represented by an increasing straight line and Equation 13:



$$\mu(x) = \begin{cases} o, & x \le a \\ \dfrac{(x-a)}{b-a)}. & a \le x \le b \\ 1, & x \ge b \end{cases} \quad (13)$$

(a) Membership function represented by a straight line with a positive slope.

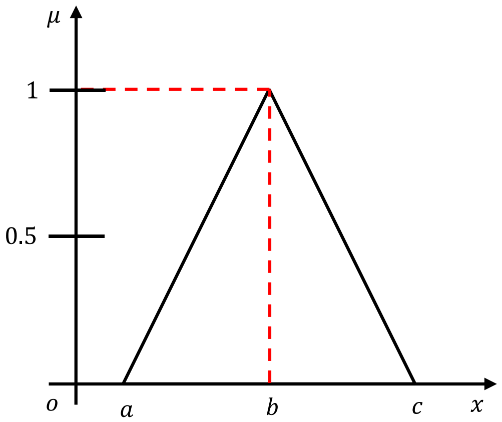
The membership function can be represented by a decreasing straight line and Equation 14 below:



$$\mu(x) = \begin{cases} o, & x \le a \\ \dfrac{(b-x)}{b-a)}, & a \le x \le b \\ 1, & x \ge b \end{cases} \quad (14)$$

(b) Membership function represented by a straight line with a negative slope.

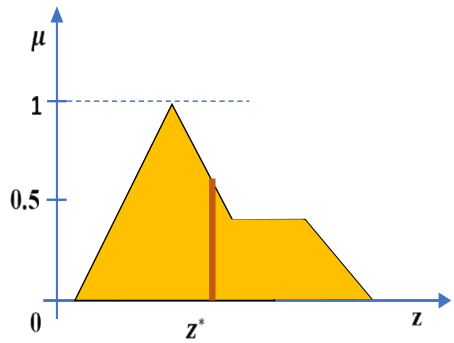
A triangle can represent the membership function Equation 15 below:



$$\mu(x) = \begin{cases} o, & x \le a \\ \dfrac{(x-a)}{(b-a)}, & a \le x \le b \\ \dfrac{(c-x)}{(c-b)}, & a \le x \le b \\ 1, & x \ge b \end{cases} \quad (15)$$

(c) Membership function represented by a triangle shape.

One of the essential defuzzification methods is the centroid, represented by Equation 16 below:



$$Z^* = \frac{\int_a^b \pi_x(z) z dz}{\int_a^b \pi_x(z) dz} = \frac{\sum Moment}{\sum Area} \quad (16)$$

$$Z^* = \frac{\sum_{j=1}^{n} zj\mu(zj)}{\sum_{j=1}^{n} \mu(jz)}$$

(d) Membership function represented by a centroid of gravitation

Figure 2.8 *Shapes and formulas for membership functions and the centroid method for defuzzification from a-d.*

Fuzzy Petri Nets combines two different sciences—the set of fuzzy logic and Petri nets theory—which are held to provide answers to vague or unclear problems in a system that is about to be examined. Therefore, we use fuzzy Petri nets to see and provide solutions to problems that are not clear, such as an asset or system that does not have historical data but wants to get a definite answer regarding the reliability and reliability of maintenance performance of these assets. Also, several previous researchers put forward their ideas in articles they wrote as follows. Cannarile *et al*. (2017) "propose a method based on the Fuzzy Expectation-Maximization algorithm, which integrates the evidence of the field inspection outcomes with information taken from the maintenance operators about the transition times from one state to another. Possibility distributions are used to describe the imprecision in the expert statements". Ladj *et al*. (2017) proposed "a new interpretation of PHM outputs to define machine degradations that are corresponding to each job. Moreover, to consider several sources of uncertainty in the prognosis process, the authors choose to model PHM outputs using fuzzy logic". Touat *et al*. (2017) mentioned that "to solve the problem, we developed two fuzzy genetic algorithms that are based on respectively the sequential and total scheduling strategies. The one respecting the sequential approach consists of two phases. In the first phase, the integrated production and maintenance schedules are generated. In the second one, the human resources are assigned to maintenance activities. The second algorithm respecting a comprehensive strategy consists of developing the integrated production and maintenance schedules that explicitly satisfy the human resource constraints". Ratnayake and Antosz (2017) mentioned that "also, a fuzzy logic-based risk rank calculation approach has been presented. The suggested RBM approach, together with the fuzzy inferencing process, enables us to minimize suboptimal calculations when the input values are at the boundaries of the particular ranges". Seiti *et al*. (2018) mentioned that "for this purpose, a model based on Fuzzy Axiomatic Design is presented, wherein each evaluation has both optimistic and pessimistic fuzzy scores, as the fuzzy evaluations themselves have risks". Babashamsi *et al*. (2016) stated that "to determine the weights of the indices, the fuzzy AHP is used. Subsequently, the alternatives' priorities are ranked according to the indices weighted with the VIKOR model". According to Cordón (2011), "The current contribution constitutes a review on the most representative genetic fuzzy systems relying on Mamdani-type fuzzy rule-based systems to obtain interpretable linguistic fuzzy models with a good accuracy". Zahabi and Kaber (2019) mentioned that "use the Mamdani max-min inference method to calculate a 'risk reliability (R-R) score based on a fuzzy definition of frequency of hazard occurrence, the severity of hazard outcomes, and system reliability. The application of the proposed model is presented in the context of a complex- human-in-the-loop system using the MATLAB fuzzy logic toolbox". According to Akgun *et al*. (2012), "For this purpose, an easy-to-use program, 'MamLand,' was developed for the construction of a Mamdani fuzzy inference system and employed in MATLAB. Using this new developing program; it is possible to construct a landslide susceptibility map based on expert opinion". According to Kacimi *et al*. (2020), "The Mamdani fuzzy system is known as a linguistic model where the semantic meaning of the fuzzy rules is an intrinsic characteristic that must be retained during the learning process while seeking for high accuracy". Lu and Sy (2009) mentioned that "A fuzzy logic approach is adopted to handle the uncertainty conditions. The fuzzy project program is coded and compiled into a DLL file". Dhimish *et al*. (2018) stated that "Mamdani fuzzy logic system interface and Sugeno type fuzzy system. Both examined fuzzy logic systems show approximately the same output during the experiments. However, there are slight differences in developing each type of the fuzzy system, such as the output membership functions and the rules applied for detecting the type of the fault occurring in the PV plant". Kraidi *et al*. (2020) stated that "A Computer-Based Risk Analysis Model (CBRAM) was designed to analyse the risk influencing factors using a fuzzy logic theory to consider any uncertainty that is associated with stakeholders' judgments and data scarcity. The CBRAM has confirmed the most critical risk influencing factors, in which this study has explained the effective methods to manage them". Khosravanian *et al*. (2016) stated that "The Mamdani-type FIS requires defuzzification. In contrast, the Sugeno-type FIS applies a constant weighted-average technique to avoid defuzzification. The results for the two field cases evaluated convincingly demonstrate that the Sugeno-type FIS is superior to the Mamdani-type FIS for WOB prediction using the same input data and membership functions". About this type of approach, the research developed by Teo *et al*. (2016, 2020 & 2021) must be considered very relevant, regardless of being focused mainly on energy management, namely for a grid-connected microgrid with renewable energy sources and energy storage system, including the design of fuzzy logic-based controllers to be embedded in a grid-connected microgrid with renewable and energy storage capability. Loures & Pascal (2005) refer to "a Diagnosis framework based on a qualitative model of the process. A Fuzzy partitioning of the variable's evolution is made from the dynamic abstraction procedure under the defined operational model, defining several qualitative states for each measured or observable variable. Then, time Fuzzy intervals representing the moment of state changes are defined. The process behaviour of the operating mode is represented by Time Fuzzy Petri Nets (TFPN) model. Its evolution is the consequence of events detection due to the partitioning bounds crossing". Milinkovic *et al*. (2013) present "a Fuzzy Petri Net (FPN) model for estimating train delays. The FPN model simulated traffic processes and train movements in a railway system with hierarchy, colour, time, and fuzzy reasoning characteristics. The trains were coloured tokens, the track sections were termed places, and discrete train movement events were termed transitions. A Fuzzy Petri Net module simulated the primary train delays in the model. The fuzzy logic system was incorporated into the FPN module in two ways: First, when there was no historical data on train delays, expert knowledge was used to define Fuzzy sets and rules, transforming the expertise into a model to calculate train delays. Second, a model based on the Adaptive Network Fuzzy Inference System (ANFIS) was used for systems where the historical data on train delays were available (from detection systems or the train dispatcher's logs)". Cheng & Yang (2009) refer that "The Fuzzy Petri Net approach was adopted to formulate the decision processes of train dispatchers in the case of abnormality. The abnormalities of the railway system in this study were CTC, ATP, and locomotive failures. Under various circumstances derived from the FPN approach, this dispatch result is consistent with validation results under possible train delay estimation. The proposed dispatching rule could be formalized in the training documents of central training centre staff. The rules could be a basis for the development of a future dispatch decision support system". Yang & Li (2018) refer that "Time fuzzy Petri nets (TFPNs) have been widely used to describe the transfer correlations among industrial process variables. However, the parameters associated with traditional TFPNs mostly rely on human expert knowledge. Additionally, traditional TFPNs have limited abilities to deal with dynamic time delays between correlated variables". Shen *et al.* (2012) "use Fuzzy theory to solve the vagueness problem. Therefore, the study presents a novel learning evaluation model that applies High-Level Fuzzy Petri Net (HLFPN) and infers via a Fuzzy reasoning method". Kim & Yang (2018) present a "specialization in Fuzzy Petri Nets (FPNs). Fuzzy logic is incorporated to better model a self-navigating robot algorithm, thanks to its versatile multi-valued logic reasoning". Liu *et al.* (2013) state, "Fault Diagnosis is of great importance to all kinds of industries in the competitive global market today. However, as a promising fault diagnosis tool, Fuzzy Petri Nets (FPNs) still suffer a couple of deficiencies: First, traditional FPN-based fault diagnosis methods are insufficient to take into account incomplete and unknown information in the diagnosis process; Second, most of the fault Diagnosis methods using FPNs are only concerned with forwarding fault Diagnosis and, no or less, consider backward cause analysis". de Figueiredo & Perkusich (1996) make "a fuzzy approach to introduce time in Petri Nets presented. The major motivation of this approach is the lack of generality of timing Petri Net extensions. This approach, Fizzy Tune Petri Net (FTPN), integrates into a complementary fashion the strength of the deterministic and stochastic extensions". Barzegar *et al.* (2011) refer that, "An adaptive fuzzy coloured Petri net has been presented, based on learning automata, to control traffic signals across intersections efficiently. The basis of the recommended algorithm was to combine Fuzzy Logic and learning automata. Learning automata were used to regulate and adjust membership functions in the fuzzy system". Cardoso *et al.* (1996) present "a short survey about the main Fuzzy Petri net models which have been recently developed. They focus on the applicability of such approaches in Discrete Events Dynamic Systems. The elements that are fuzzily filed in Petri Nets are also presented". Qiao *et al*. (2008) refer that, "A new kind of Fuzzy Petri Nets based rescheduling model (FPN-R) for semiconductor production line has been proposed. It has three obvious advantages: Firstly, it combines two aspects of the rescheduling strategy problem, namely start-up decision and method-choice decision, into one model; Secondly, it tries to set a formal model for the unstructured rescheduling problem to be calculated with the matrix; Lastly, it introduces the threshold to consider practical factors". Liu *et al.* (2017) refer, "Fuzzy Petri nets (FPNs) are a potential modelling technique for knowledge representation and reasoning of rule-based expert systems. To date, many studies have focused on the improvement of FPNs. Various new algorithms and models have been proposed in the literature to enhance the modelling power and applicability of FPNs". Pedrycza & Camargo (2003) "introduced a new class of Fuzzy Petri Nets by incorporating a concept of time with the interval and Fuzzy set-based models of temporal relationships. The factor of time is incorporated into the structure of the net in two different ways: augmenting temporal relationships at the level of the transitions or/and places – the authors provided several illustrative examples to analyse the impact of the time factor on the performance of the net expressed in terms of the ring of the transitions and the distribution of the level of marking the input and output places”. Tüysüz & Kahraman (2010) present “an approach for modelling and analysis of time-critical, dynamic and complex systems using stochastic Petri nets together with Fuzzy sets. The presented method consists of two stages: The first stage is the same as the conventional stochastic Petri Nets with the difference that the steady-state probabilities are obtained parametrically in terms of transition firing rates; In the second stage, the transition firing rates are described by Fuzzy triangular numbers and then by applying Fuzzy mathematics, the fuzzy steady-state probabilities are calculated”. Zhang *et al*. (2017) refer that, “a method of Fuzzy Inference Petri Nets (FIPN) to represent the HM hybrid system comprising a Mamdani-type Fuzzy model of OFS and a logical switching controller in a unified framework, in which the task-load level is dynamically reallocated between the operator and machine based on the model-predicted OFS”. Sotirov *et al*. (1991) refers to “an approach to modelling and control of manufacturing systems using Fuzzy Petri Nets (FPN). It is shown that an FPN can be derived from a classical Petri net by fuzzification of places and transitions”. Mhalla *et al*. (2013) refer to “a monitoring module based on P-Time Petri Nets (P-TPN) for manufacturing job-shops with time constraints. The monitoring consists of a set of two collaborative PNs: The first is used for modelling the normal behaviour of the system by the temporal spectrum of the marking; The second model, Synchronized Fuzzy Petri Nets (SinFPN), corresponds to monitoring activities”. Hamed (2018) refers that “A novel approach of FPN is presented to quantitative modelling of gene networks following through Fuzzy set. The FPN model system, as presented in this paper, determines the gene network behaviour of specific organic processes even though the kinetic rate data are known just somewhat”. Tang & Pang (1994) refer to “A Continuous Fuzzy Petri Net approach that can deal with real-time continuous inferencing. For process control and modelling at a high level in the presence of uncertainty. Continuous Fuzzy Petri Net integrates several paradigms and technologies: fuzzy control; Petri Nets; and real-time expert systems". Amin & Shebl (2014) refer that "Petri Nets and Fuzzy Petri Nets as modelling formalism are not adaptable according to the arc weight changes. Weights are the parameters that represent the new incoming data of the system modelled by a (Fuzzy) Petri net". Hu *et al*. (2011) refer that "Fuzzy Petri Nets are used to solve the backward reasoning problems arising in many areas. A max-algebra and reversed Petri Nets-based algorithm is proposed such that the reasoning process can be implemented formally and automatically". Huang *et al*. (2008) refer that, "The material arrangement agent adopts Dynamic Fuzzy Petri Nets and the proposed extended model to introduce a process called Standardized Course Generation Process. Standardized courses correspond to the SCORM standard and arrange adaptive auxiliary materials dynamically". Shen *et al*. (2015) refer that, "A high-level Fuzzy Petri Net is used for the analysis and the development of identifying human actions, including normal action, exercising, and falling. The results of this study can be used in the appropriate equipment or the field of home nursing". Ain *et al*. (2018) "we have proposed a Fuzzy Inference System (FIS) that uses humidity as an additional input parameter to maintain the thermostat set-points according to user comfort. Additionally, we have used indoor room temperature variation as feedback to proposed FIS to get better energy consumption".

2.16 The Stochastic Time Petri Nets (STPNs) and Markov Chains

The Stochastic Time Petri Nets combines two different sciences: The Stochastic Processes and the Time Petri Nets theory, which are held to provide answers to complicated and challenging problems in a system that is about to be examined. We use Stochastic Time Petri Nets to model and simulate systems behaviour to identify potential problems. This type of approach is essential when a system does not have historical data but is too relevant for the organization to have rigorous knowledge about its Reliability, Availability and Maintenance to improve its performance. There are several research papers about this subject, like the followings: Lee & Mitici (2020) "propose a formal framework to assess the safety and efficiency of maintenance strategies employing agent-based modelling, stochastically and dynamically coloured Petri Nets, and Monte Carlo simulation". Rommelfanger (2007) mentions a "new approach that represents a general interactive solution for solving multicriteria linear programming systems with crisp, fuzzy or stochastic data". According to Das *et al*. (2011), "The models have been formulated as profit maximization problems in stochastic and fuzzy-stochastic environments by considering some inventory parameters imprecise in nature". According to Li *et al*. (2007), "An integrated fuzzy-stochastic risk assessment (IFSRA) approach was developed to systematically quantify both probabilistic and fuzzy uncertainties associated with site conditions, environmental guidelines, and health impact criteria". Jiang *et al*. (2017) refer that "The fuzzy stochastic model is created by combining the fuzzy clusters of input vectors with the radial basis activation functions in the stochastic neural network".

Sharifi *et al*. (2020) "Used a stochastic fuzzy-robust approach to tackle the uncertainty of parameters. For solving the multi-objective model, the weighted addition method was successfully applied". Slowinski & Teghem (1993) "have developed a FLIP method (Fuzzy Linear Programming) based on Fuzzy numbers for modelling inaccurate data. On the other hand, we have proposed STRANGE (Strategy for Nuclear Generation of Electricity), a stochastic approach to the same problem. Both methods are interactive and, at each step, present to the Decision-Maker (DM) a large representation of efficient solutions". Buckley (1990) "discusses solutions to multiobjective linear programs where some, or all, of the parameter values, may be uncertain. The uncertainty is modelled using random variables (stochastic programming) or Fuzzy variables (possibilist programming)". Lefebvre *et al.* (2009) mention that "Reliability analysis is often based on stochastic discrete event models like Markov models or stochastic Petri nets)". Lei *et al.* (2006) state that "Most maintenance policy optimizations rely on accurately modelling the production system and maintenance operations. Petri Nets (PNs) have been widely used for simulation, modelling and analysis of discrete event dynamical systems, because of their versatile capability for modelling concurrent, asynchronous, distributed, and stochastic systems)". According to Mahdi *et al.* (2017), "in SPN, we initiate "time factor", the associated times on each transition are random variables which follow distribution laws (generally exponential ones for PV systems). We can also associate Monte-Carlo simulations, Markovian chains, or other state diagrams)". Balakrishnan & Trivedi (1996) mention that "the stochastic process underlying a GSPN is a homogeneous continuous-time Markov chain and solution methods for Markov Chains apply)". Molloy (1981) states that "since there is some probability that a Markov model changes state in a period, there is more structure to the Markov Model than the Petri Net model. Therefore, the extension of Petri Nets to Stochastic Petri Nets allows the extraction of additional information on behaviour)". Volovoi & Peterson (2011) stat that "Markov chains, where each state represents the system as a whole, in SPN the states of individual components are described, and the state of the system inferred from the states of its components". Dhople *et al.* (2014) "propose a framework to analyse Markov reward models, which are commonly used in system performance analysis. The framework builds on a set of analytical tools developed for a class of stochastic processes referred to as Stochastic

Hybrid Systems (SHS)". Wang *et al*. (2010) "incorporate the Markov chain concept into a fuzzy stochastic prediction of stock indexes to attain better accuracy and confidence". Ye *et al*. (2019) propose "an MINLP model that represents the stochastic process of system failures and repairs as a continuous-time Markov chain, based on which it optimizes the selection of redundancy and the frequency of inspection and maintenance tasks for maximum profit".

Thus, Stochastic Time Petri Nets (STPN) is a sophisticated tool that understands very complex and multidimensional; therefore, researchers must understand it well for their purposes.

Stochastic Petri Net (SPN) is a six-tuple (P, T, I, O, M0, Λ) in which (P, T, I, O, M0) is a Petri net, Λ: T → R is the set of firing rates whose entry λ_k is the rate of the exponential individual firing time distribution G_k (x | M) associated with the transition t_k, and

P (Places) = {P1, P2, …, P24}

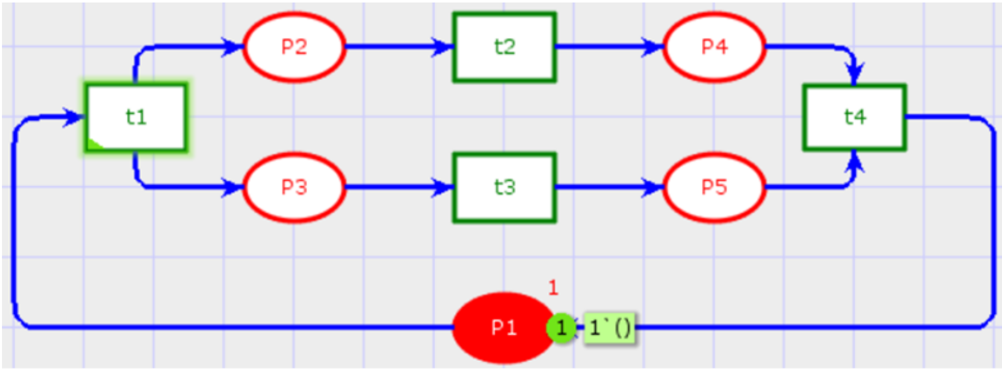
T (Transitions) = {T1, T2, …, T22}

I (Input)

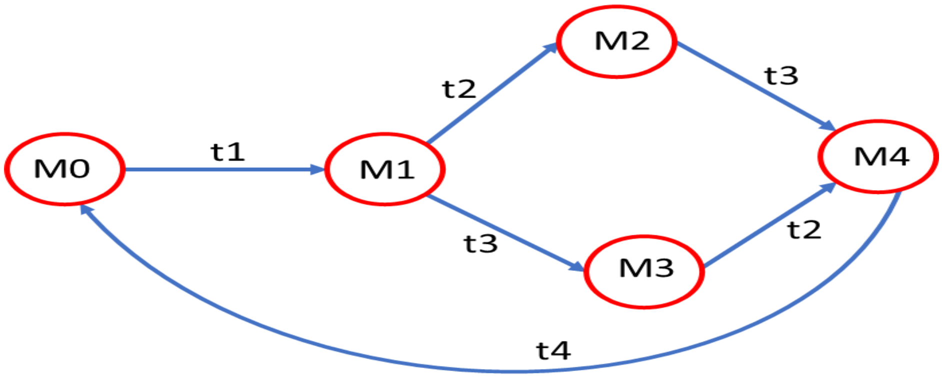
O (Output)

M0 (Marking).

Figure 2.9 presents an example of an STPN.



(a)



(b)

Figure 2.9 *(a) the STPN model and (b) reachability graph*

with:

M0 = (1 0 0 0 0) $^{\mathbf{T}}$, M1 = (0 1 1 0 0)$^{\mathbf{T}}$, M2 = (0 0 1 1 0)$^{\mathbf{T}}$, M3 = (0 1 0 0 1)$^{\mathbf{T}}$, M4 = (0 0 0 1 1)$^{\mathbf{T}}$.

$$(\pi_0, \pi_1, \pi_2, \pi_3, \pi_4)\begin{bmatrix} -\lambda_1 & \lambda_1 & 0 & 0 & 0 \\ 0 & -(\lambda_2+\lambda_3) & \lambda_2 & \lambda_3 & 0 \\ 0 & 0 & -\lambda_3 & 0 & \lambda_3 \\ 0 & 0 & 0 & -\lambda_2 & \lambda_2 \\ \lambda_4 & 0 & 0 & 0 & -\lambda_4 \end{bmatrix} = 0 \quad (17)$$

$$\pi_0,\ \pi_1, \pi_2, \pi_3, \pi_4 = 1 \quad (18)$$

Our case study, a large hospital in Europe without historical data, used the Petri Nets to identify the most critical equipment and systems in the electrical power system. We have used the Fuzzy Inference System (FIS) to find the reliability function. However, we use another approach to compare them to confirm the results we have reached: the "Stochastic *versus* Fuzzy" process. Additionally, we use the Markov Chains to simplify the matrix for the simulation. The supporting concepts are as follows:

- Stochastic Classification Process

i. A stochastic process is a random variable that also depends on time. Hence, a function with two arguments, X (t, ω), where:

- $t \in \tau$ is time, with τ as a possible set of times, usually (0, ∞), (−∞, ∞),
- {0, 1, 2 ,. . .}, or {. . . , −2, −1, 0, 1, 2 ,. . .};
- ω ∈ Ω, as before, is the result of the experiment, where Ω is the entire sample space.
- The value of X (t, ω) is called a state.

ii. The stochastic process X (t, ω) is a discrete state if the variable X_t (ω) is discrete for each time t, and the state is continuous if X_t (ω) is also continuous.

iii. The stochastic process X (t, ω) is a discrete-time process if the time set τ is discrete; it consists of separate and isolated points. In the continuous-time process, if τ is a connected interval, it may be infinite.

iv. The stochastic process X (t) is Markov chain if for every $t_1 <... <t_n < t$ and there is a set A; $A_1, . . . , A_n$

$P(X(t) \in A \mid X(t_1) \in A_1, . . . , X(t_n) \in A_n\}$

$= P(X(t) \in A \mid X(t_n) \in A_n)$.

The conditional distribution of X *(t)* is the same in two different conditions,

(1) Observing process X at several moments in the past;

(2) Only given the most recent observations of X.

Continuous-Time Markov Chain (CTMC) is a Stochastic Process with the Markovian property. The distribution of the condition of the future state in time t + s, given the present state, if all past states depend only on the present state and are independent of the past:

P {future | past, present} = P {future | now}.

Then, only its current state matters for the future development of the Markov process, and it doesn't matter how the process came to be in this state.

- Discrete-Value Process and Continuous-Value

X *(t)* is a discrete-value process if the set of all possible values of X *(t)* at all times t is the computable set S*x*; otherwise, X *(t)* is a continuous value process.

- Discrete-Time and Continuous-Time Process

The stochastic process X *(t)* is a discrete-time process if X *(t)* is defined only for a set of instantaneous times, $t_n = nT$, where T is a constant and *n* is an integer; otherwise, X *(t)* is a continuous-time process.

A Markov chain with discrete-time (Discrete-Time Markov Chain) is a Markov process with discrete-time and X*(t)* having a discrete value.

Mathematically, the probability of moving from state *i* to *j* in time *t* is expressed as:

$p_{ij}\,(t) = P\,(X_{(t+1)} = j \mid X\,(t) = i)$

$= P\,(X_{(t+1)} = j \mid X_{(t)} = i,\ X_{(t-1)} = h,\ X_{(t-2)} = g, \ldots)$

Probability transition for h-step:

$P_{ij}^{(h)}\,(t) = P\,(X_{(t+h)} = j \mid X_{(t)} = i)$

There are three main procedures to be carried out for the Markov analysis process, namely:

1. To construct a transition probability matrix;
2. To calculate the probability of an event in the future;
3. To determine the steady-state conditions.

- Matrix approach

All one-step transition probabilities p_{ij} can be conveniently written in an $n \times n$ transition probability matrix:

					From state:
P =	p11	p12	…	p1n	1
	p21	p22	…	p2n	2
	…	…	…	…	…
	pn1	pn2	…	pn3	n
To state:	1	2	…	n	

(19)

The intersection of the *i-th* row and the *j-th* column is p_{ij}, the transition probability from state *i* to state *j*.

A Markov chain makes a transition to one and only one state from each state. States destinations are disjoint and exhaustive events; therefore, each row total equals 1:

$$p_{i1} + p_{i2} + \ldots + p_{in} = 1. \qquad (20)$$

2.17 The CPNTools Software Simulator Description

According to Jensen and Kristensen (2009), “The Coloured Petri Nets modelling language is a general-purpose modelling language. It aims to model a specific class of systems, but it aims to a comprehensive class of systems characterized as competing systems. Typical application domains for CPN networks are communication protocols, data networks, distributed algorithms and embedded systems. However, CPN networks are also more generally applicable to modelling systems where simultaneity and communication are key features. Examples of this are business processes and workflows, manufacturing systems and agent systems. Petri Nets are traditionally divided into low-level Petri Nets and high-level Petri Nets. CPN networks belong to the class of high-level Petri Nets characterized by the combination of Petri Nets and programming languages”. The definition of the Petri Net model using the CPNTools software is shown in Figure 2.10. The definition of the Petri Net model using the CPNTols software is shown in Figure 2.10, which also consists of places, transitions, arcs and tokens.

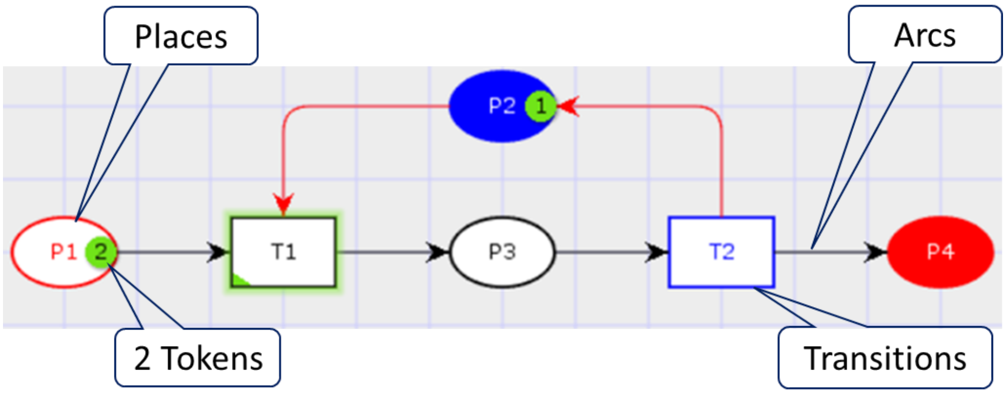


Figure 2.10 *shows the definition of Petri nets with CPNTools software.*

According to Wang (1998), "Colored Petri Nets definition is a tuple (P, T, C, I, O, M_0) where:

1. $P = \{p_1\ p_2, \ldots , pm\}$ is a finite set of places;

   $T = \{t_1, t_2, \ldots , t_n \}$ is a finite set of transitions such that $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$.

2. $C(p_i)$ and $C(t_i)$ are sets of colors associated with place $p_i \in$ P and $t_i \in T$, respectively, given by,

   $C(p_i) = \{a_{i1}, a_{i2}, \ldots , a_{iu}\}, u = |\ C(p_i)|, i = 1,2, \ldots , m;$

   $C(tj) = \{b_{j1}, b_{j2}, \ldots , b_{jv} \}, v = |\ C(tj)|, j = 1,2, \ldots , n.$

3. $I(t, p)$: $C(t) \times C(p) \rightarrow N$ is an input function that defines directed arcs from places to transitions, where N is a set of nonnegative integers, and $O(t, p)$: $C(t) \times C(p) \rightarrow N$ is an output function that defines directed arcs from transitions to places.

4. $M_0(p)$: $C(p) \rightarrow N$ defines the initial marking of the net".

CHAPTER 3. ELECTRICAL SYSTEM OF A LARGE EUROPEAN HOSPITAL

3.1 The Description of an extensive European Hospital profile

Under the study, a prominent European Hospital is a medical care building that started in 2005 and got accreditation from the National Health Care Agency in 2010. The unit has a total construction area of 90.000 m2, consisting of the following constructions: Main building, consisting of 21 structural bodies, where all health care services are installed; Building A with 14 levels of distinct pavements, located between floor four and floor seven (roofing); Support building that comprises facilities and equipment services management, warehouses, workshops and thermal power plants, designated by building B. This thesis focuses on the Hospital's Emergency Power Supply System (EPSS). This system has the following equipment: two units of 1000KVA generators; one unit of 500KVA generator; two units of UPS (Uninterrupted Power Supply) with 300KVA; one unit of UPS of 8KVA; 20 units of UPS of 20KVA; one unit of ATS (Automatic Transfer Switch); Three transformer units connect the protection relay; two PT (Power Transformers) units; three LVDB (Low Voltage Distribution Board) input units; six LVDB central output units and other peripheral instruments (Correction Batter, LV Distribution Network, Indoor Lighting (Normal/Emergency), Output and Obstruction Signalling, Normal/Emergency Outlets); and Ground Network. This thesis uses Petri Net Time methods to analyse and diagnose the power system's operation and reliability and propose a new design to improve its Availability.

3.2 Modelling of the Hospital's Electrical System Using Block Diagrams

To model the hospital's electrical system, they were designed the following steps: observation and identification of asset systems; asset system definition and analysis; asset system modelling; simulation and evaluation of asset systems; and determination of the research steps to be modelled in the assets, as is shown in Figure 3.1.

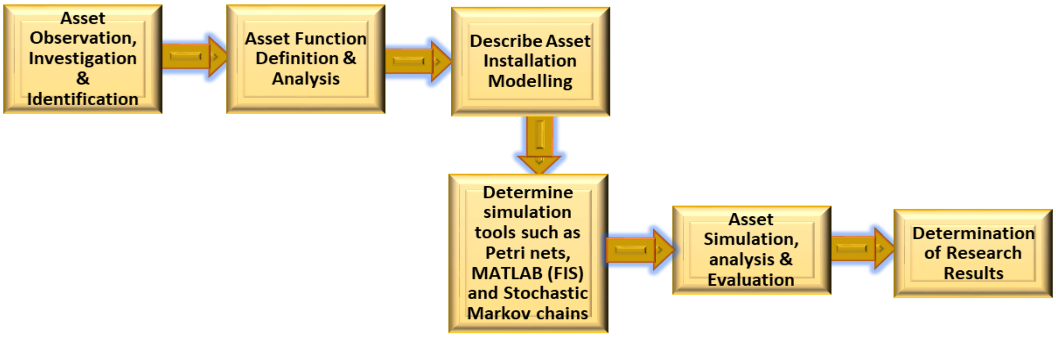


Figure 3.1 *Step by step, the research methodology uses block diagrams.*

To modelled a Petri Net of an Asset complex system, the following method may be used: Asset Hierarchy Block Diagram (AHBD); Asset Functional Block Diagram (AFBD); Asset Process Flow Diagram (APFD) and Asset Petri Net Modelling.

The Asset Hierarchy Block Diagram, shown in Figure 3.2, illustrates the maintenance reliability system, which is recommended by the Reliability Cantered Maintenance (RCM) standard, created to facilitate the flow of institutional system management; so, it can be seen which part will carry out and who is responsible for that part, does not have overlaps the responsibility and is easily arranged as a good work team.

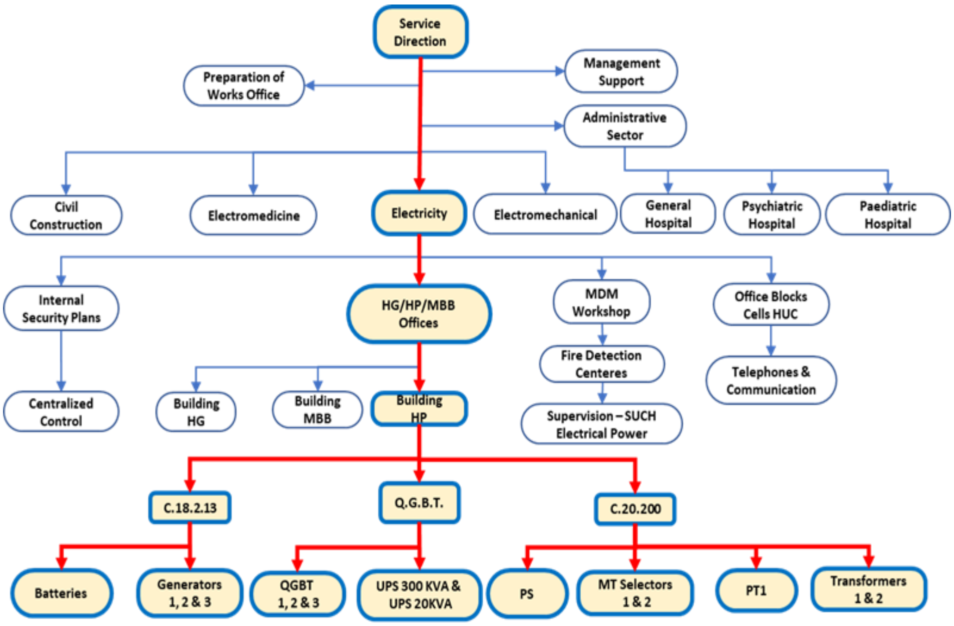


Figure 3.2 *Asset Hierarchy Block Diagram (AHBD), Facilities and Equipment Services*

3.3 The Group of Generators, Automatic Transfer Switch and UPS

In addition to the UPS, the power system ensures a part of the hospital's operation; in case of power failure of the external energy supplier, the hospital is equipped with three generators, two of 1000 KVA and one of 500 KVA, powered by Diesel engines. The command and transfer board of the most potent groups has also installed a synchronization system between the two groups that can operate parallel after synchronization between both groups (Figure 3.3).

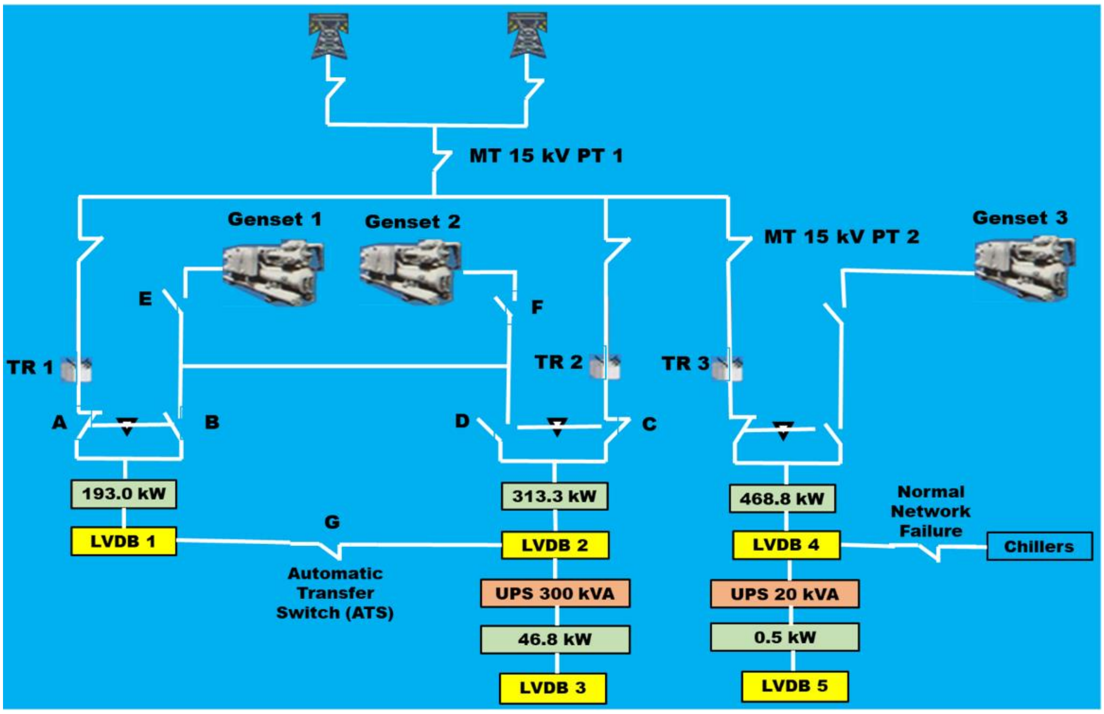


Figure 3.3 *Diagram of the Electric Power System in Hospital*

Figure 3.4 shows, synthetically, how the hospital system works: The main entrance to public electricity, which supports the entire hospital system; the input from two power generators, each with 1000 KVA to feed critical units; The input from one power generator, with 500 KVA for non-critical units; and Output for end-users in all hospitals, both critical and non-critical. With information from the asset's functional block diagram, the treatment plan is better defined according to the hospital's standards.

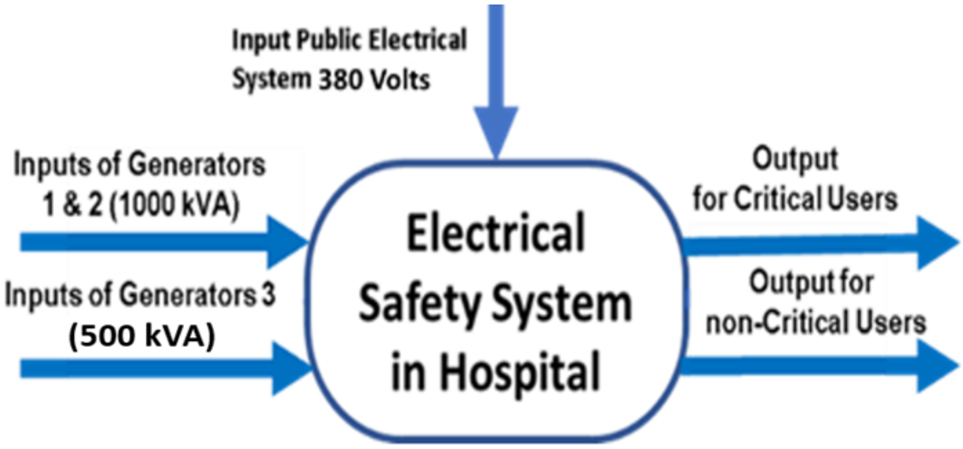


Figure 3.4 *Asset Functional Block Diagram (AFBD)*

Figure 3.5 shows the process block flow Diagram of the Physical Assets, which is modelled using a block diagram to make it more clearly visible to stakeholders to know how the flow of electric current occurs in the circuit.

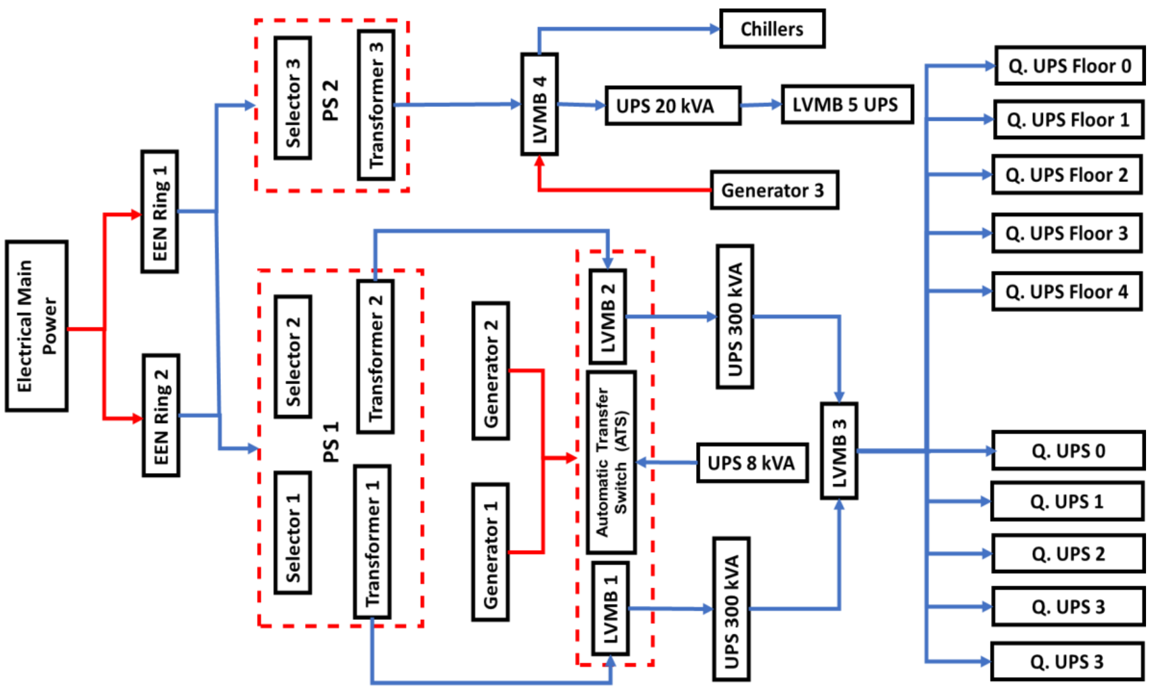
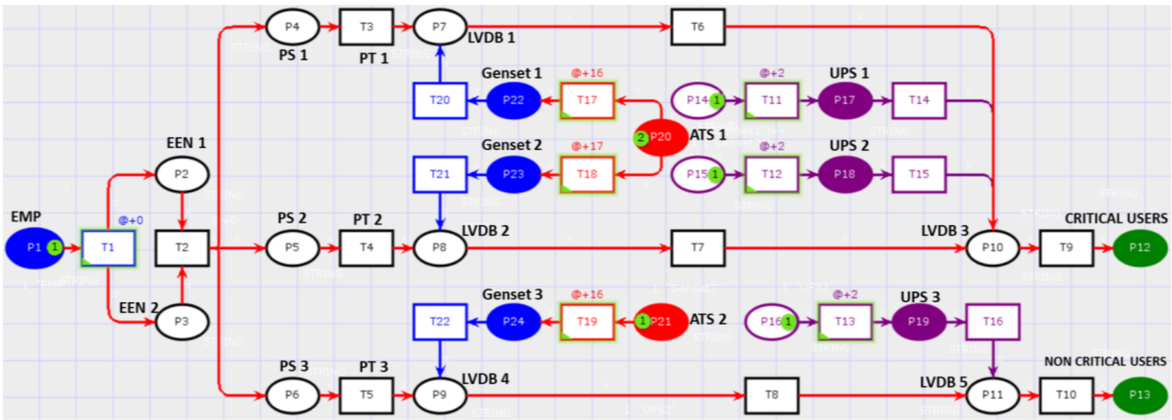


Figure 3.5 *Asset Process Flow Diagram (APFD)*

Based on the block diagram in Figure 3.3 or Figure 3.5, the assets can be modelled using Petri net, as shown in Figure 3.6, using the CPNTools simulator software with some tokens to show an image of the assets system.



DESCRIPTION:

EMP = Electrical Main Power (380 volts)
EEN = External Electric Network Rings 1& 2
PS = Power Selectors 1, 2 & 3
PT = Power Transformers 1, 2 & 3 (1000 kVA)
LVDB = Low Voltage Distribution Boards 1, 2, 3 & 4
ATS = Automatic Transfer Switches 1, 2, & 3
Genset = Generator Sets (1000 kVA)
UPS = Uninterruptible Power Supplies 1, 2, & 3 (300 kVA)

Figure 3.6 *Asset process Petri Net Modelling.*

CHAPTER 4. DYNAMIC MODELLING OF THE HOSPITAL´S ELECTRICAL SYSTEM USING PETRI NETS, FIS AND STOCHASTIC OR MARKOV CHAIN

4.1 Modelling of the Hospital Electrical system by Petri nets simulator CPNTools

One objective of the research supporting this thesis is to analyse the dynamics of the hospital power system and its weaknesses. A Petri net model can adequately represent this type of behaviour. Figure 3.6 illustrates the series of Petri Nets implementations using the CPNTools software program to simulate the hospital's electric power supply diagram under consideration, as shown in Figures 3.3 and 3.5. and 3.6, regarding the Petri Nets circuit, shows the primary current from the Electrical Main Power (EMP) that enters through the External Electric Network (EEN 1 and 2); then, it goes to selectors 1, 2 and 3; from the selector, it continues to transformer 1, 2 and 3; the electrical current continues to Low Voltage Distribution Board (LVDB) 1, 2 and 4, forwarded to UPS 1, 2, and 3; then, it goes to LVDB 3 and 5 and, finally, to the user, that is the hospital in regular operation (Figures 4.1- 4.5). The Petri Net circuit, in some transitions, has a time set; then, there are the changes that fire out tokens from the generators in the time when the UPS runs out of energy, that is, between 15 and 20 seconds. The contributions use Petri Nets to define and analyse this case study to determine the system's essential critical items or modules. In this way, we can easily control the physical assets to provide management maintenance procedures to guarantee reliability and availability conditions. It is possible to mitigate new asset failures.

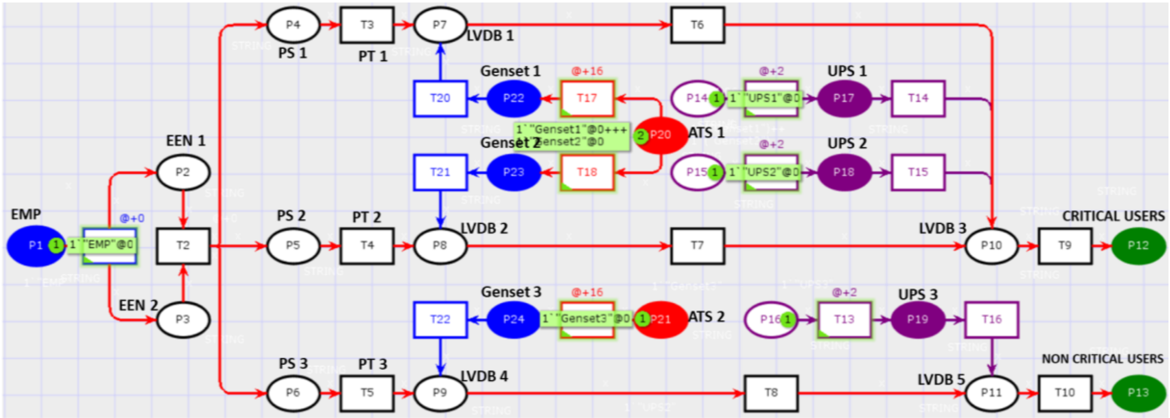


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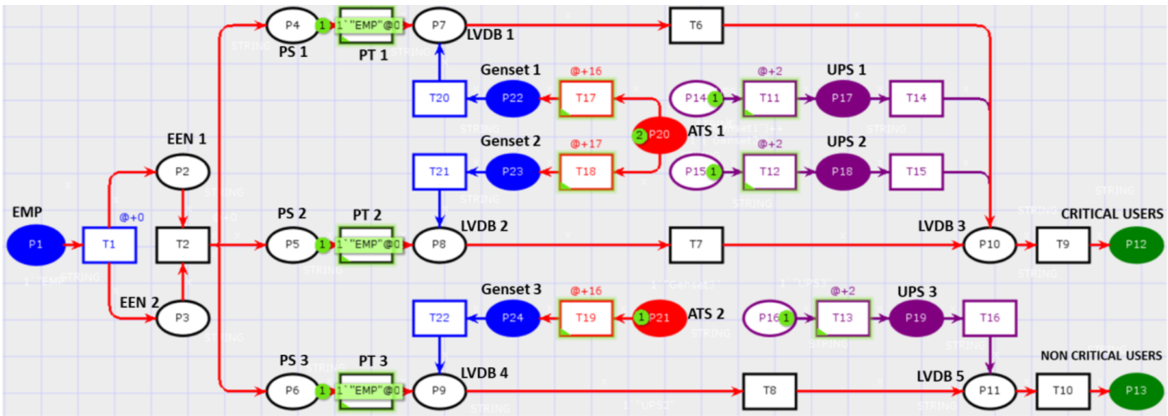
Figure 4.1 *Using CPNTools software for modelling and simulating STPNs on electric power systems*



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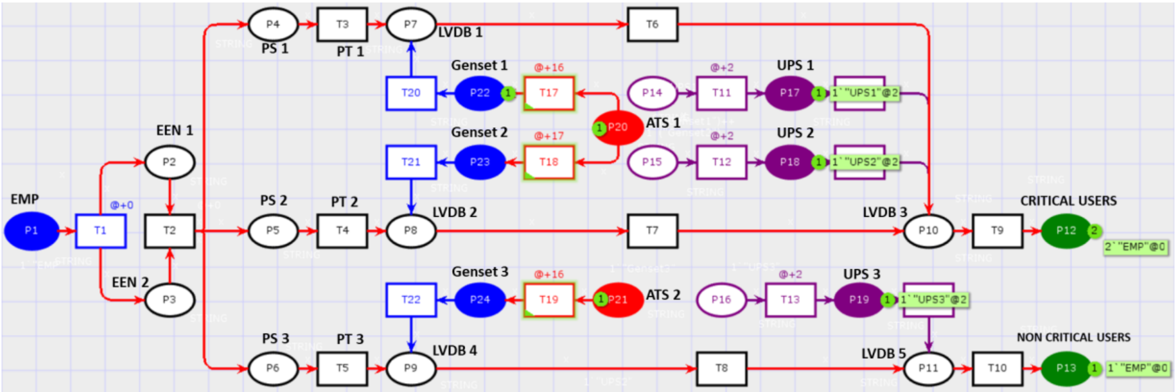
ATS = Automatic Transfer Switches 1, 2, & 3
Genset = Generator Sets (1000 kVA)
UPS = Uninterruptible Power Supplies 1, 2, & 3 (300 kVA)

Figure 4.2 *Modelling and simulating in stochastic time Petri nets of the electrical power system, tokens from EMP move to PS 1, 2 & 3 positions*



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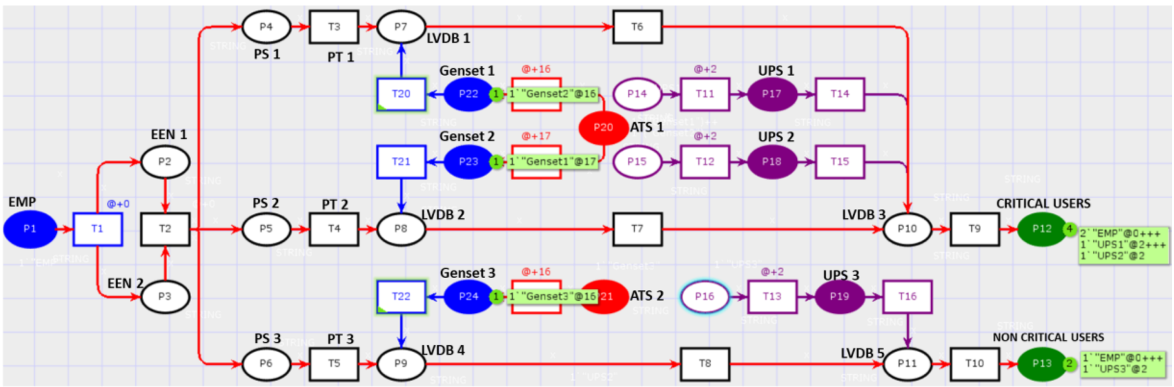
PT = Power Transformers 1, 2 & 3 (1000 kVA)
LVDB = Low Voltage Distribution Boards 1, 2, 3 & 4
ATS = Automatic Transfer Switches 1, 2, & 3
Genset = Generator Sets (1000 kVA)
UPS = Uninterruptible Power Supplies 1, 2, & 3 (300 kVA)

Figure 4.3 *The UPS 300KVA 1, 2 and 3 tokens are ready to move to the LVDB 3 & 5, acting to replace electricity that does not work or leaves the 380 volts main energy supply (EMP)*



DESCRIPTION:
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PS = Power Selectors 1, 2 & 3
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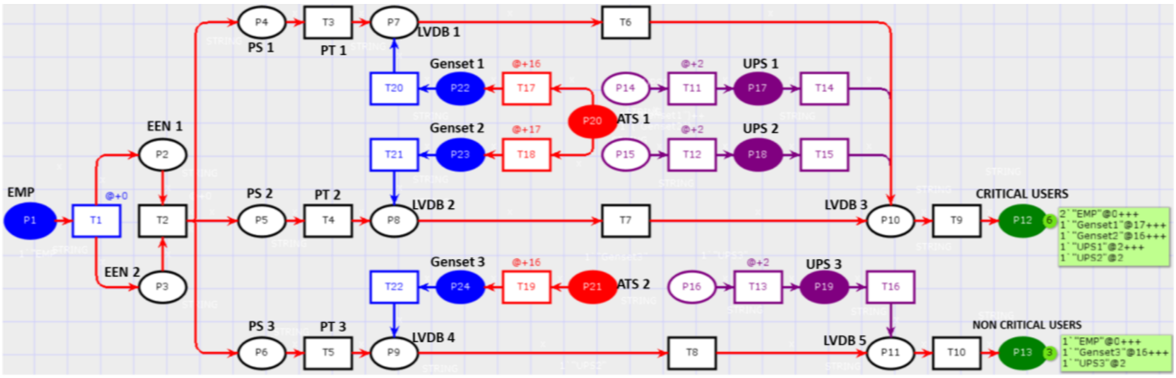
ATS = Automatic Transfer Switches 1, 2, & 3
Genset = Generator Sets (1000 kVA)
UPS = Uninterruptible Power Supplies 1, 2, & 3 (300 kVA)

Figure 4.4 *When UPS 300 KVA 1, 2 and 3 continue to guarantee power to the user, ATS 1 & 2 activate generators 1, 2 and 3 1000 KVA and 500KVA to ensure safety and continuity of power in the system*



DESCRIPTION:
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Genset = Generator Sets (1000 kVA)
UPS = Uninterruptible Power Supplies 1, 2, & 3 (300 kVA)

Figure 4.5 *In this series of STPNs, all tokens from EMB, UPS 1, 2 & 3 and Genset 1, 2 & 3 have transferred their tokens to the Users, and the situation could be back to regular operation.*

Figures 4.1- 4.5 show a Petri net that corresponds to a schematic diagram of a series of emergencies hospital electricity systems (Figure 3.3 or 3.5), which are the research targets to ensure the most sensitive and critical equipment, which, it fails, it implies severe problems to the hospital operations. This approach permits the analysis and simulation of schematic diagrams representing the electrical systems through the moving tokens from one place to another, according to the system's natural functioning; easily, the sensitive and critical equipment of the hospital emergency electrical circuit can be identified. Using Petri Nets simulation ensures that the most critical instrument is the Automatic Transfer System (ATS) activated by an electronic or computer. The power system has only one ATS installed; if a failure occurs, the generators must be activated manually, which may imply high risks.

4.2 Modelling the Hospital Electrical System by Block Diagrams

According to European standards, this section aims to ascertain if the hospital's electrical installation is entirely safe in terms of Reliability. After observing and tracing the whole sequence of events, the questions to answer are the following:

- What is ascertained is the most critical component or equipment?
- Does the entire series follow the security standards recommended by the international security standards?

The ATS drawing presented in Figure 4.6, corresponding to the schematic diagram, describes the electrical sequences that exist in the hospital according to the above questions. From the block diagram of Figure 3.5, it can be seen that Electrical Main Power (EMP) enters through two boards of External Electric Network (EEN), rings 1 & 2; then, it connects to PS 1 & 2 (Power Station), from where it continues to the sectors 1, 2 & 3 and Transformers 1, 2 & 3 inboard one. So, it continues through the LVDB 1 & 2 (Low Voltage Distributions Board), in which it is connected to an Automatic Transfer Switch (ATS) by a Genset activator if something fails. Then, the LVDB 1 & 2 is forwarded to UPS 1 & 2 (Uninterruptible Power Supply) of 300 KVA. After that, all power sources are delivered through LVDB 3 and continue to the 20 KVA UPS directly to the user. The energy that enters PS 2 (is not widely discussed because it connects loads that are not critical). The subject's in-depth study is the energy that goes into PS1 connected to the critical hospital units; from here, we must observe or analyse the essential systems in the electrical hospital’s circuits. To determine if the requirements are followed, one by one, about all functions and malfunctions of the power circuits, we can ensure the devices and systems that may cause failures in physical assets’ functioning and how to solve them. If the Main Electric Power (EMP) fails, then UPS 1 and 2 with 300 KVA automatically take over the function and continue to supply power to the system; thus, being able to overcome the dangers that occur during downtime, UPS 1 and 2 300 KVA will be backed up by generators 1 and 2 with 1000 KVA.

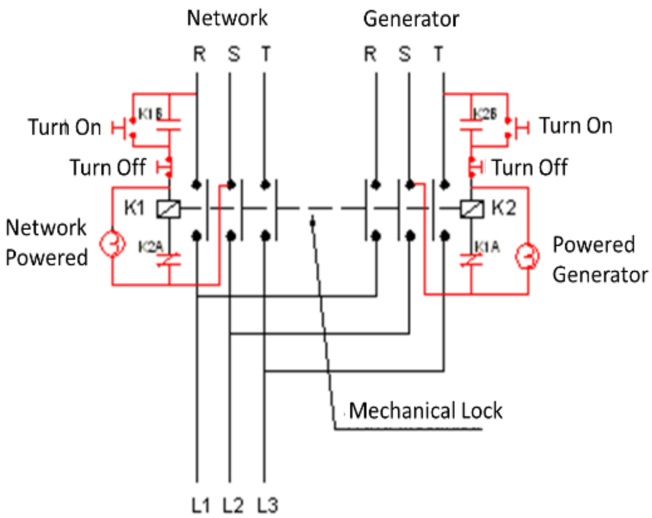


Figure 4.6 *A T S (Automatic Transfer Switch).*

The ATS manages the generators - if it does not work, the generators must be activated manually, which harms the system. Additionally, it can be emphasized that only one ATS is installed. So, the question arises: how has the above circuit met to respond to the expected security system? To answer this question, let us simulate the present situation and the proposed solution to solve the identified handicap with block diagrams, as shown in Figures 4.7 – 4.10.

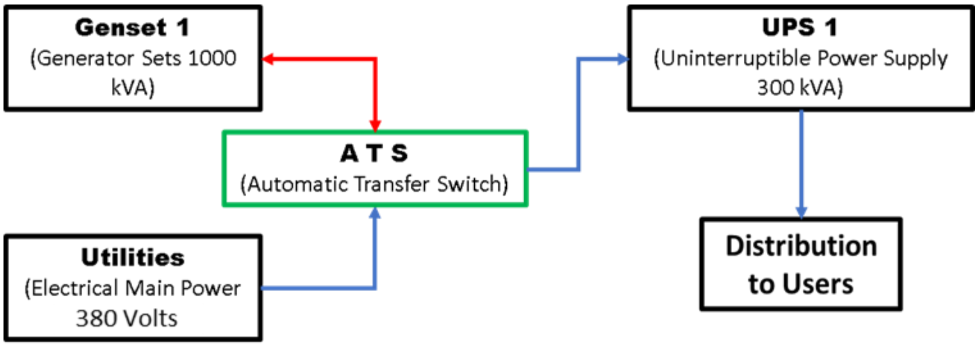


Figure 4.7 *Design with an evident weakness, with one ATS, one UPS and one Genset*

In the block diagram of Figure 4.7, we emphasize the hypothesis of a fault in the current from the mains power when the UPS takes over the primary function. In this situation, the ATS activate the Generator that replaces the UPS while waiting for the main electrical power to be on again; unfortunately, if one of the ATS, UPS, and Generator fails, then a fatal accident occurs, which permits infer that this is a very weakness module.

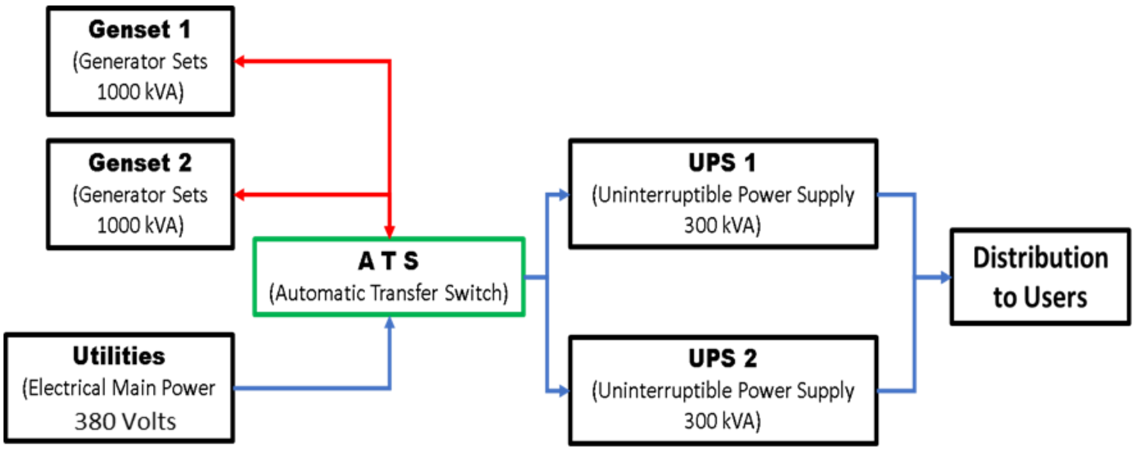


Figure 4.8 *Weakness module with increased reliability, through 1 ATS, 2 UPS and 2 Genset*

In the block diagram of Figure 4.8, if there is a current break from the main power, UPS 1 & 2 will turn on. Then, ATS activates Genset 1 & 2 to replace the UPS function while waiting for that main electrical power to be on again; if one UPS or Genset fails, another UPS will replace the Genset. A fatal accident occurs when the ATS fails because there is only one installed; this design corresponds to a weak module because it is deemed less reliable, implying additional maintenance costs.

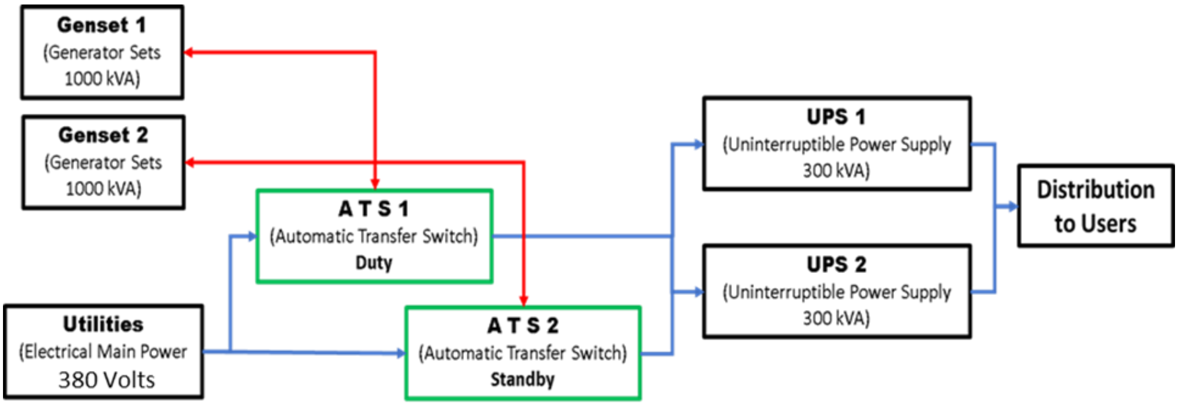


Figure 4.9 *Improved Design - better reliability due to the redundancy, with 2 ATS, 2 UPS and 2 Gensets*

In the block diagram of Figure 4.9, if there is a current break from the main power, UPS 1 & 2 will turn on. Then, ATS activates Genset 1 & 2 to replace the UPS function; while waiting for that, the main electrical power is on again; if one of the UPS, Genset or ATS, fails, then it will be replaced by UPS, Genset, and other ATS; so, no fatality accident occurs, what may be considered a suitable design module, because it is considered to be reasonably reliable; however, the cost of system and maintenance increase.

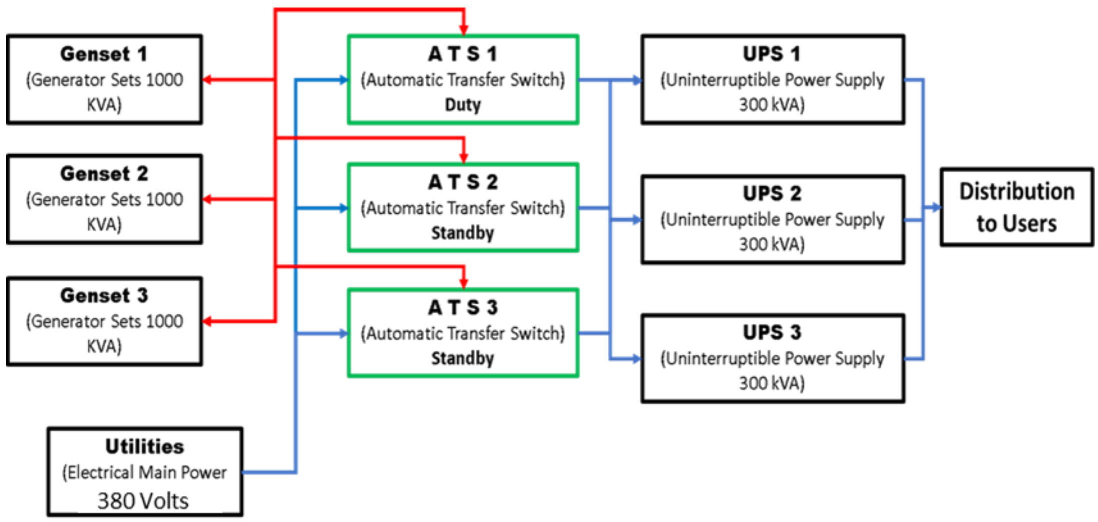


Figure 4.10 *Increased reliability due to the introduction of another level of redundancy, with 3 ATS, 3 UPS and 3 Genset*

In the block diagram of Figure 4.10, if there is a current fault from the main power, the UPS 1, 2 & 3 will turn on the main power's functions. Then, ATS activates Genset 1, 2 & 3, replacing the UPS function, while waiting for an intervention from the maintenance team; if one of the UPS, Genset or ATS, fails, then it will be replaced by the other UPS (Genset and ATS) because there is a redundancy of three units, so, no more fatality accidents occur. This design can be considered Good Design because it is considered reliable; however, the system's cost and maintenance are more expensive because they need to install more equipment. It can be concluded that the components of the system are critical to the electrical hospital functioning, and the ATS is the most critical item. Consequently, the electrical sequences that must be carefully targeted for research were discussed and analysed to identify each module's main functions and failures for the installed load. However, because the hospital does not provide historical data, this is a substantial barrier to this research. Therefore, this research will support the next steps in

Fuzzy Petri Nets and, when possible, in stochastic Petri Nets to continue analysing this problem.

4.3 Modelling and analyzing with Fuzzy Inference System

The author uses the MATLAB fuzzy tool and the fuzzy Mamdani method for computing.

Fuzzification Data Processing

After analysing the electricity system of the hospital, using Petri nets and the block diagrams design to find the most critical instruments or items in the asset, now we use fuzzy MATLAB to determine how reliable and available the system is according to their several states to determine the input and output functions of the system by the specified setpoint; it will use information and conditions, such as main electric power worth 420, Genset 1 and 2 700, ATS 140, and UPS 1 and 2 220. The removal of all inputs and outputs is presented in Figures 4.11 – 4.14.

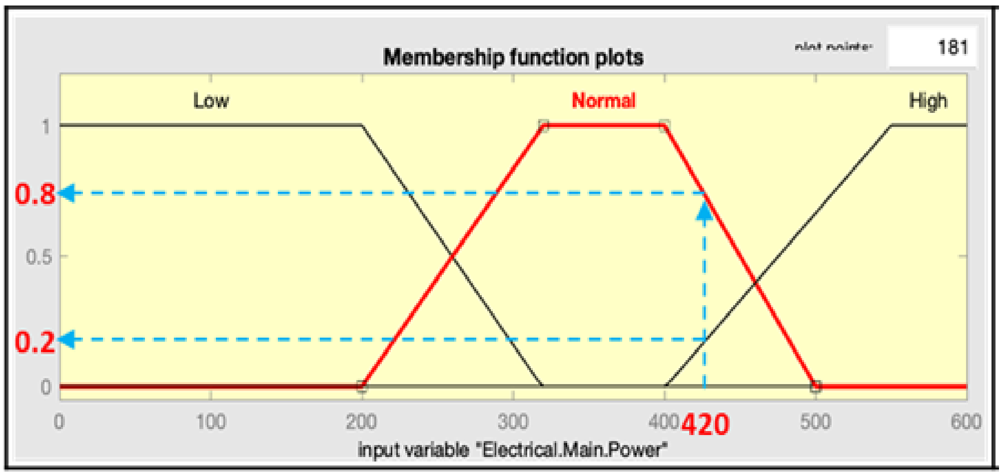


Figure 4.11 *Electrical Main Power*

$$\mu Normal\ \ (420)\ =\frac{(500-420)}{(500-400)}=\mathbf{0.8}$$

$$\mu High(420)=\frac{(420-400)}{(500-400)}=\frac{20}{100}=\mathbf{0.2}$$

Thus, we can conclude that the Fuzzy set for input "Electrical Main Power" is as follows:

Fuzzy Low set - µLow (420) = 0

Fuzzy Normal set - µNormal (420) = 0.8

Fuzzy High set - µHigh (420) = 0.2

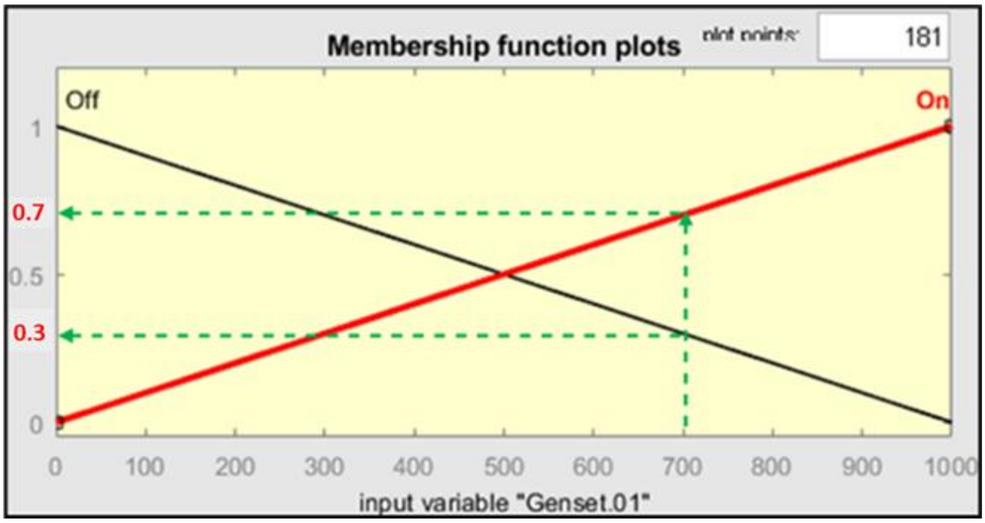


Figure 4.12 *Genset 01 & 02*

$$\mu On(700)=\frac{\mathbf{700-0}}{\mathbf{1000-0}}=\frac{\mathbf{700}}{\mathbf{1000}}=\frac{\mathbf{7}}{\mathbf{10}}=\mathbf{0.7}$$

$$\mu Off(700)=\frac{\mathbf{1000-700}}{\mathbf{1000-0}}=\frac{\mathbf{300}}{\mathbf{1000}}=\frac{\mathbf{3}}{\mathbf{10}}=\mathbf{0.3}$$

Thus, we can conclude that the Fuzzy set for input "Genset 01 = Genset 02" is as follows:

Fuzzy set On: µOn (700) = 0.7

Fuzzy set Off: µOff (700) = 0.3

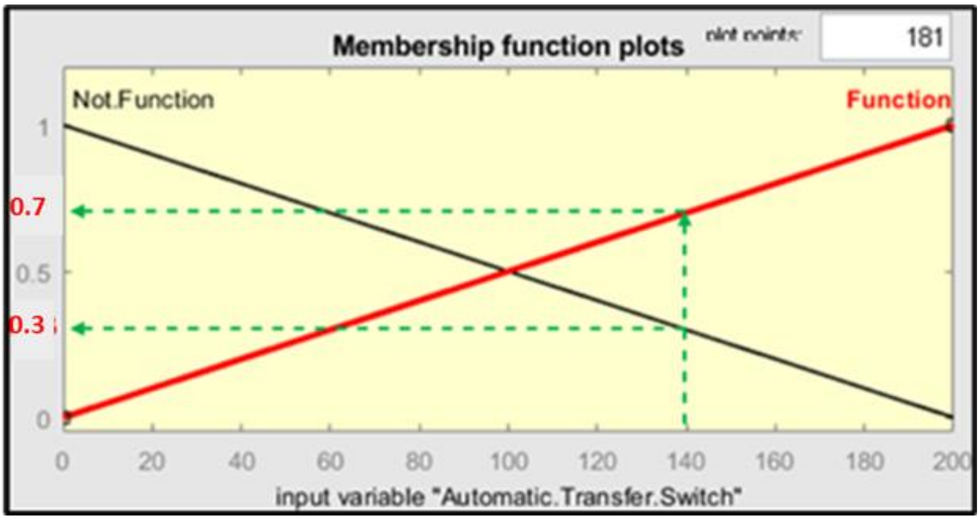


Figure 4.13 *ATS*

$$\boldsymbol{\mu Function(140) = \frac{140-0}{200-0} = 0.7}$$

$$\boldsymbol{\mu Not\ Function(140) = \frac{200-140}{200-0} = 0.3}$$

Thus, we can conclude that the Fuzzy set for the input of the Automatic Transfer Switch is as follows:

Fuzzy Function set - µFunction (140) = 0.7

Fuzzy Not Function set - µOff (700) = 0.3

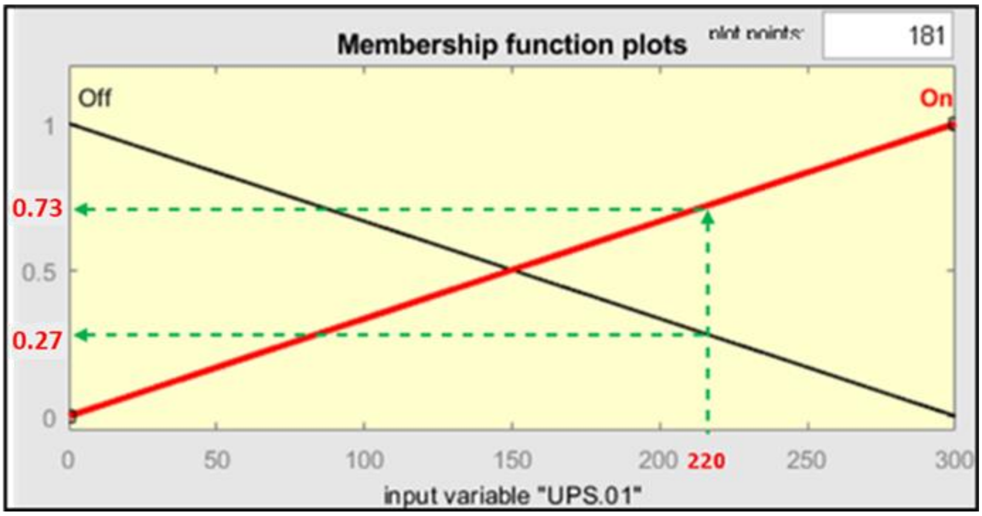


Figure 4.14 *UPS 01 & 02*

$$\mu On(220) = \frac{\mathbf{220-0}}{\mathbf{300-0}} = \mathbf{0.73}$$

$$\mu Off(220) = \frac{\mathbf{300-220}}{\mathbf{300-0}} = \mathbf{0.27}$$

Thus, we can conclude that the fuzzy set for input UPS 01 = UPS 02 is as follows:

Fuzzy On set: µOn (220) = 0.73

Fuzzy Off set: µOff (220) = 0.27

If we collect all input variables: Electrical Main Power = 420; Genset 01 and 02 = (700 x 2); Automatic Transfer Switch = 140 and UPS 01 & UPS 02 = (220 x 2). Then, we get the following values:

Fuzzy Low set: µLow (420) = 0

Fuzzy Normal set: µNormal (420) = 0.8

Fuzzy High set: µHigh (420) = 0.2

Fuzzy set On: µOn (700) = 0.7

Fuzzy set Off: µOff (700) = 0.3x2 (the value of two Genset)

Fuzzy Function set: µFunction (140) = 0.7

Fuzzy Not Function set: µOff (700) = 0.3

Fuzzy set On: µOn (220) = 0.73

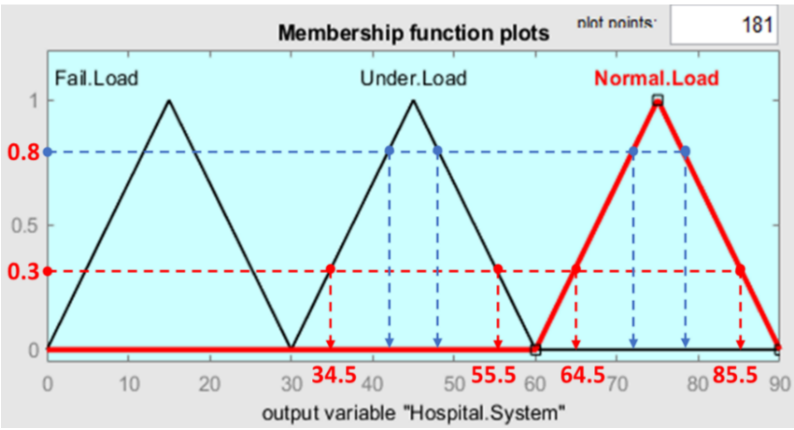
Fuzzy set Off: µOff (220) = 0.27x2 (the value of two UPS)

So, the Maximum and Minimum Values of the above calculation are as follows:

Maximum Value: $\mu 1 = 0$; $\mu 2 = 0.8$; $\mu 3 = 0.7$; $\mu 4 = 0.7$; $\mu 5 = 0.7$; $\mu 6 = 0.73$ and $\mu 7 = 0.73$

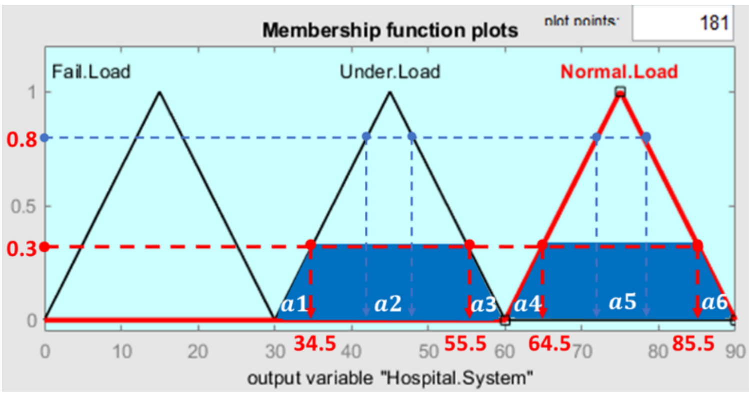
Minimum Value: $\mu 1 = 0$; $\mu 2 = 0.2$; $\mu 3 = 0.3$; $\mu 4 = 0.3$; $\mu 5 = 0.3$; $\mu 6 = 0.27$ and $\mu 7 = 0.27$.

Using the Fuzzy set operator "AND", the value taken is the lowest, so: {0.2 + (0.3 * 2) + 0.3 + 0.27 * 2)} / 6 = 0.28 ≈ 0.3 (minimum total value of input variable) (Figures 4.15 - 4.16).



$$\mu Under\ Load(0.3) = \frac{x - 30}{45 - 30}$$
$x - 30 = 0.3 * 15$
$x1 = 34.5$
$$\mu Under\ Load(0.3) = \frac{60 - x}{60 - 45}$$
$60 - x = 0.3 * 15$
$x2 = 55.5$
$$\mu Normal\ Load(0.3) = \frac{x - 60}{75 - 60}$$
$x - 60 = 0.3 * 15$
$x3 = 64.5$
$$\mu Normal\ Load(0.3) = \frac{90 - x}{90 - 75}$$
$90 - x = 0.3 * 15$
$x4 = 85.5$

Figure 4.15 *Output maximum and minimum point in fuzzification*



$$a1 = \frac{(34.5 - 30) * 0.3}{2} = 0.68$$
$$a2 = (55.5 - 34.5) * 0.3 = 6.3$$
$$a3 = \frac{(60 - 55.5) * 0.3}{2} = 0.68$$
$$a4 = \frac{(64.5 - 60) * 0.3}{2} = 0.68$$
$$a5 = (85.5 - 64.5) * 0.3 = 6.3$$
$$a6 = \frac{(64.5 - 60) * 0.3}{2} = 0.68$$

Figure 4.16 *Output area of fuzzification*

The Defuzzification method used is the Centroid Of Gravity (COG).

In this case, we used the minimum value of μ because the rules are “AND” follow Fuzzy logic requirements.

Minimum Value:

$\mu1 = 0; \mu2 = 0.2; \mu3 = 0.3; \mu4 = 0.3; \mu5 = 0.3; \mu6 = 0.27$ and $\mu7 = 0.27.$

$$Z^* = \frac{(\mu2 * x1) + (\mu3 * x2) + (\mu4.5 * \ x3) + (\mu6.7 * x4)}{(\mu2 + \mu3 + \mu4.5 + \mu6.7)}$$

$$Z^* = \frac{(0.2 * 34{,}5) + (0.3 * 55.5) + (0.3 * 64.5) + (0.27 * 85.5)}{(0.2 + 0.3 + 0.3 + 0.27)} = \mathbf{61.3}$$

The other way to solve the Centroid of Gravity method is using calculus mathematics as follows:

$$\mu(z) = \begin{cases} 0, & x \le or\ x \ge 90 \\ \dfrac{x-30}{45-30}, & 30 \le x \le 34.5 \\ 0.3, & 34.5 \le x \le 55.5 \\ \dfrac{60-x}{60-45}, & 55.5 \le x \le 60 \\ \dfrac{x-60}{75-45}, & 60 \le x \le 75 \\ 0.3, & 64.5 \le x \le 85.5 \\ \dfrac{90-x}{90-75}, & 85.5 \le x \le 90 \end{cases} \quad \Rightarrow \quad \mu(z) = \begin{cases} 0, & x \le or\ x \ge 90 \\ 0.067x - 2, & 30 \le x \le 34.5 \\ 0.3, & 34.5 \le x \le 55.5 \\ 4 - 0.067x, & 55.5 \le x \le 60 \\ 0.067x - 4, & 60 \le x \le 75 \\ 0.3, & 64.5 \le x \le 85.5 \\ 6 - 0.067, & 85.5 \le x \le 90 \end{cases}$$

The Defuzzification method uses the centroid of gravity (COG):

$$M1 = \int_{30}^{34.5} (0.0666z - 2)z\,dz = \int_{30}^{34.5} (0.00666z^2 - 2z)dz = 0.0222z^3 - z^2|_{30}^{34.5} = 21.9625$$

$$M2 = \int_{34.5}^{55.5} (0.3)z\,dz = \int_{34.5}^{55.5} (0.3z)dz = 0.15z^2 - z^2|_{34.5}^{55.5} = 283.5$$

$$M3 = \int_{55.5}^{60} (4 - 0.0666z)z\,dz = \int_{55.5}^{60} \left(4z - 0.00666z^2\right)dz = 2z^2 - 0.0222z^3\,|_{55.5}^{60} = 39.4761$$

$$M4 = \int_{60}^{64.5} (0.0666z - 4)z\,dz = \int_{60}^{64.5} (0.00666z^2 - 4z)dz = 0.0222\,z^3 - z^2|_{60}^{64.5} = 41.362$$

$$M5 = \int_{64.5}^{85.5} (0.3)z\,dz = \int_{64.5}^{85.5} (0.3z)dz = 0.3z^2\,|_{64.5}^{85.5} = 472.5$$

$$M6 = \int_{85.5}^{90} (6 - 0.0666z)z\,dz = \int_{85.5}^{90} \left(6z - 0.00666z^2\right)dz = 3z^2 - 0.0222z^3\,|_{85.5}^{90} = 61.0356$$

The calculation of the centre point (centroid of gravity) is given as follows:

$$Z^* = \frac{(M1 + M2 + M3 + M4 + M5 + M6)}{(a1 + a2 + a3 + a4 + a5 + a6)}$$

$$Z^* = \frac{(21.9625 + 283.5 + 39.4761 + 41.362 + 472.5 + 61.0356)}{(0.68 + 6.3 + 0.68 + 0.68 + 6.3 + 0.68)} = \mathbf{60}$$

Therefore, the centre of gravity of the calculated drawing area is x=60 and point=0 as a balance of the hospital system's average electrical current (Figure 4.17).

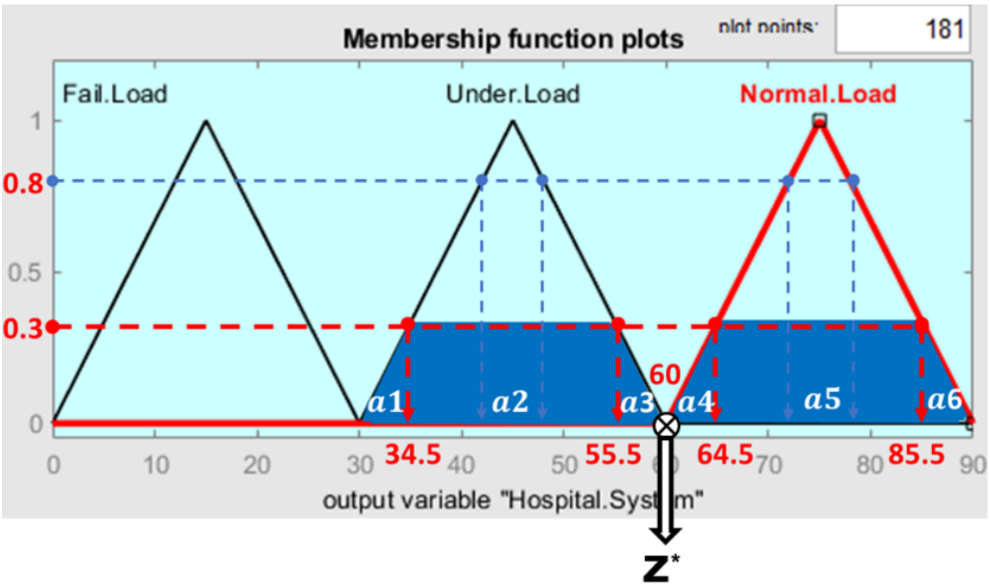


Figure 4.17 *The centre of gravity at coordinates x = 60 and μ = 0 of the drawing*

4.3.1 Fuzzy Logic Designer

Fuzzy Logic Designer in this study involves parameters including six inputs:

The fuzzy inference system (FIS) designer in this study involves parameters including six inputs: a) Electrical Main Power (380 MVA); b) two Gensets 01 & 02 (1000KVA); c) one Automatic Transfer Switch (ATS) and d) two UPS 01 & 02 (300KVA). The output parameter is shown in Figure 4.18.

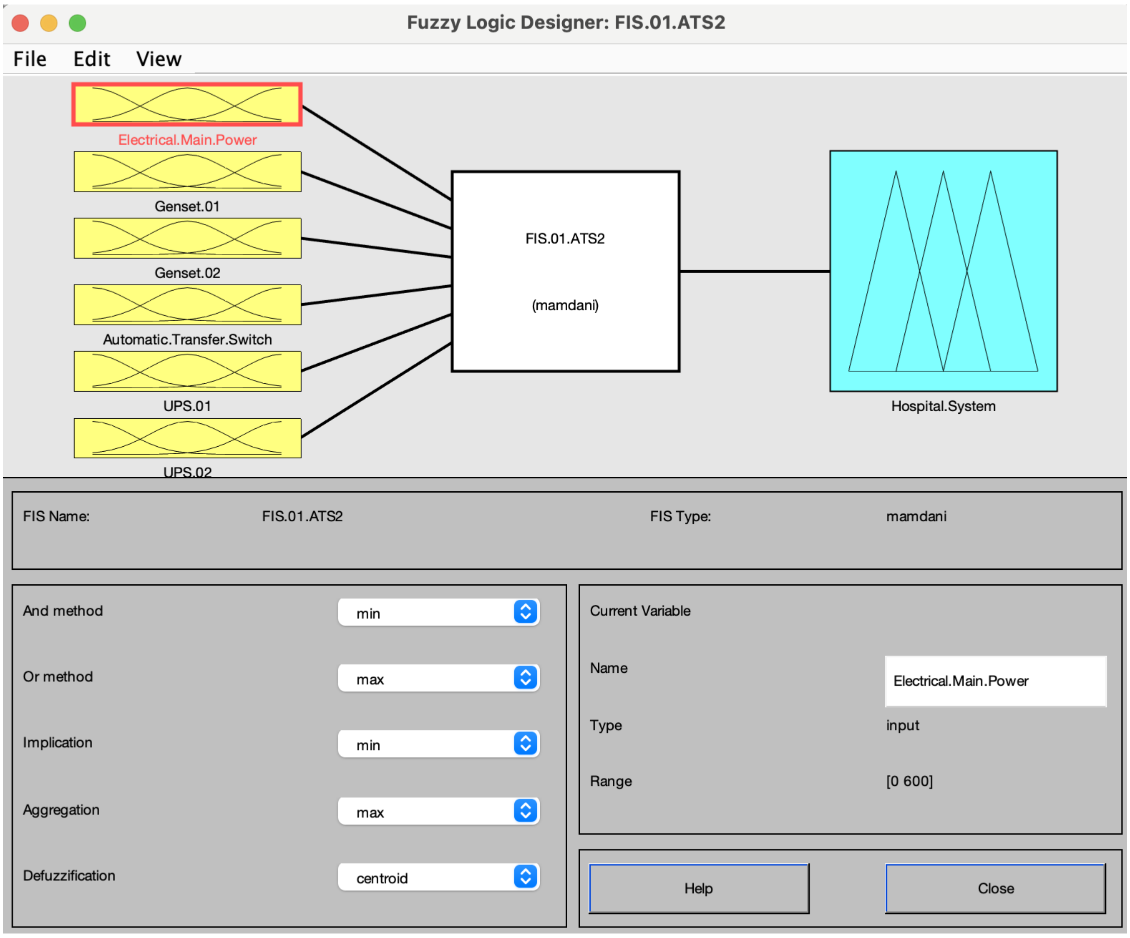


Figure 4.18 *Fuzzy Logic Design Variable Inputs and Output*

4.3.2 Membership Function Editor

The Membership Function Editors of Fuzzy Logic Design input variables are shown in Figures 4.19 - 4.24.

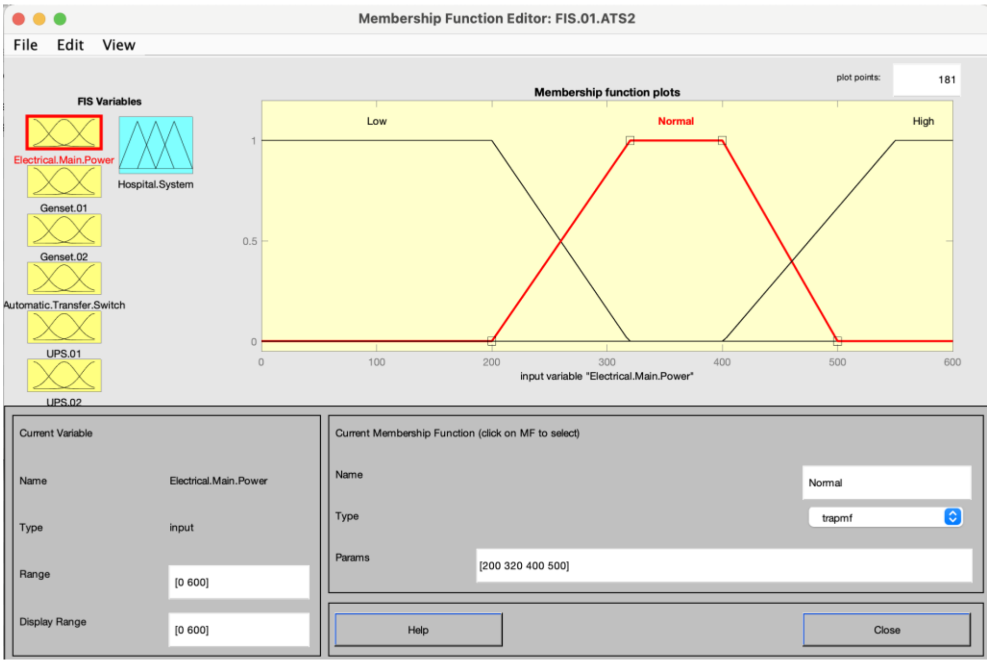


Figure 4.19 *Membership Function Editor input variable "Electrical Main Power"*

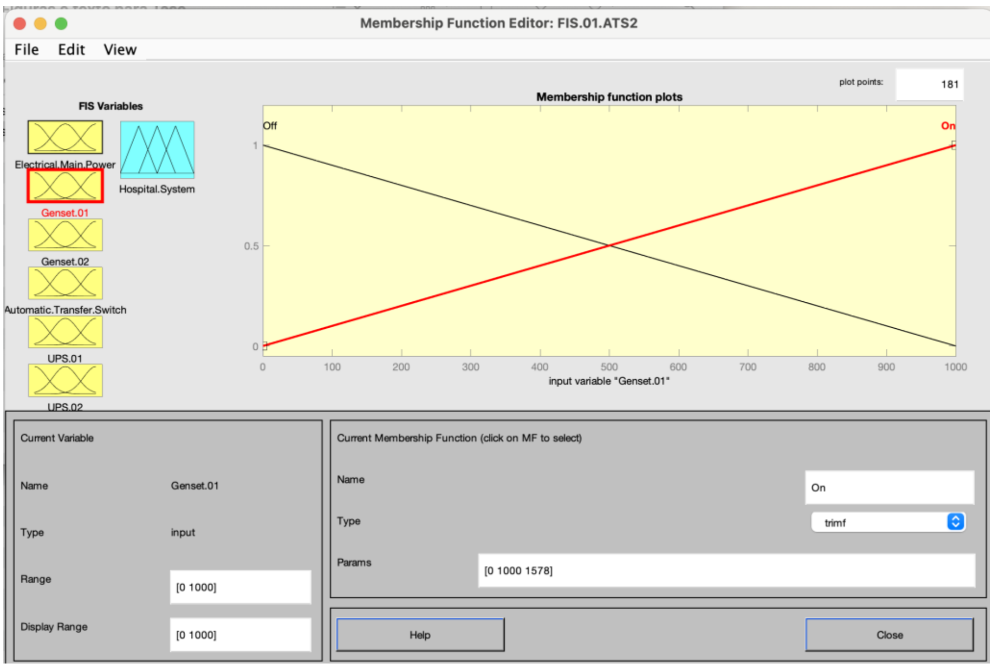


Figure 4.20 *Membership Function Editor input variable "Genset 01"*

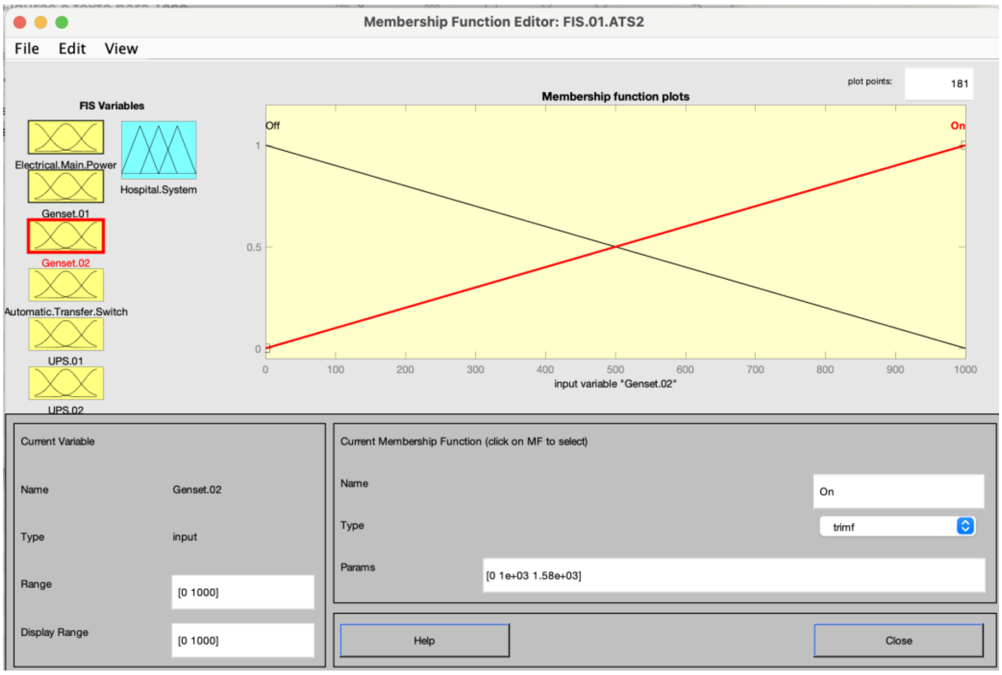


Figure 4.21 *Membership Function Editor input variable "Genset 02"*

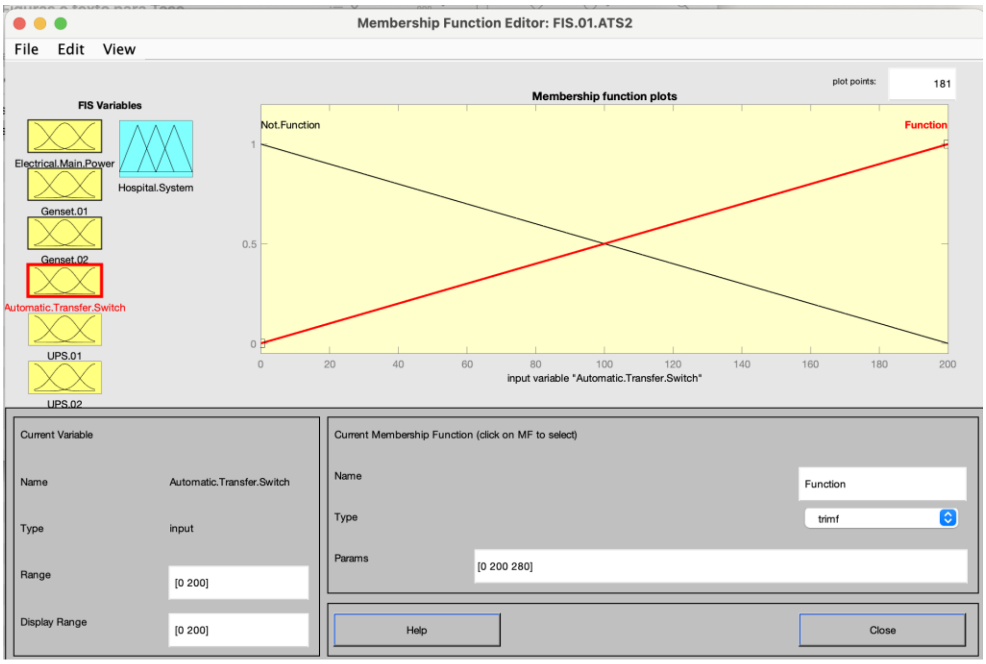


Figure 4.22 *Membership Function Editor input variable "Automatic Transfer Switch"*

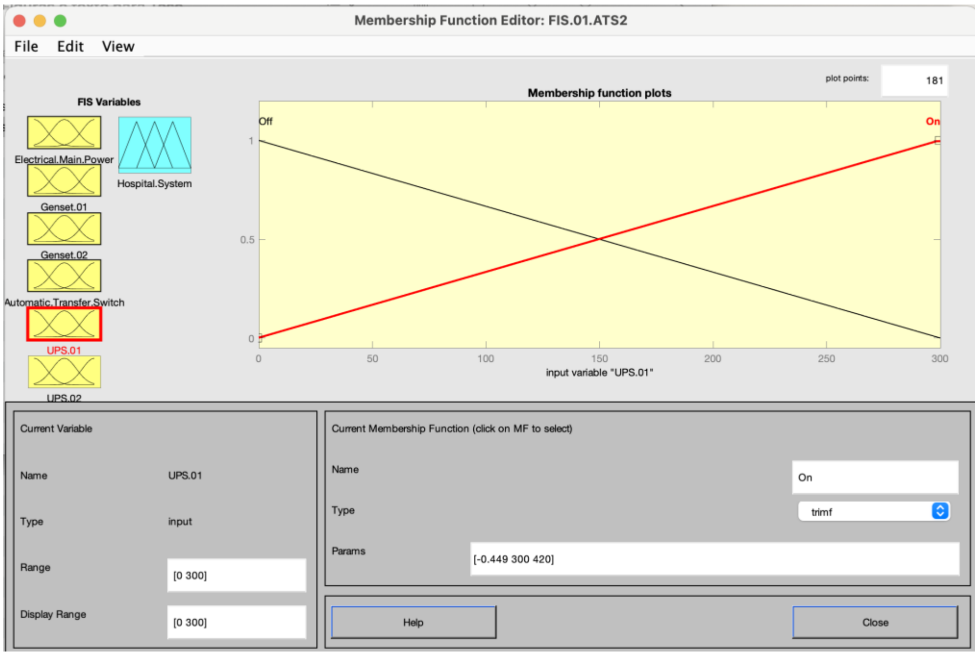


Figure 4.23 *Membership Function Editor input variable "UPS 01"*

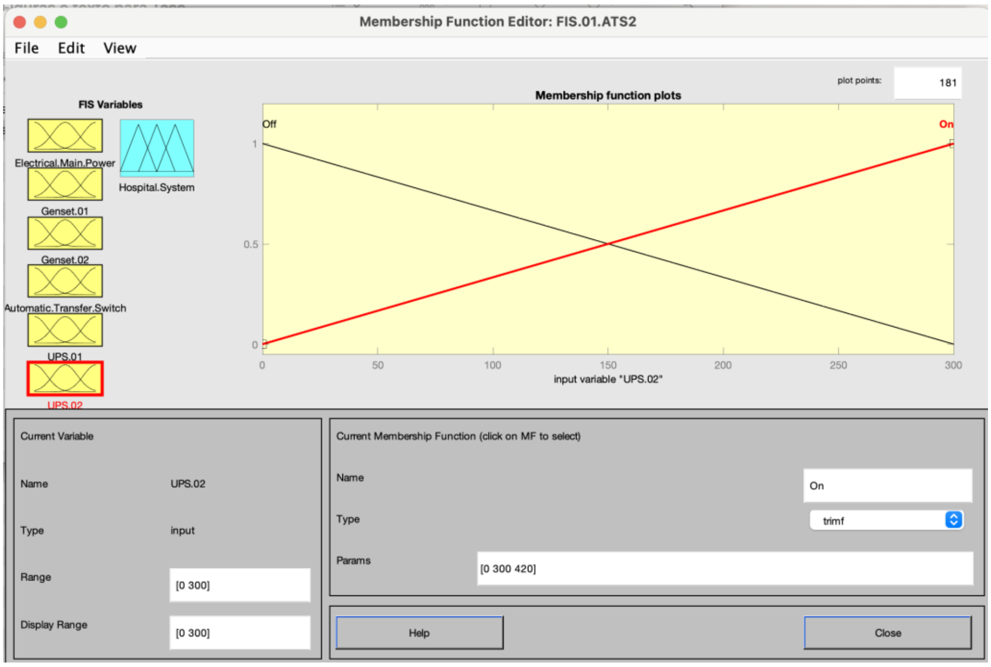


Figure 4.24 *Membership Function Editor input variable "UPS 02"*

Figures 4.19 – 4.24 show that the elements contained in it are intervals and parameters; however, the approach can be seen in Table 4.1, according to the respective related items in the Figure above in order.

Table 4.1 *Membership Function Editor corresponds to Figures 4.19 – 4.24, respectively.*

Input Function "EMP"			
Situation	Low	Normal	High
Range	(0 600)	(0 600)	(0 600)
Parameters	(-300 0 200 319)	(200 320 400 500)	(401 550 699 799)

(Corresponding to Figure 4.19)

Input Function "Genset 1 = Genset 2"		
Situation	Off	On
Range	(0 1000)	(0 1000)
Parameters	(-512 0 1000)	(0 1000 1578)

(Corresponding to Figures 4.20-4.21)

Input Function "ATS"		
Situation	Not Function	Function
Range	(0 200)	(0 200)
Parameters	(-80 0 200)	(0 200 280)

(Corresponding to Figure 4.22)

Input Function "UPS 1 = UPS 2"		
Situation	Off	On
Range	(0 300)	(0 300)
Parameters	(-120 0 300)	(0 300 420)

(Corresponding to Figures 4.23-4.24)

The Membership Function Editor of Fuzzy Logic Design for "output" variables is designed based on the input voltage variation: if the voltage received on the system for Underload is 34.5% up to 55.5% and, at Normal load is 64.5% up to 85.5%, then, the output that appears in the Fuzzy MATLAB simulation is shown in Figure 4.25.

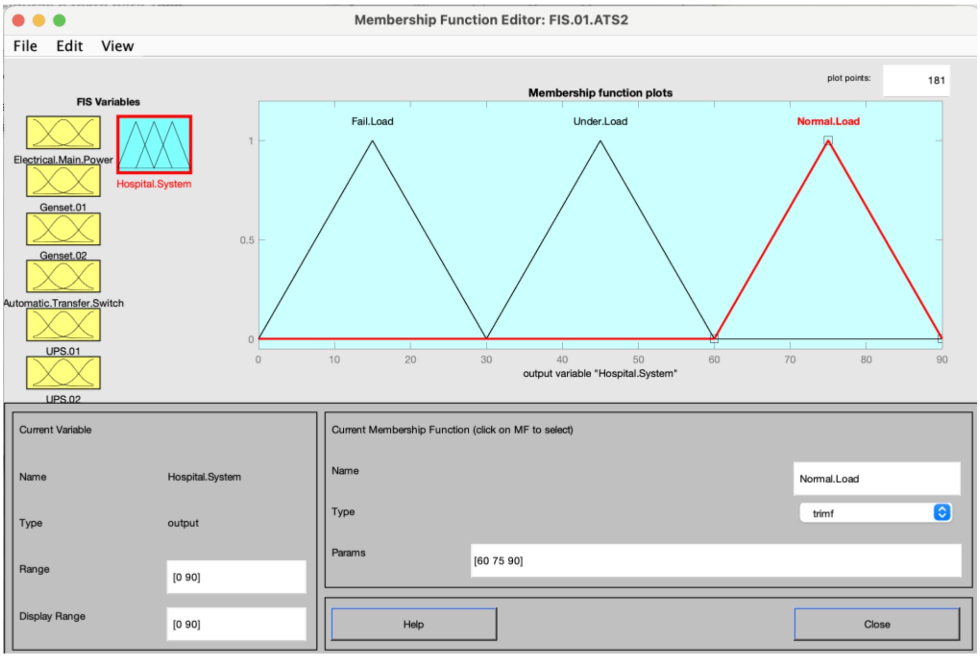


Figure 4.25 *Membership Function Editor output variable "Hospital System"*

In Figure 4.25, it is clear that the elements enclosed in it are the intervals and parameters; however, they can be supported by Table 4.2.

Table 4.2 *Output function "Hospital System".*

Output Function "EMP"			
Situation	Fail Load	Under Load	Normal Load
Range	(0 90)	(0 90)	(0 90)
Parameters	(0 15 30)	(30 45 60)	(60 75 90)

4.3.3 Rules of the Editor of Software

The next step is to apply the Fuzzy operator "AND & THEN" in fuzzy rules and the Fuzzy regulations that are by data collected and processed according to Fuzzy logic with the following 17 rules:

(1) If (Electrical Main Power is Low) and (Genset1 is Off) and (Genset2 is Off) and (Automatic Transfer Switch is Not Function) and (UPS1 is Off) and (UPS2 is Off) then (Hospital System is Failing Load);

(2) If (Electrical Main Power is Low) and (Genset1 is On) and (Genset2 is Off) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Under Load);

(3) If (Electrical Main Power is Low) and (Genset1 is Off) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Under Load);

(4) If (Electrical Main Power is Low) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is Off), then (Hospital System is Under Load);

(5) If (Electrical Main Power is Low) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is Off) and (UPS2 is On), then (Hospital System is Under Load);

(6) If (Electrical Main Power is Low) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Not Function) and (UPS1 is On) and (UPS2 is On) then (Hospital System is Under Load);

(7) If (Electrical Main Power is Low) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Normal Load);

(8) If (Electrical Main Power is Normal) & (Genset1 is Off) and (Genset2 is Off) and (Automatic Transfer Switch is Not Function) and (UPS1 is Off) and (UPS2 is Off) then (Hospital System is Failing Load);

(9) If (Electrical Main Power is Normal) and (Genset1 is Off) and (Genset2 is Off) and (Automatic Transfer Switch is Not Function) and (UPS1 is On) and (UPS2 is On) then (Hospital System is Under Load);

(10) If (Electrical Main Power is Normal) and (Genset1 is Off) and (Genset2 is Off) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Normal Load);

(11) If (Electrical Main Power is High) and (Genset1 is Off) and (Genset2 is Off) and (Automatic Transfer Switch is Not Function) and (UPS1 is Off) and (UPS2 is Off) then (Hospital System is Failing Load);

(12) If (Electrical Main Power is High) and (Genset1 is On) and (Genset2 is Off) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Under Load);

(13) If (Electrical Main Power is High) and (Genset1 is Off) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Under Load);

(14) If (Electrical Main Power is High) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is Off), then (Hospital System is Under Load);

(15) If (Electrical Main Power is High) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is Off) and (UPS2 is On), then (Hospital System is Under Load);

(16) If (Electrical Main Power is High) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Not Function) and (UPS1 is On) and (UPS2 is On) then (Hospital System is Under Load);

(17) If (Electrical Main Power is High) and (Genset1 is On) and (Genset2 is On) and (Automatic Transfer Switch is Function) and (UPS1 is On) and (UPS2 is On), then (Hospital System is Normal Load).

To support the fuzzy rules above is necessary to sort out the working orders of some critical equipment in the electrical power system of the hospital that is being analysed. Based on MATLAB software, the fuzzy inference system simulated how reliable and available their functions are to prevent failure. The support of the fuzzy rules that show the simulation of the referred electrical circuits functioning is shown in Table 4.3.

Table 4.3 ***Rules editor with numerical values for the fuzzy inference system of electrical systems.***

Rules Editor in terms of numerical in the fuzzy inference system								
	FIS membership fuctions inputs						FIS Membership outputs	
No.	EMP	Genset 1	Genset 2	ATS	UPS 1	UPS 2	Hospital System	
1	0	0	0	0	0	0	15	Fail
2	0	1000	0	200	300	300	45	Under Load
3	0	0	1000	200	300	300	45	Under Load
4	0	1000	1000	200	300	0	45	Under Load
5	0	1000	1000	200	0	300	45	Under Load
6	0	1000	1000	0	300	300	45	Under Load
7	0	1000	1000	200	300	300	75	Normal Load
8	360	0	0	0	0	0	15	Fail
9	360	0	0	0	300	300	45	Under Load
10	360	0	0	200	300	300	75	Normal Load
11	600	0	0	0	0	0	15	Fail
12	600	1000	1000	200	300	300	45	Under Load
13	600	0	1000	200	300	300	45	Under Load
14	600	1000	1000	200	300	0	45	Under Load
15	600	1000	1000	200	0	300	45	Under Load
16	600	1000	1000	0	300	300	45	Under Load
17	600	1000	1000	200	300	300	75	Normal Load

4.3.4 Rules Viewer

If (Electrical Main Power is Low) and (Genset1 is off) and (Genset2 is off) and (Automatic Transfer Switch is not function) and (UPS1 is off) and (UPS2 is off) then (Hospital System is failing load) – Figure 4.26.

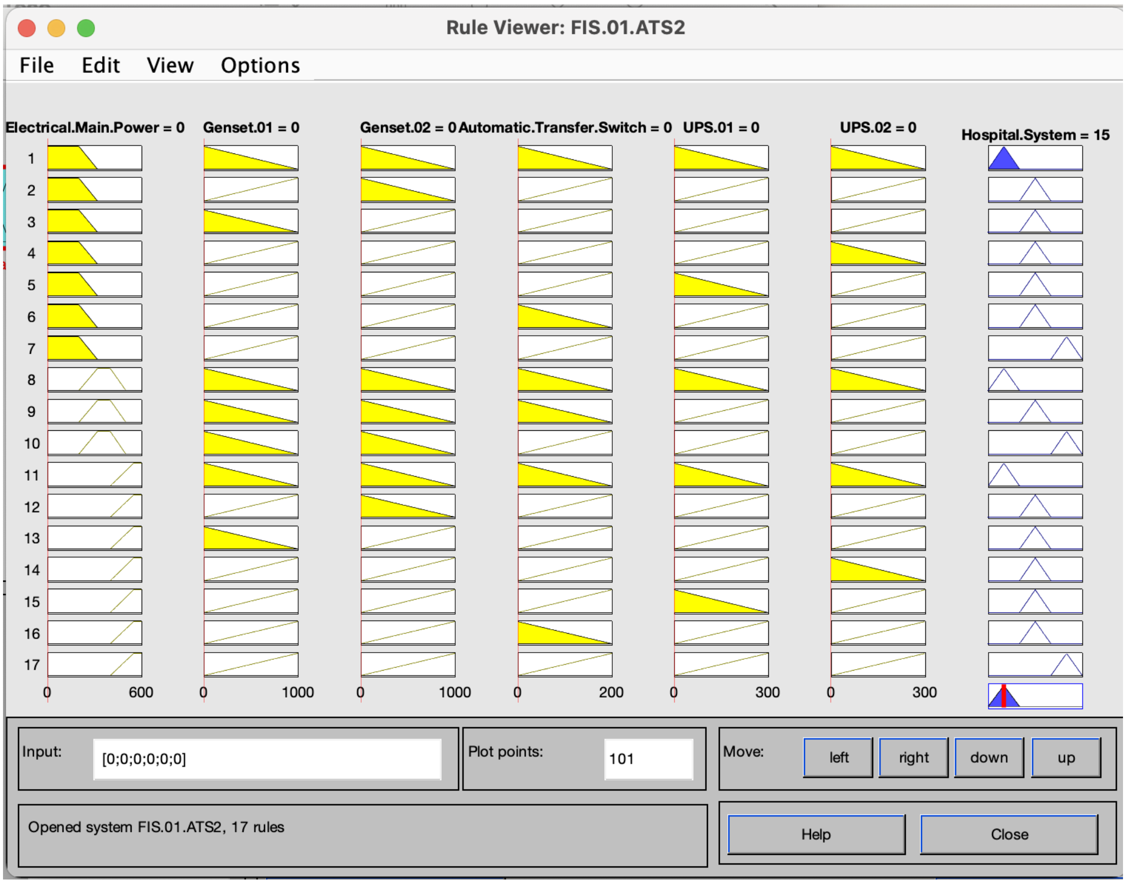


Figure 4.26 *Rules viewer of Fuzzy Logic System for Failing Load*

If (Electrical Main Power is standard) and (Genset1 is off) and (Genset2 is off) and (Automatic Transfer Switch is not function) and (UPS1 is on) and (UPS2 is on) then (Hospital System is Under Load) – Figure 4.27.

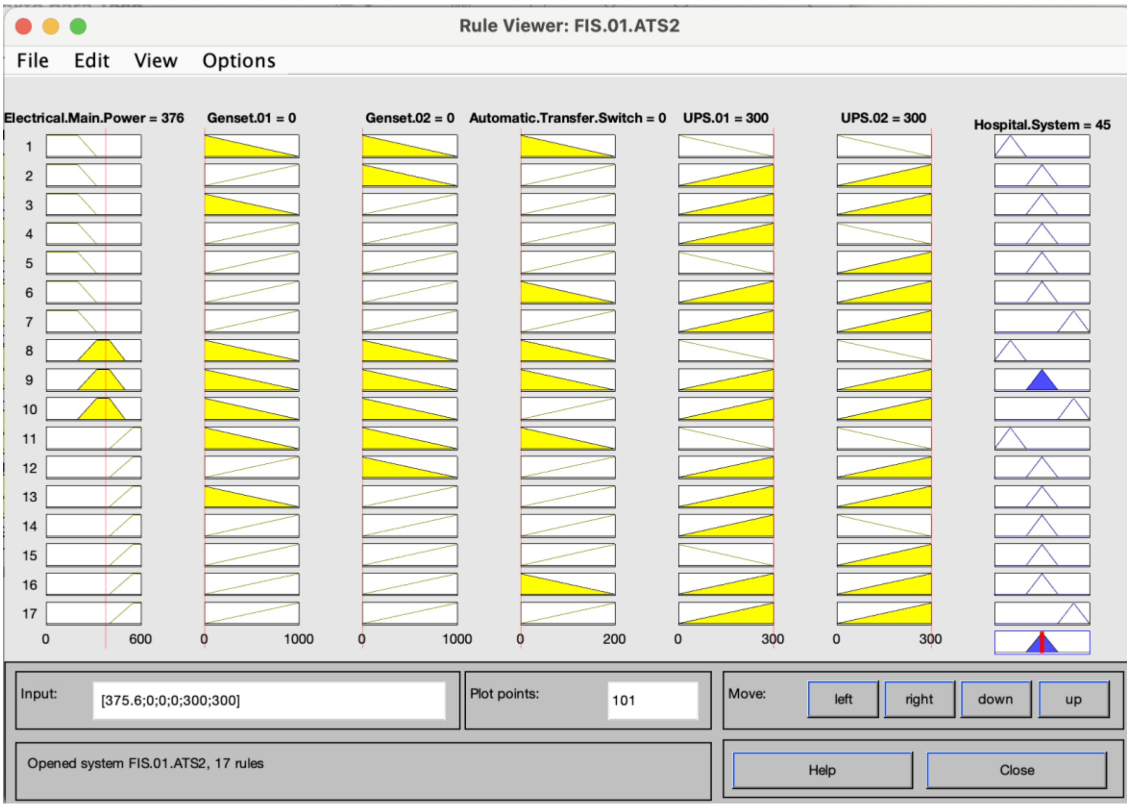


Figure 4.27 Rules viewer of Fuzzy Logic System for Under Load

If (Electrical Main Power is Low) and (Genset1 is on) and (Genset2 is on) and (Automatic Transfer Switch is a function) and (UPS1 is on) and (UPS2 is on) then (Hospital System is Normal load) – Figure 4.28.

Figure 4.28 Rules viewer of Fuzzy Logic System for Normal Load

4.3.5 Surface Viewer

If (Electrical Main Power is Low) and (Genset1 is off) and (Genset2 is off) and (Automatic Transfer Switch is not function) and (UPS1 is off) and (UPS2 is off) then (Hospital System is failing load) – Figure 4.29.

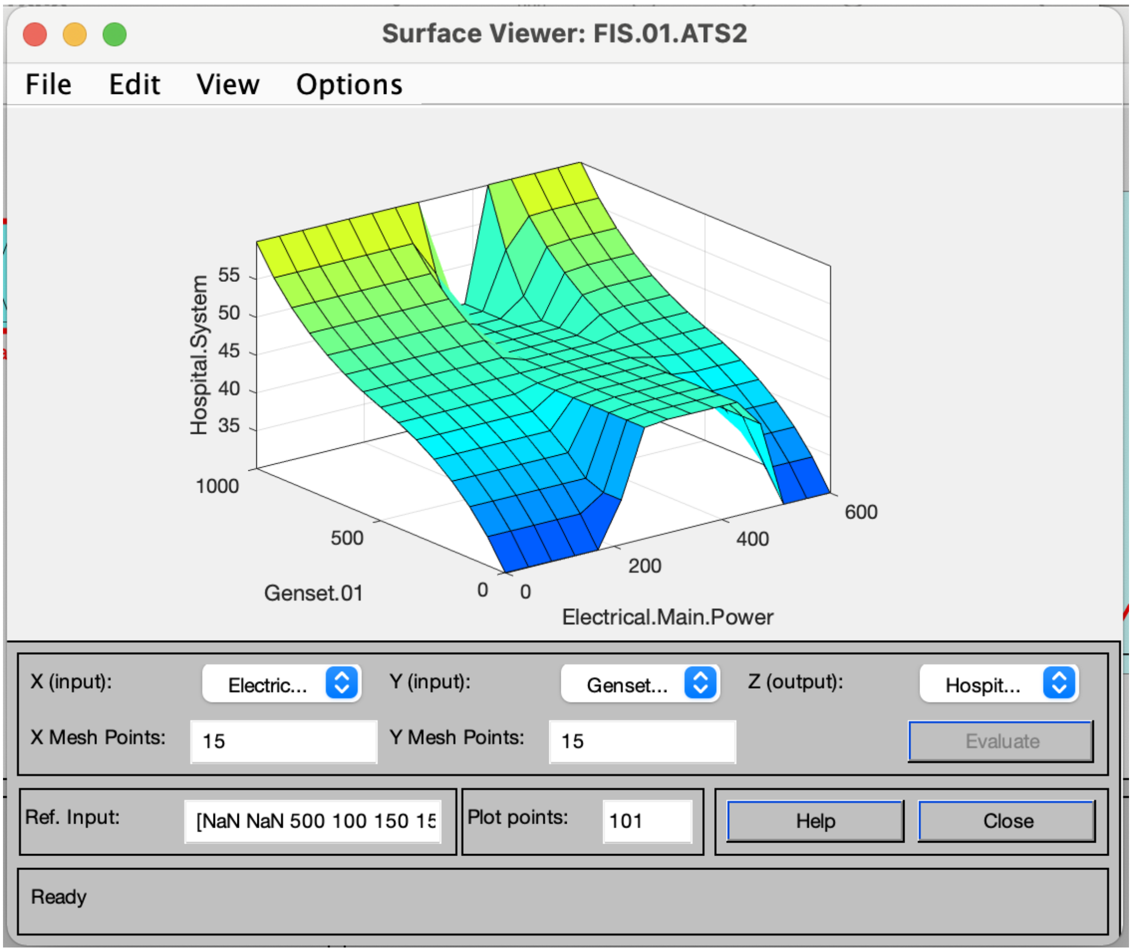


Figure 4.29 *The surface viewer of Fuzzy Logic System for EMP and Genset 01=02*

If (Electrical Main Power is Normal) and (Genset1 is off) and (Genset2 is off) and (Automatic Transfer Switch is not function) and (UPS1 is on) and (UPS2 is on) then (Hospital System is failing load) – Figure 4.30.

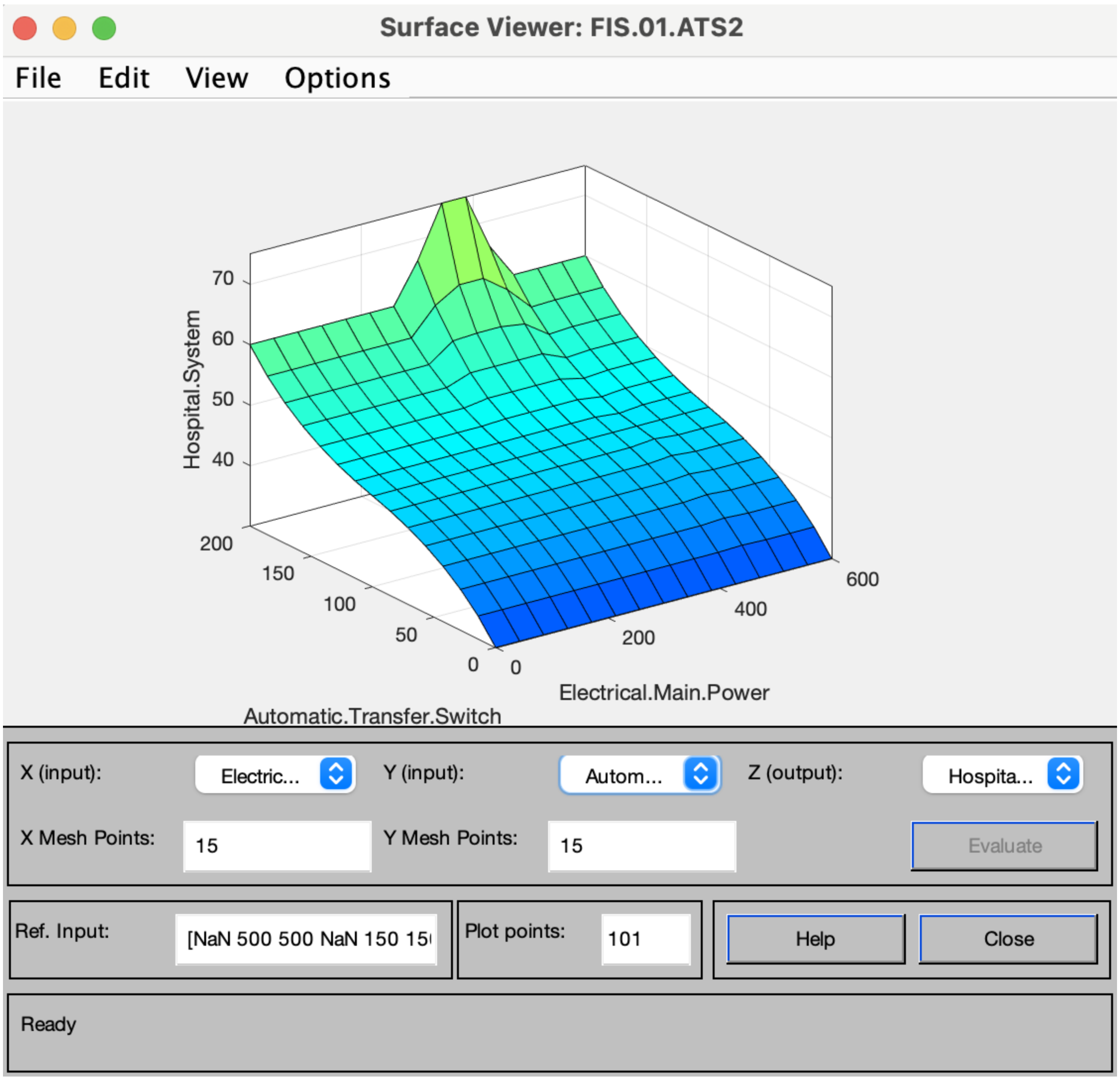


Figure 4.30 *The surface viewer of Fuzzy Logic System for EMP with ATS*

If (Electrical Main Power is Low) and (Genset1 is on) and (Genset2 is on) and (Automatic Transfer Switch is a function) and (UPS1 is on) and (UPS2 is on) then (Hospital System is Normal load) – Figure 4.31.

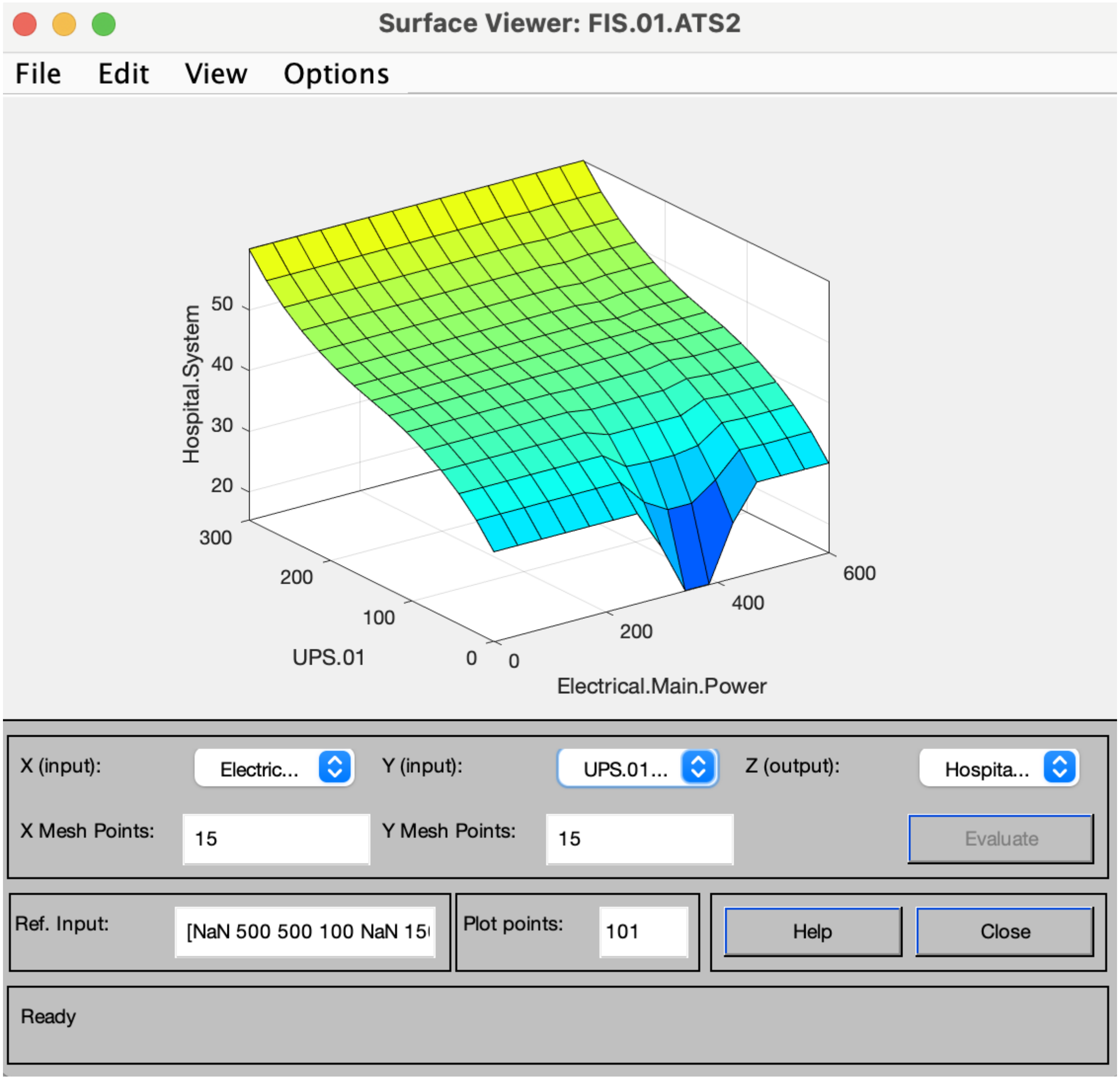


Figure 4.31 *The surface viewer of Fuzzy Logic System for EMP with UPS 01 = UPS 02*

4.3.6 Synthesis of FIS

The synthesis of the steps FIS shown in previous sections is shown in Figure 4.32, representing the inference process corresponding to five inputs, 17 rules systems, and one output plot.

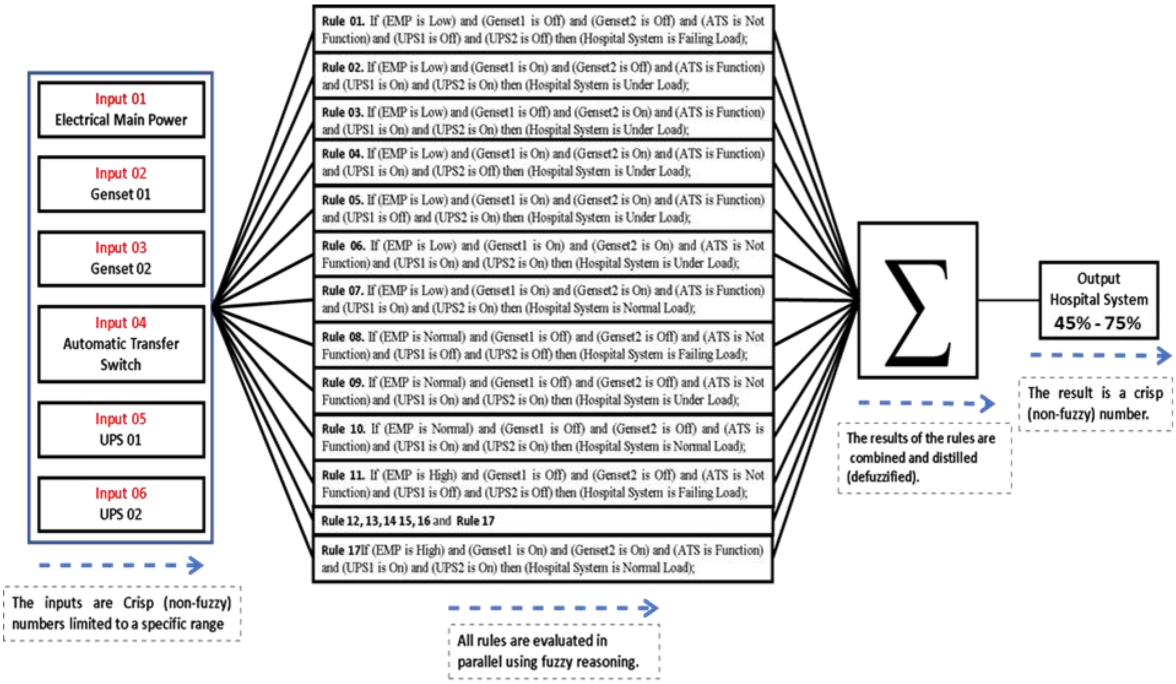


Figure 4.32 *The surface viewer of the fuzzy logic system for the process cycle.*

4.4 Modelling with Markov Chains and Stochastic Matrixes Processes Analyzing

As we have seen, the research site does not provide any historical data, and we use Fuzzy (FIS) to reveal vague and unclear data. To prove it with other sciences, namely Stochastic, are our findings relevant according to the rules contained therein.

Based on Figures 4.11, 4.12, 4.13 and 4.14, the results of the defuzzification of each vital instrument in the hospital electrical circuit using the Markov chain can be simulated as follows in (Figure 4.33); assuming that the minimum defuzzification value is fuzzy as the return value at the source and the maximum value at the defuzzification result as the transfer value to the next source in the circuit.

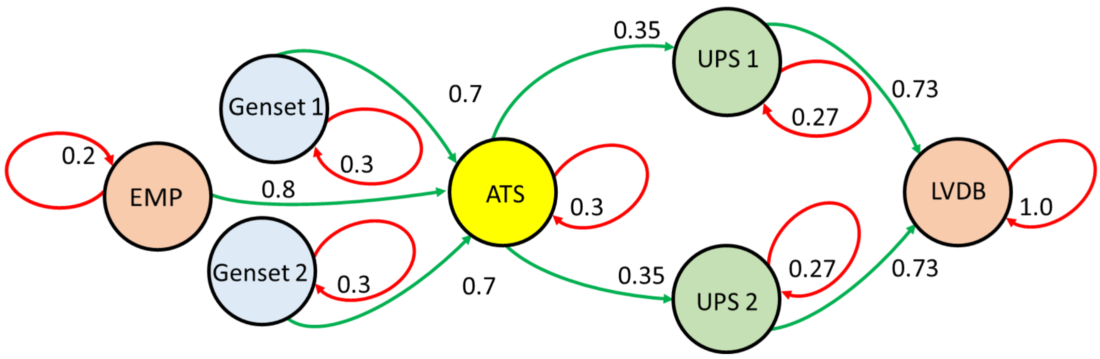


Figure 4.33 *Simulation of Markov Chain*

After simulating the data contained in the defuzzification results in the form of a Markov chain, now we must transfer the data into a table matrix so that we can analyse it according to the following stochastic rules:

Table 4.4 *The arrangement of the matrix Stochastic from Figure 4.33.*

From →

	EMB	ATS	Genset 1	Genset 2	UPS 1	UPS 2	LVDB
EM	0.2	0	0	0	0	0	0
ATS	0.8	0.3	0.7	0.7	0	0	0
Genset 1	0	0	0.3	0	0	0	0
Genset 2	0	0	0	0.3	0	0	0
UPS 1	0	0.35	0	0	0.27	0	0
UPS 2	0	0.35	0	0	0	0.27	0
LVDB	0	0	0	0	0.73	0.73	1

To ↓

Based on Table 4.4 formed, we can change its shape to a stochastic matrix, where the parameter "from ==> to" the same column is 1 (one), as shown below.

$$A = \begin{bmatrix} 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.8 & 0.3 & 0.7 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.3 & 0 & 0 & 0 \\ 0 & 0.35 & 0 & 0 & 0.27 & 0 & 0 \\ 0 & 0.35 & 0 & 0 & 0 & 0.27 & 0 \\ 0 & 0 & 0 & 0 & 0.73 & 0.73 & 1 \end{bmatrix}$$

After the stochastic matrix is formed, we must determine the variables involved in the stochastic process; generally replaced by the symbols π1, π2, π3 and πn. Where is the formula as follows:

$$\pi A = \pi$$

Based on the transition matrix formula, we can arrange the multiplication matrix equation as follows:

$$[\pi 1\ \pi 2\ \pi 3\ \pi 4\ \pi 5\ \pi 6\ \pi 7]\begin{bmatrix} 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.8 & 0.3 & 0.7 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.3 & 0 & 0 & 0 \\ 0 & 0.35 & 0 & 0 & 0.27 & 0 & 0 \\ 0 & 0.35 & 0 & 0 & 0 & 0.27 & 0 \\ 0 & 0 & 0 & 0 & 0.73 & 0.73 & 1 \end{bmatrix} = [\pi 1\ \pi 2\ \pi 3\ \pi 4\ \pi 5\ \pi 6\ \pi 7]$$

Then with the substitution method and the elimination method, we can change the form of the above matrix into the following equations; according to the rules of algebra that apply.

$$\begin{array}{cccccccccc} 0.2\pi 1 & +0.8\pi 2 & +0\pi 3 & +0\pi 4 & +0\pi 5 & +0\pi 6 & +0\pi 7 & = & \pi 1 \\ 0\ \pi 1 & +0.3\pi 2 & +0\pi 3 & +0\pi 4 & +0.35\pi 5 & +0.35\pi 6 & +0\pi 7 & = & \pi 2 \\ 0\ \pi 1 & +0.7\pi 2 & +0\ .3\pi 3 & +0\pi 4 & +0\pi 5 & +0\pi 6 & +\ 0\pi 7 & = & \pi 3 \\ 0\ \pi 1 & +0.7\pi 2 & +0\pi 3 & +0.3\pi 4 & +0\pi 5 & +0\pi 6 & +0\pi 7 & = & \pi 4 \\ 0\ \pi 1 & +0\pi 2 & +0\pi 3 & +0\pi 4 & +0.27\pi 5 & +0\pi 6 & +0.73\pi 7 & = & \pi 5 \\ 0\ \pi 1 & +0\pi 2 & +0\pi 3 & +0\pi 4 & +0\pi 5 & +0.27\pi 6 & +0.73\pi 7 & = & \pi 6 \\ 0\ \pi 1 & +0\pi 2 & +0\pi 3 & +0\ \pi 4 & +0\pi 5 & +0\pi 6 & +1\pi 7 & = & \pi 7 \end{array}$$

$$\begin{array}{cccccccccc} -0.8\pi 1 & +0.8\pi 2 & +0\pi 3 & +0\pi 4 & +0\pi 5 & +0\pi 6 & +0\pi 7 & = & 0 \\ 0\pi 1 & +-0.7\pi 2 & +0\pi 3 & +0\pi 4 & +0.35\pi 5 & +0.35\pi 6 & +0\pi 7 & = & 0 \\ 0\pi 1 & +0.7\pi 2 & +-0.7\pi 3 & +0\pi 4 & +0\pi 5 & +0\pi 6 & +0\pi 7 & = & 0 \\ 0\pi 1 & +0.7\pi 2 & +0\pi 3 & +-0.7\pi 4 & +0\pi 5 & +0\pi 6 & +0\pi 7 & = & 0 \\ 0\pi 1 & +0\pi 2 & +0\pi 3 & +0\pi 4 & +-0.73\pi 5 & +0\pi 6 & +0.73\pi 7 & = & 0 \\ 0\pi 1 & +0\pi 2 & +0\pi 3 & +0\pi 4 & +0\pi 5 & +-0.73\pi 6 & +0.73\pi 7 & = & 0 \\ \pi 1 & +\pi 2 & +\pi 3 & +\pi 4 & +\pi 5 & +\pi 6 & +\pi 7 & = & 1 \end{array}$$

After that, we rearrange them into separate sequences according to the laws of matrix algebra, which are named matrices A, B and π, as shown below:

$$\underbrace{\begin{bmatrix} -0.8 & 0.8 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.7 & 0 & 0 & 0.35 & 0.35 & 0 \\ 0 & 0.7 & -0.7 & 0 & 0 & 0 & 0 \\ 0 & 0.7 & 0 & -0.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.73 & 0 & 0.73 \\ 0 & 0 & 0 & 0 & 0 & -0.73 & 0.73 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \pi 1 \\ \pi 2 \\ \pi 3 \\ \pi 4 \\ \pi 5 \\ \pi 6 \\ \pi 7 \end{bmatrix}}_{\pi} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}_{B}$$

To find the values of the π variables, we must find the value of the inverse matrix A because the algebraic formula is as follows:

$$A\,\pi = B \implies A^{-1} A\,\pi = A^{-1} B \implies \pi = A^{-1} B$$

We compute the inverse value of matrix A with Microsoft Excel or MATLAB software facilities based on this formula. The result is multiplied by the value of the matrix B, so we get the importance of the π variables quickly and easily, as follows:

$$\underbrace{\begin{bmatrix} -1.070 & -0.613 & 0.206 & -0.101 & 0.197 & -0.097 & 0.144 \\ 0.180 & -0.613 & 0.206 & -0.101 & 0.197 & -0.097 & 0.144 \\ 0.180 & -0.613 & -1.223 & -0.101 & 0.197 & -0.097 & 0.144 \\ 0.184 & 0.832 & 0.210 & -0.802 & 0.202 & 0.601 & 0.147 \\ 0.173 & -0.588 & 0.197 & -0.097 & -1.181 & -0.093 & 0.138 \\ 0.176 & 0.798 & 0.202 & 0.601 & 0.193 & -0.794 & 0.141 \\ 0.176 & 0.798 & 0.202 & 0.601 & 0.193 & 0.576 & 0.141 \end{bmatrix}^{-1}}_{A^{-1}} \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}_{B} = \underbrace{\begin{bmatrix} 0.144 \\ 0.144 \\ 0.144 \\ 0.147 \\ 0.138 \\ 0.141 \\ 0.141 \end{bmatrix}}_{\pi}$$

π1 = EMP
π2 = ATS
π3 = Genset 1
π4 = Genset 2
π5 = UPS 1
π6 = UPS 2
π7 = ELVDB

From this calculation, the results are shown in Table 4.5.

Table 4.5 *The result of calculations*

0.144	=	$\pi 1$	=	EMP
0.144	=	$\pi 2$	=	ATS
0.144	=	$\pi 3$	=	Genset 1
0.147	=	$\pi 4$	=	Genset 2
0.138	=	$\pi 5$	=	UPS 1
0.141	=	$\pi 6$	=	UPS 2
0.141	=	$\pi 7$	=	LVDB
$\sum$ **= 1**				

From the results of the length calculation, we can see that the value of all π variables that have been added together is equal to 1 or, in other words, the importance of one (1); this is the uniqueness of the stochastic. So can conclude that each variable involved in the stochastic process contributes 14.3% to the system's function for work following its context (Table 4.5).

4.4.1 Stochastic versus Fuzzy Process

Researchers often have to choose science or tools to analyse the data collected clearly and accurately, which is unclear and inaccurate, even worse if data in the field is unavailable. We can look for statistics under the circumstances we face, as in the references Pinto et al. published. The author uses Petri Nets (PN) to calculate or analyse how reliable these assets are using the Fuzzy Inference System (FIS) to find the most sensitive and critical instruments or items in an asset. However, there is an opinion that the situation faced if the data collected is inaccurate and unclear can also use the Stochastic Time Petri net. However, let us examine these two sciences; and how useful they are in our current situation. Let us consider some of the similarities and some of the differences between the two sciences in terms of what we call "Stochastic versus Fuzzy Processes"; Our intention is not to look for the advantages and disadvantages of these sciences but only to look for the differences in the uses between the two, as seen in Table 4.6, which was filled based on the research done.

Table 4.6 *Stochastic versus Fuzzy*

Problems faced by researchers	**Stochastic Vs Fuzzy**	
Unclear and inaccurate data	YES	YES
Data not available in the field	NO	YES
Data that can be added according to human experience	NO	YES
Rules are made based on human logic on data	NO	YES
Discrete state and continuous state	YES	YES
Discrete-time and continuous-time	YES	YES
Multidimensional problems	YES	YES
Complicated data	YES	YES

It can be seen in the table that there are several differences; however, quotes from previous studies suggest that it is better to use integrated stochastic and fuzzy science to produce more reliable and valuable research results. Since there are problems that have to be solved by Fuzzy and some issues that have to be solved by stochastics, it is finally concluded that the two are complementary. Because in stochastic, every tool/item that performs its function sequentially is detected through careful analysis. We found 14.3% where the number of tools involved was 7, then 7 x 0.143 = 1; this is what the Stochastic Markov chain required.

CHAPTER 5. DISCUSSION OF RESULTS AND SOLUTIONS

This research on the hospital's electrical energy system uses several tools such as Petri Nets (PN), Fuzzy Inference System (FIS) and Stochastic Markov chains.

Based on the results of the research, it is possible to facilitate several asset documents according to Reliability, Availability, Maintainability and Safety (RAMS) requisites, as follows:

1. Provide an Asset Hierarchy Diagram to facilitate the identification of the entire order flow properly as suggested by Reliability Centered Maintenance (RCM);
2. Provide Functional Block Diagrams to facilitate the identification of the work functions of all components of the asset;
3. Provide Process Flowcharts to facilitate the identification of how asset processes work;
4. Provide a list of equipment or barcode numbering to facilitate the identification of all equipment installed on the asset, both for operators and maintenance;
5. Establish system boundaries according to asset functions to facilitate the identification of work process limitations for each group of equipment;
6. Provide Petri Net modelling and MATLAB simulation on the system to convince decision-makers;
7. Establish reliable functions and avoid operational failure;
8. Provide Reliability Analysis and Critical Equipment Risk.

Based on the Reliability, Availability, Maintainability and Safety (RAMS) documents, it is possible to describe several additional documents for management and operation purposes as follows:

1. Provide Quality Standard Manual for Managers;
2. Provide Standard Operating Procedures (SOP) for Supervisors;
3. Provide Work Instructions for Operators;
4. Provide Check Sheets for Workers;
5. Provide Electrical, Mechanical and Safety Insulation;
6. Provide Work Permit Standards;
7. Provide a Failure Notice Sheet;
8. Provide Daily, Weekly, Monthly and Annual Maintenance Schedules.

Based on the preceding, as a supporting guide for the field operation system, it is necessary:

1. Identify the system's weakest points;
2. Redesign the asset system to eliminate system weaknesses;
3. Simulating practical solutions to improve asset system reliability;
4. Determine the best decision for the desired system reliability.

Strict strategic management should ensure reliability based on the above information. In this case, the hospital's electric power system was used as a case study. The decision to use the most reliable new design for the asset system can be adjusted to the capacity of human resources and equipment installed.

However, there are still many things related to the documents being discussed because producing these documents requires in-depth analysis related to international conventions, international standards and laws and regulations that apply to the location or situation where the assets are installed.

CHAPTER 6. CONCLUSIONS

This thesis demonstrates the advantages of using a powerful and relevant tool such as the Petri net to model and analyse complex hospital electrical systems. However, it can be generalized to other organizations, regardless of its nature. This thesis also shows how Petri nets can help identify weaknesses in complex electrical systems, simulate more reliable solutions, and validate them. We can identify the hospital's most sensitive and critical component with Petri Nets: the automated transfer system (ATS). However, since no historical maintenance was available, the author used a fuzzy inference system (FIS) versus Petri net stochastic time (STPN) to analyse the system with excellent results. This thesis emphasizes Petri nets, Stochastic and fuzzy logic as powerful tools in maintenance management, providing system analysis and simulation to improve reliability and availability in asset operations. The analysed case studies show that the average asset function only reaches 60% in terms of reliability and availability because the asset function in its utility is only 45% to 75%. Meanwhile, each installed tool contributes 14.3% based on the Stochastic/Markov chain analysis. It is hoped that other researchers can continue similar research to reveal better, more reliable and reliable results for further scientific development.

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