TÉCNICO LISBOA

Analytical and Simulation Models for RAMI Analysis of a Complex System

A Contribution to the ITER PPR System

João Pedro Bachega Cruz

Thesis to obtain the Master of Science Degree in

Mechanical Engineering

Supervisors: Prof. Elsa Maria Pires Henriques

Prof. Virgínia Isabel Monteiro Nabais Infante

Examination Committee

Chairperson: Prof. Luis Filipe Galrão dos Reis

Supervisor: Prof. Elsa Maria Pires Henriques

Member of the Committee: Dr. Alberto Manuel Martinho Vale

November 2018

Acknowledgments

Initially, I let here all my appreciation to my supervisors Elsa Maria Pires Henriques, Virginia Isabel Monteiro Nabais Infante from *Instituto Superior Técnico (IST)* and Paulo Fernando Ferreira Frutuoso e Melo from *Universidade Federal do Rio de Janeiro (UFRJ)* for delicacy in transmit knowledge for different manners, during our meetings, discussions and advises. Without forget the importance of the Maintenance and Safety classes helping as theoretical background for this document.

I would like to acknowledge *Instituto de Plasmas e Fusão Nuclear (IPFN)* from *Instituto Superior Técnico (IST)* for the continued support, especially, Bruno Soares Gonçalves, Paulo Jorge Gonçalves Varela and Alberto Vale, for all the opportunities and vital learning experiences with so renowned professionals.

To my roommates on Residence *Engenheiro Duarte Pacheco* and other friends acquired in my stay in Portugal, thanks for the reception, travels and good company in our living here at this amazing country.

All my gratitude for sharing my time here in Lisbon with Julio Arantes. For all sessions of study, coffee breaks, lunches, workouts, travels and advises in personal life, thank you to become a brother for me.

Expressly for my parents João Carlos Cruz and Maria Irene Bachega, besides my family, I want to praise for all love and unlimited support at each stage of my life and education. My success is based on make you proud, honor and happy.

This work was partly supported by *FCT – "Fundação para a Ciência e a Tecnologia",* under project F4E 375 SG02 – 1018P.04333.

Abstract

Intending to increase the guarantee that the Plasma Position Reflectometry (PPR) System meets the requirements in terms of Reliability (continuity of correct operation), Availability (readiness for correct operation), Maintainability (ability to undergo repairs and modifications) and Inspectability (ability to undergo visits and controls), this thesis document contributes with the updated RAMI and Availability Analysis for one of the main diagnostic systems in ITER Operation, which intend to be the first device to maintain fusion for long periods of time, with a 500MW controlled plasma, proving the feasibility of fusion on large-scale and carbon-free source of energy, based on the same principle that power the sun and the stars.

Based on the actual design of the PPR System and getting as input the Preliminary RAMI Analysis, a systematic approach has been used, and significant new assumptions have been made to access Reliability and mainly Availability measures for System, Sub-System and components levels.

The Analysis was made to get the best profit of ITER PPR System, guiding to a better operation, considering three individual main objectives: study the potential Impact of the PPR System activity on ITER Operation, the effect on Electron Density Profile Measurement and the effect on the Plasma Position Function.

A new interpretation made for Functional Analysis (FA), culminate in new list of critical components for the three objectives cited before, guiding the RAMI team for new Failure Modes, Effects and Criticality Analysis (FMECA) and Reliability Block Diagrams (RBD). So, it was possible to access Reliability and Availability measures for different perspectives, using Reliability and Maintainability parameters from databases, together with analytical equations resulting for theoretical background.

To achieve trustworthy results and complement the analytical model calculations, a Discrete Event Simulation (DES) was performed, based on Monte Carlo Method, to accomplish, by statistical sampling, Availability estimations, besides a wide range of information regarding the PPR System, how a confidence interval for Availability calculations.

The results achieved for both models (analytical and simulation) conclude that Impact to ITER Operation, done by PPR system, is under the requirements in terms of Availability, making mitigation actions needed, guiding the RAMI team to suggest design actions for increase the Reliability of components and essentially to reduce the number of components involved in this analysis.

For the effect in PPR System's measurement and function, alarming results was achieved for Availability, specially for main objective of PPR, the Plasma Position Function, being detected one component in special, the Pin Switches of the Fast Shutter, as the main contributor for the warning, but not the only one. Thus, the study for a separated analysis of preventive maintenance for this component was led, in front of necessity for better options.

Further iterations of the analysis are needed not only to accommodate the design evolution, but also to increase the accuracy and representativeness of the components input data and specially to include the missed Reliability and Maintainability data of some of the components.

Keywords: RAMI; PPR System; ITER; Availability; Reliability; Discrete Event Simulation.

Resumo

Com o propósito de aumentar a garantia que o Sistema *Plasma Position Reflectometry* (*PPR*) cumpra os requisitos em termos de Fiabilidade (continuidade do funcionamento correto, sem falhas), Disponibilidade (predisposição para operação correta), Manutenibilidade (capacidade de ser submetido a reparos e a trocas) e Inspeção (capacidade de ser submetido a visitas e inspeção), esse documento de tese contribui para uma análise de tipo *RAMI* e de Disponibilidade para o principal sistema de diagnóstico do Operação *ITER*, a qual deseja concluir o primeiro reator de fusão nuclear experimental a alcançar geração de energia líquida no mundo.

Baseado no atual *design* do Sistema *PPR* e recebendo como *input* a análise *RAMI* preliminar, uma abordagem sistemática foi utilizada e novas hipóteses significantes foram feitas para ter acesso aos valores para Fiabilidade e principalmente Disponibilidade do sistema, subsistemas e componentes.

A análise foi feita para guiar o Sistema *PPR* do *ITER* para uma situação de melhor operação, considerando três principais objetivos: estudo do potencial Impacto do Sistema PPR para a Operação *ITER*, o efeito na Medida do Perfil de Densidade *(Electron Density Profile Measurement)* e no efeito para a Função de Posicionamento do Plasma *(Plasma Position Function).*

Uma nova interpretação foi feita para a Análise Funcional, culminando em uma nova lista de componentes críticos para os três objetivos citados antes, guiando desta maneira a equipe de *RAMI* para uma nova Análise de Modos de Falha, Efeitos e Criticidade (*FMECA*) e Diagrama de Blocos de Fiabilidade (*RBD*). Então, foi possível ter acesso a valores Fiabilidade e Disponibilidade para diferentes perspetivas, usando parâmetros de Fiabilidade e Manutenibilidade dos bancos de dados, junto com equações analíticas advindas de um antecedente teórico.

Para atingir resultados confiáveis e complementar o modelo de cálculos analíticos, foi feito uma Simulação de Eventos Discretos (*DES*), baseada no Método de Monte Carlo, para assim alcançar através de amostragens estatísticas, estimações de Disponibilidade, além de uma vasta gama de informação no que se diz respeito ao Sistema PPR, como por exemplo um intervalo de confiança para os cálculos de Disponibilidade.

Os resultados alcançados para os dois modelos (analítico e simulacional) concluíram que para o estudo do Impacto para a Operação *ITER* os requisitos de Disponibilidade não foram alcançados, tornando necessárias ações de mitigação, guiando assim a equipe de RAMI a sugerir ações no *design* para aumentar a Fiabilidade dos componentes e essencialmente diminuir o número de componentes envolvido nesta análise.

Para o efeito da medida e da função realizados pelo Sistema PPR, resultados alarmantes foram alcançados para a Disponibilidade, principalmente para o caso do objetivo principal, a Função de Posicionamento do Plasma, sendo detetado um componente em especial, o *Pin Switches of the Fast Shutter*, como o principal contribuinte para esse alerta, mas não o único. Assim foi conduzido uma análise separada de manutenção preventiva para esse componente, em frente a necessidade por melhores opções.

Novas iterações da análise são necessárias não somente para acomodar a evolução no design, mas para também aumentar a exatidão e representatividade dos dados de *input* para os componentes e principalmente para incluir os dados restantes de Fiabilidade e Manutenibilidade para certos componentes.

Palavras-Chave: RAMI; Sistema PPR; ITER; Disponibilidade; Fiabilidade; Simulação de Eventos Discretos.

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List of Symbols

$A_p(t)$	Availability for active parallel connection at time t
$A_i(t)$	Availability for component i at time t
$A_{moutn}(t)$	Availability for "*m* out *n*" parallel connection at time t
$A_s(t)$	Availability for series connection at time t
A_o	Average Availability
i	Components numeration
CMT_i	Corrective Maintenance/repair time for component i
F_{TTF}	Cumulative Distribution Function used in simulation
N[0,t]	Expected number of failures for a mission with length t
f(t)	Failure Density Function
λ	Failure Rate
λ_i	Failure Rate for component i
λ_{risk}	Failure Rate for risk classification
$\lambda(t)$	Hazard or time dependent failure rate
A(t)	Instantaneous Availability
Δt	Mission time
"*m* out *n*"	Number of operational *m* units besides *n* total units
k	Number of Units
P	Probability
f_{TTF}	Probability Density Function used in simulation
F(t)	Probability of failure

T	Random variable age of failure
R	Reliability
R(t)	Reliability at time t
R[Δt, λ_i]	Reliability for a certain mission length and component i
R_p(t)	Reliability for active parallel connection at time t
R_1(t)	Reliability for component 1 at time t
R_2(t)	Reliability for component 2 at time t
R_i(t)	Reliability for component i at time t
R_{moutn}(t)	Reliability for "*m* out *n*" parallel connection at time t
R_s(t)	Reliability for series connection at time t
R_n(t)	Reliability for umpteenth (n) component at time t
μ	Repair Rate
μ_i	Repair Rate of component i
A_{st}	Steady State Availability
t	Time
$ToR_{anterior}$	Time of Replacement anterior
ToR_1	Time of Replacement initial
TTF_{actual}	Time to Failure actual
ToR_i	Time to Replacement i
TTF_1	Time to Failure 1
TTF_i	Time to Failure i

Nomenclature

A	Availability
CDC	Combiner/De-Combiner
CDF	Cumulative Distribution Function
CFD	Cumulative Failure Distribution
CODAC	Control, Data Access and Communication
CIS	Central Interlock System
CMT	Corrective Maintenance/repair Time
DAQ	Data Acquisition
DC	Direct Current
DES	Discrete Event Simulation
ECRH	Electron Cyclotron Resonance Heating
ELM	Edge Localized Mode
EP##	Equatorial Port ##
EPP##	Equatorial Port Plug ##
FA	Functional Analysis
FM	Failure Mode
FR	Failure Rate
FER	Fusion Experimental Reactor
FM-CW	Frequency Modulated-Continuous Wave
FMECA	Failure Modes, Effects and Criticality Analysis
HFS	High Field Side
IEWT	In-Vessel/Ex-Vessel Waveguide Transition

IO	ITER Organization
IPFN	Instituto de Plasmas e Fusão Nuclear
IST	Instituto Superior Técnico
IF	Intermediate Frequency
ITER	International Thermonuclear Experimental Reactor
LFS	Low Field Side
LFS CTS	Low Field Side Collective Thomson Scattering
LTM	Long Term Maintenance
PPR	Plasma Position Reflectometry
MCM	Monte Carlo Method
MDT	Mean Down Time
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
O-mode	Ordinary mode of wave propagation
PBS	Plant Breakdown Structure
PC	Port-Cell
PCS	Plasma Control System
PDF	Probability Density Function
POS	Plasma Operation State
PPR	Plasma Position Reflectometry
QO	Quasi-Optical
R	Reliability

RAMI	Reliability Availability Maintainability Inspectability
RBD	Reliability Block Diagrams
REQ	Requirement
RF	Radio Frequency
RT	Real Time
SIC	Safety Important Class
SVS	Service Vacuum Service
TCS	Test and Conditioning State
TL	Transmission Line
ToR	Time of Replacement
TTF	Time to Failure
UP##	Upper Port ##
UPP##	Upper Port Plug ##
WG	Waveguide

1. Introduction

1.1. Context

Collecting efforts from 35 countries, among China, European Union countries, India, Japan, Russia, South Korea and the United States of America, the International Thermonuclear Experimental Reactor (ITER) operation is one of the most ambitious energy projects in the world, intending to be the first device to maintain fusion for long periods of time, with a 500MW controlled plasma. The Fusion Experimental Reactor (FER) has the largest Tokamak existent (a device that uses powerful magnetic field to confine hot plasma) is designed to reach the output power 10 times bigger than the input, proving the feasibility of fusion on large-scale and carbon-free source of energy, based on the same principle that power the sun and the stars. [1]

The machine operation will be carried out in three 8 hours shifts during typically 16-month operation periods separated by 8-month shutdown periods for maintenance and/or further installation. ITER aims to demonstrate the physics and technological basis for future fusion power plants. [2,3]

Instituto Superior Técnico (IST) and Instituto de Plasmas e Fusão Nuclear (IPFN) take part to the ambitious project, proportionating expertise in analysis, diagnostics and developments of components.

Collaborating for development and elaboration of Plasma Position Reflectometry (PPR) system, used in diagnostic and analysis, the IST and IPFN provide, among a huge range of areas, competence in RAMI (Reliability, Availability, Maintainability and Inspectability) analysis of components during the design phase, pretending to help in safety issues of tasks, and risk management.

RAMI is the acronym designation of a safety process stands for characterizing performance measures delimited for an specific engineering project, ITER Operation, being an association of analytical methods and integrative concepts aiming to drive the system design process towards a better control of technical risks in the system operation phase, through to control the system's Reliability (system's ability of correct continuous operation); Availability (system's readiness to operate correctly at a given point in time); Maintainability (ability with which a system can be repaired or modified); and Inspectability (system's ability to be visited and controlled). This analysis must work in an iterative way, thereby the project can evolve from design and formulation until the work phase, guided for a safety analysis. [4]

Investigation of maintenance and safety during development and project allows engineering improvements, like design and material mitigation actions, converging for enticing characteristics. Maximize the availability of an operation is fortunate, being for ITER Organization (IO) and specially for PPR case (this thesis) one project requirement, which can be achieved through a RAMI application in iterative way.

1.2. Objectives and Scope of work

This study pretends to investigate the PPR system, one of ITER's main systems, used for diagnostics, collecting information about the Plasma through a specific measure, the Electron Density Profile Measurement, accomplishing to the Plasma Position, essential function of the system. The analysis intends to increase the probability that the ITER device meets the project requirements in terms of Reliability, Availability, Maintainability, and Inspectability.

The RAMI Analysis is focused on the functional analysis of the ITER PPR at system and sub-system level, on the Reliability of the components involved in the execution of each function, on the identification of their failure criticality and on the definition of risk mitigation actions intending to achieve the availability requirements of the project. The process is divided into 5 stages:

- System Functional Analysis (FA);
- Reliability Block Diagrams (RBD);
- Failure Modes, Effects and Criticality Analysis (FMECA);
- Risk mitigation actions;
- RAMI requirements.

Following the iterative RAMI methodology stages listed before and according to the functions and components defined in a reinterpretation of IO System Functional Analysis, this document wants to produce new FMECA and RBD models, changed from last iterations of RAMI, to accommodate modifications on the reliability-wise relationships between components, introduction of new components and elimination of removed components, in accordance with the design evolution of the ITER PPR system.

Based on the architecture of the current RBD models the Reliability and Availability of the system must be calculated/estimated involving different studies:

- Evaluation of the Impact of the PPR system on the ITER Operation;
- Evaluation of Availability and Reliability of the ITER PPR Electron Density Profile Measurements;
- Evaluation of Availability and Reliability of the ITER PPR Plasma Position Function.

The calculation/estimation can be subdivided by approaches, being:

- Analytical approach made through analytical equations application for Reliability and Availability, based on the relationships between components;
- Discrete Event Simulation approach made by a Synchronous Model, using the Monte Carlo Simulation as base.

1.3. Thesis Structure

The thesis document is divided into 3 parts, composed of six chapters added of references and annexes, following the structure presented in Figure 1-1 and explained next.

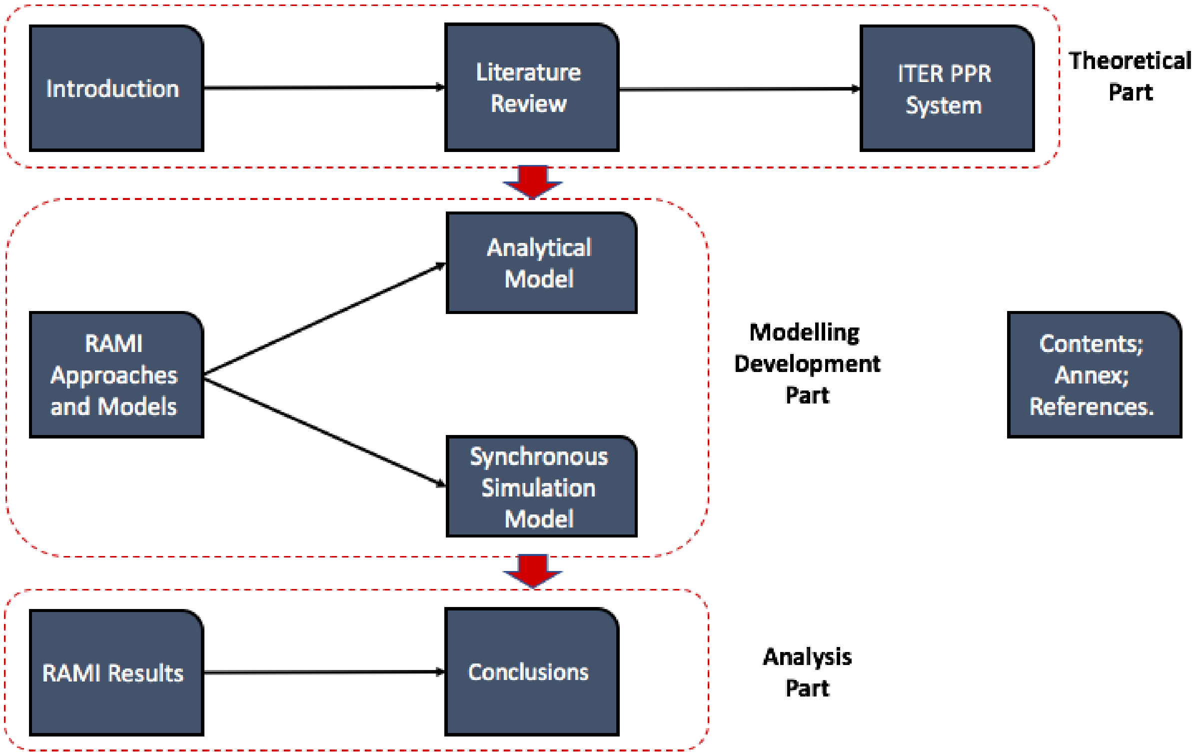

Figure 1-1: Thesis Structure.

1.3.1. Theoretical Part:

Initially, in the first 3 chapters, the focus is to introduce and construct a solid basis for the remaining of the document. Explanations of ITER operation, about system in detail: PPR System, and around RAMI Analysis on the project, are done in these chapters.

Chapter 1 – In the first chapter an introduction for the study is plotted, to give to the reader a dimension of the topic.

Chapter 2 – The chapter two is the theoretical basis for all the remaining thesis document.

Chapter 3 – This chapter describes the ITER Operation, the PPR System, its components and characteristics.

1.3.2. Modelling and Development Part:

Chapter 4 – During this chapter, the system is modeled and different approaches are used to achieve measures and analysis about safety and maintenance. Among them, there are functional breakdown, a RBD plot, a FMECA, and two developed models, the analytical and simulation.

1.3.3. Analysis Part:

Chapter 5 – Presentation of the results for different models and a breath comprehension about the outputs.

Chapter 6 – This chapter is dedicated for plot conclusions and make recommendations about the project and over a future work.

Contents, Annex and References – Separate sections for attach lists of contents, figures, tables, symbols at the initial part of document and another for present schemes and bibliography of this thesis at the final of the document.

2. Literature Review

The work developed in this thesis document consists in a RAMI (Reliability, Availability, Maintainability and Inspectability) investigation. This specific analysis process was stablished for IO, being an apparatus for continuous commitment in better guarantee that the device meets the requirements in terms of Reliability, Availability, Maintainability and Inspectability measures of a ITER dispositive.

However, the urgency for maximize project's Maintainability and Safety have been one of engineering's main efforts in past decades, brought to perspective the System Reliability Analysis as scientific discipline by mass production for the manufacturing of large quantities of goods from standardized parts (rifle production at the Springfield armory, 1863 and Ford Model T car production, 1913) and converted in an actual emergence in engineering market by the vacuum tube (specifically the triode, invented by Lee de Forest in 1906, which at the onset of World War II initiated the electronic revolution, enabling a series of applications such as the radio, television, radar, and others) and the study of failure created in its surroundings. [5,6]

This topic is composed in three subchapters, committed to explain about the theoretical basis for the complete study, being composed of RAMI concepts, engines, techniques and approaches, in addition to Discrete Event Simulation background.

In the first subchapter was addressed the terms in RAMI acronym, giving a description of concepts and a mathematical base to quantify these parameters, making possible to use as measures to construct an analytical analysis.

The second one presents the discussion about the RAMI process and its applications to ITER Operation, where each step of procedure, Functional Analysis (FA), Failure Modes and Criticality Analysis (FMECA), Reliability Block Diagram (RBD), Risk Mitigation Actions and RAMI requirements are explained and examined apart.

Lastly, a brief description about Discrete Event Simulation (DES) is found, giving an attention to definition, function and possible applications.

2.1. RAMI Analysis

The RAMI process, which is based on analytical methods and integrative concepts, aims to ensure that in a certain time, the system in study is Reliable (continuity of correct operation until the time instant), Available (readiness for correct operation), Maintainable (ability to undergo repairs and modifications) and Inspectable (ability to undergo visits and controls), guiding the project to frame in requirements specified.

Understand the divisions of the project in study is the first step to achieve the final ambition of RAMI Analysis, being necessary to separate the system's objective(s)/function(s), sub-systems/sub-functions until reach the most basic units in the project, the separated components and then tracing hierarchical relationships between them. Therefore, it is possible to predict the functionality of the system, described through Reliability and Availability measures that should agree with the project requirements.

This process starts in earlier design phases and follow the development of the project, having different iterations during this advance looking for the project needs.

2.1.1. Reliability

To guide the called System Reliability Analysis is important to define and introduce equations for the Reliability as an important parameter in the Maintenance and Safety study.

In engineering terms, Reliability is the probability that an item (general name for call a system, a sub-system or a component) will perform its stated mission satisfactorily for the given period when used under the specified conditions. In other words, can be described as the continuity of correct operation at a given time, with no interruptions, of an item.

Looking for the probabilistic character of Reliability, denoted as R(t), it can be understood as the successful side of an operation, at a given time t.

$$R(t) = P\,(T > t), \qquad t \geq 0 \tag{1}$$

For the Equation (1), T is a random variable representing the “age of failure”. If T is greater than t, the unit is considered operational, at time t.

The variation of probability P with the time is the continuous function reliability R(t), with axiomatic boundary conditions:

- $R(0) = 1$, a unit can’t be “down” (not operational) in the beginning of mission (t=0);
- $R(\infty) = 0$, the function R(t) decreases with time, meaning that no item can operate infinitely with no failure (having an infinite operational life).

Therefore, the other side of probabilistic event Reliability is the probability of failure, F(t), defined as the possibility that a system has failed by the time T, making probabilities R(t) and F(t) complementary events, therefore is possible to use Equation (3), the application of the complementary event property for this case.

$$F(t) = P\,(T \leq t), \qquad t \geq 0 \tag{2}$$

$$F(t) + R(t) = 1 \tag{3}$$

$F(t)$ is defined as failure distribution function (also called Cumulative Failure Distribution, CFD, or Cumulative Distribution Function, CDF), being the cumulative failure distribution function until the time t. Having a failure Probability Density Function (PDF) associated denoted f(t), and by the equation presented next is possible to understand as a rate, or percentage, of components that fail per unit of time, at instant t, in relation to the initial number of components.

$$\mathrm{f(t)} = \frac{-dR(t)}{dt} \Leftrightarrow \quad F(t) = \int_0^t f(t).dt$$

(4)

In reliability analysis of engineering systems, it is often assumed that the hazard or time-dependent failure rate of items follows the shape of a bathtub as shown in Figure 2-1. Represented by λ(t), this parameter is defined as a failure function too, but differently from f(t), the rate has as relation the number of components in the instantaneous time, and not the initial number of components.

$$\lambda(\mathrm{t}) = \frac{f(t)}{R(t)}$$

(5)

The curve shown in Figure 2-1 has three distinct regions: “Infant mortality period”, “Useful life period”, and “Wear-out period”. [7]

The “Infant mortality period” is also known as “Break-in period” or “Burn-in period”. During this first time frame the hazard rate decreases and the failures occur due to causes such as problems during project, manufacture, over-stressed actuations, incorrect installation, poor quality control, etc, i.e. it is a certain period of time where failures can happen in a prototype or initial design of components due to project imperfections.

In the “Useful life period”, the hazard (failure) rate is constant and the failures occur randomly or unpredictably, being the failures described with a stochastic behavior.

The “Wear-out period” begins when the item passes its useful life period. During the wear-out period the hazard rate increases. Some causes for the occurrence of wear-out region failures are: wear due to aging, inadequate or improper preventive maintenance, limited-life components, wear due to friction, misalignments, corrosion and creep, and incorrect overhaul practices. Therefore, can and should be reduced significantly by executing effective replacement and preventive maintenance policies and procedures.

Manipulating the equations presented before, and with a graphical acknowledgment of λ(t) is possible to finally achieve the Reliability general function for unit.

$$R(t) = e^{-\int_0^t \lambda(t).dt}$$

(6)

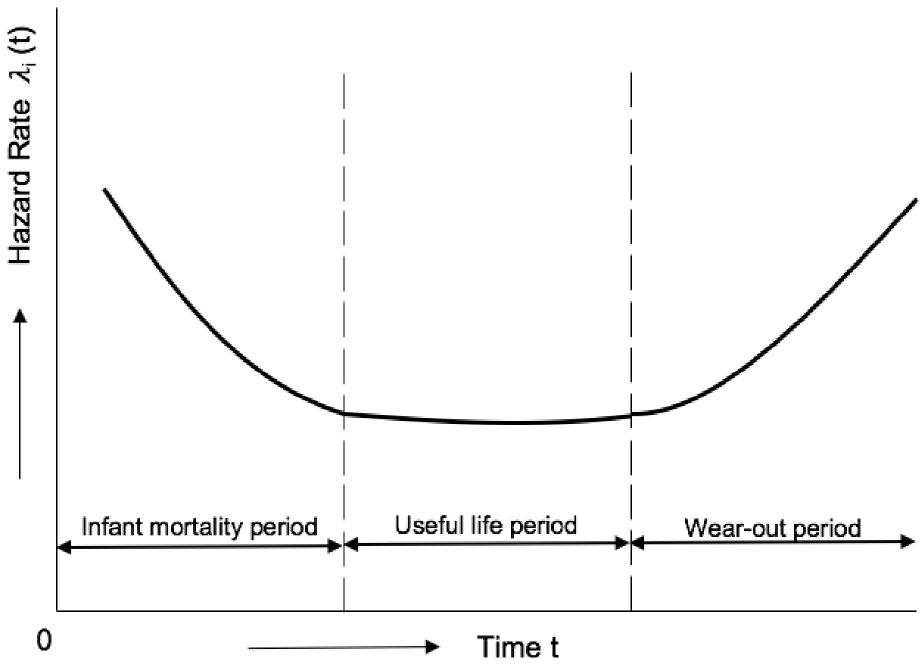

Figure 2-1: Hazard Rate graph, known as "Bathtub curve". [7]

For the scope of this analysis, directed for ITER, all the components, designed for an important nuclear project, are modeled in a useful life model behavior, with exponential behavior, once the good quality used in production, maintenance and inspection imply in an irrelevant burn-out period. Being even an intention of the maintenance and safety team to prevent the components to enter in Wear-out period, making mitigation actions for problematic units, like preventive maintenance. The ITER databases gives constant MTBF for components, which agree with the supposition.

The data bases received from ITER, used in this RAMI actions, gives for all units an exponential behavior for Reliability and Availability of components, corresponding to a Useful life behavior, with constants failure rates and down times, what agrees with the realistic behavior of components made for a project of this proportion. [2]

Therefore, as told before, all the components will be considered with a constant failure rate λ_i, where the denotation i refers to a certain component i, having at this analysis stochastic behavior of the process, where the failure can occur randomly. For this reason, the main equations to represent the Reliability Analysis of a unit i, for a mission in useful life model, can be observed next: [7]

$$f(\Delta t) = \lambda_i \,.\, e^{-\lambda_i.\Delta t}, \qquad \Delta t > 0$$

(7)

$$R(\lambda_i, \Delta t) = e^{-\lambda_i.\Delta t}$$

(8)

Being the last Reliability equation plotted for a mission, with duration equal to Δt. This equity implies that two components with the same value associated for failure rate λ_i in the same mission, have the same result for Reliability R (Δt, λ_i), with the output value in percentage.

Others essential parameters in Reliability Engineering are the Mean Time to Failure (MTTF) or Mean Time Between Failures (MTBF). These values are literally the average numbers of hours that a component works until reach a failure, but the difference between them is the fact of the MTBF is used for reparable components (while MTTF is used for non-reparable) and it is usually used for general denomination too, what happens during this study, where at this stage of design, all components are considered as reparable or replaceable.

Looking firstly for the general case (Equation (9)) and then applying the Equation (8) in Equation (9), the MTBF can be quantify for one unit i as: [7]

$$MTBF = \int_0^\infty R(t).dt$$

(9)

$$MTBF = \frac{1}{\lambda_i}$$

(10)

2.1.2. Maintainability

Maintainability is another parameter in the Maintenance and Safety scientific area, that can be described as the probability that a failed item return to initial situation (by repair or replacement), with adequately working condition. Being considered one important design parameter, has as objective to reduce repair time for reparable units and/or replace time for non-reparable ones, trying to maximize equipment and facility Availability (another parameter explained in the sequence). Therefore, is contemplate as opposed to maintenance, that is the act of servicing a component.

As part of engineering projects, should be explored through application of scientific knowledge and skills to develop components that is inherently able to be maintained as measured by favorable maintenance characteristics as well as performance.

There are different characteristics of the component or location that can impact the Maintainability of them. For the purpose of this study, delimited for a system used in Nuclear Fusion Reactor, will be referenced just two parameters to be aware, the accessibility to certain areas and the standardization of units.

Accessibility may be described as the relative ease with which a component can be reached for inspection and replacement or repair. Inaccessibility is a frequent cause of ineffective maintenance, that is an important problem to be notice in PPR System, but also in all ITER operation, once there are certain parts of the ITER building with high levels of radiation, where the access is limited for short periods of time and only during specific sessions of maintenance.

“The standardization may be described as the attainment of maximum practical uniformity in an item’s design”. Due the importance of the ITER project, the parameter should be a central goal of design because use of nonstandard parts could result in lower Reliability and increased maintenance. [7]

Maintainability functions are used to predict the probability that a repair, starting at time t = 0, will be completed in a time t.

There are different measures for quantify the Maintainability Analysis being the Mean Time To Repair (MTTR) and the Mean Down Time (MDT) the two measures chose for ITER OPERATION for studies.

The measure known as Mean Time to Repair (MTTR) is a value that estimate a mean elapsed time required to perform a given maintenance activity. MTTR is expressed in the Equation (11). [7]

$$MTTR = \frac{\sum_{i=1}^{k} \lambda_i \times CMT_i}{\sum_{i=1}^{k} \lambda_i} \tag{11}$$

Where k is the number of units or parts, λ_i is the failure rate of component i (for i = 1, 2, 3, ..., k) and CMT_i is corrective maintenance/repair time required to repair component i.

Usually, times to repair follow exponential, lognormal, and normal probability distributions, needing a bigger statistical study or simulation to predict this kind of behavior, being even one new future work presented for this thesis at the end of Chapter 6.

The other parameter, Mean Down Time (MDT) as the main Maintainability parameter for this thesis document, described as the total time required either to restore system to a given performance level or to keep it at that level of performance. It is composition (sum) of any kind of maintenance, delays, time to get accessibility, time due setups, etc.

Once this document present analysis that will consider all the tools and replacement components in readiness, and constant tabled values for accessibility, besides standardization, the average value for MDT, or just the total time in which the component is not in a satisfactory operable condition, is consider a good approximation for the MTTR, being both considered as synonyms. [7]

In PPR system analysis, focus of this study, as in other ITER RAMI analysis, is considered one constant mean value for the MDT for each component, that will be the parameter expressed for Maintainability in all the text, as told before as a synonym of MTTR.

The MDT can be expressed mathematically following a approach similar with the MTBF:

$$MDT = \frac{1}{\mu_i}$$

(12)

Where μ_i is the repair rate (similar approach as failure rate λ_i) of a certain component i, e.g. a value in hours^{-1} representing the rate that a component is repaired.

2.1.3. Availability

Another item of interest for a theoretical background of a RAMI Analysis is the system Availability, which is qualitative defined as the ability of a system to fulfill the function for which it is operated. It applies to systems which can be maintained, restored to operation or renovated upon failure depending on the strategy adopted to optimally assure its function, that are described below in form of maintenance type classification: [5]

- Corrective (Off-schedule) Maintenance, i.e., replacement or repair of the failed system;
- Preventive Maintenance, i.e., regular inspections, and possibly repair, based on a structured maintenance plan;
- Condition-based Maintenance, i.e., performance of repair actions upon detection of the degraded conditions of the system;
- Predictive Maintenance, i.e., replacement of the system upon prediction of the evolution of the degradation conditions of the system.

According with the type of maintenance selected for the project, different Availability measures can be used to estimate the system ability to fulfill their own function.

The called Instantaneous Availability is the first value to be characterized, being the probability that the system is operating at time t. Although the resembling probabilistic meaning of Availability, it differs from Reliability, which is instead used to characterize the ability of the system of achieving the objectives of its specified mission within an assigned period of time, by the probability that the system functions with no failures up to time t. Operatively, the time-dependent Instantaneous Availability function of a system is synthesized by point values. [5]

Now, looking inside the quantitative meaning of Instantaneous Availability, denoted as A(t), can be easily described as the probability that the system is in “up” condition, i.e. available, at a specific instantaneous time t of the mission Δt.

To achieve the Instantaneous Availability A(t) probability of interest for the study, it is necessary first introduce what is a Two-State Markovian Analysis, illustrated in Figure 2-2.

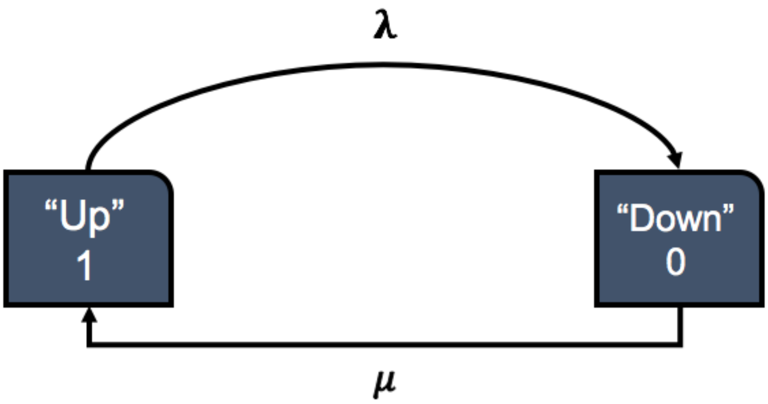

Figure 2-2: Two-State Markovian Analysis applied for a component's working condition.

This Analysis consists in a two-state (two-possibilities) model in which the system is either available ("up" condition), represented by 1, or unavailable ("down" condition), represented by 0.

So, the Two-State Markovian Analysis consider that all units (components, sub-systems, systems and all ITER Operation) can be modelled having just these two possibilities and that each unit can moves from state 1 to state 0 at a rate λ_i, where λ_i is the rate that the component can stop the operation and become unavailable (therefore the failure rate of the item defined in Section 2.1.1.), and moves from state 0 to state 1 with rate μ_i, where μ_i is the rate that the component can recover work condition and come back to operation (therefore the repair rate of the item defined in Section 2.1.2.). Must be noticed that the failure and repair rates do not necessarily have similar figures, being even common that a component presents both parameters even in different order of magnitudes, with the failure rates much lower than the repair rate.

The Instantaneous Availability of these specific systems over a limited deployed period, for specified missions, is desired, and if the systems start in an available state and the total mission length is small in comparison to the MTBF, then the transient first part will be important, what is the case of PPR System study, where the values of MTBF collected are in large scale bigger that the ITER mission, what can be compared when defined the Data Base and ITER Scenario in the following Chapter.

The Instantaneous Availability A(t) can be calculated as a function of time, being the probability of the unit be in the state 1, i.e. available, in the instant t, that is equate in Equation (13). [4]

$$\mathrm{A}(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\mu+\lambda)t} \tag{13}$$

On the other hand, for systems under Periodic Maintenance, the Average Availability A_o, over a given mission of time, is introduced as a new indicator of performance.

This measure is known also as Operational Availability such as cited before as the item's readiness to operate correctly at a given point in time. Therefore, is the percentage of time that an item is either operating or capable of operating, e.g. operationally capable of performing an assigned mission, considering effects of other items failures.

It represents the expected proportion of time that the system is operating in the considered period, being equated in the following formula.

$$A_o = \frac{uptime}{uptime + downtime}$$

(14)

A_o is quantitatively defined like a percentage, being a ratio between two terms equate above in general form, where the uptime is measure of time that an item is available (capable to operate) and downtime is the measure of not-operational time, when the item is "down", e.g. unavailable.

Looking for general Equation (14) it is visible that an improve in A_o should be done by increasing the uptime and reducing downtime, what can be achieved by design improvements such as the addition of redundancies in parallel, spares, simplest maintenance and better inspection. This improve is commonly a requirement in engineering projects, as ITER operation case.

For units or systems under Corrective Maintenance, the limiting or Steady State Availability A_{st} is defined as the mathematical limit of the Instantaneous Availability function (Equation (13)) in time as this latter grows to infinity. It represents the probability that the system is functioning at an arbitrary moment of time, after the transient of the failure and repair processes have stabilized. It is obviously undefined for systems under Periodic Maintenance, for which the limit does not exist.

This alternative form of Availability is described next in Equation (15), being named as Steady State Availability, a composition of terms MTBF and MDT, stablished in sections 2.1.1. and 2.1.2., i.e. first term is the average time between events causing the system to go down and the second is the average of downtime. Equation (15) would be a good measure to be observed if the systems were to run continuously for a long period of time, being another kind of mean value.

$$A_{st} = \frac{MTBF}{MTBF + MDT} = \frac{\mu}{\lambda + \mu}$$

(15)

It is notable that when MTBF and MDT are calculated based on observed data, the alternative Equation (15) is exactly equivalent to the general one (Equation (14)). What can be easily understood looking for next two equations.

$$MTBF = \frac{uptime}{number\ of\ downing\ events}$$

(16)

$$MDT = \frac{downtime}{number\ of\ downing\ events}$$

(17)

If the item starts in an available condition, the Instantaneous Availability begins at 100% and just approaches the Mean Availability and/or Steady State Availability after a few failures/repairs cycles. Otherwise, for systems that operate continuously, once the system passes an initial start-up period, A_i equals the A_o/A_{st}.

For some cases, the period of interest is such that the startup transient is negligible and ignored, being the Equation (14) and (15) good approximations to be applied.

2.1.4. Reliability and Availability Connections:

Sections 2.1.1. until 2.1.3. detailed the theoretical background, parameters and equations needed to achieve the Reliability and Availability calculations, but all presentation was focus in a single unit model, being applied for one component for example, but not for a connection composed of them.

The new Section, 2.1.4. introduce the connections between units, each one with particular hierarchical organizations (logic blocks) and its interdependencies, resulting in different equations to be applied for Reliability and Availability.

PPR System is divided in hierarchical sub-systems that can be defined as a connection of components. These connections can be basically organized in different types of organizations, i.e. collections of units. This study addresses the three standard connections presented in engineering projects, being: Series, Active Parallel and "*m* out *n*" Parallel Connections. These 3 connections are the three kinds used for modelling in this thesis document.

Each relationship connection has his own mathematical approach and equations in accordance with the proposed logic. Each connection was explained in the sequence, used for Reliability and Availability.

2.1.4.1. Series Connection:

The Series Connection can be represented by the following logic block diagram, illustrated in Figure 2-3.

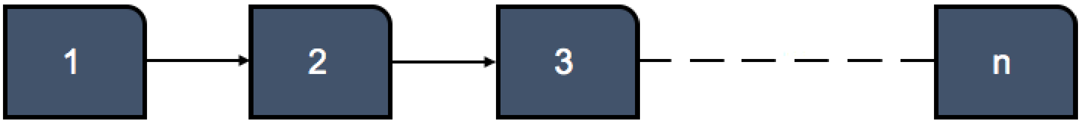

Figure 2-3: Series Connection for Reliability and Availability. [7]

In this case, *n* number of units form a Series System. The arrows in the diagram shows the relationship between the separate units as a path to achieve a correct operation. [7]

The Series Connection logic showed represent a collection of units where if any of the units fails, the system fails, i.e. all system units must work normally for successful operation of the full system.

A typical example of a series system is four wheels of a car. If any one of the tires punctures, the car for practical purposes cannot be driven. Thus, these four tires form a series system, with four components.

With the purpose of calculate the Reliability and Availability of systems presented in the Modelling Development Part of this thesis document, a series connection formed for independent and non-identical *n* units, shown in Figure 2-3, can the equated simply as the multiplication factor of separated Reliability and Availability of the units. Once both Reliability and Availability have they probability side, by simple application of probability and statistical knowledge, the correct operation side of each component precede the correct operation of wholly system, resulting in the multiplicand of separated probabilities, once the multiplication represent the occurrence of both probabilities multiplied.

$$R_S(t) = \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} e^{-\lambda_i t} \tag{18}$$

$$A_s(t) = \prod_{i=1}^{n} A_i(t) \tag{19}$$

2.1.4.2. Active Parallel Connection:

The Active Parallel Connection can be represented by the following logic block diagram, illustrated in Figure 2-4.

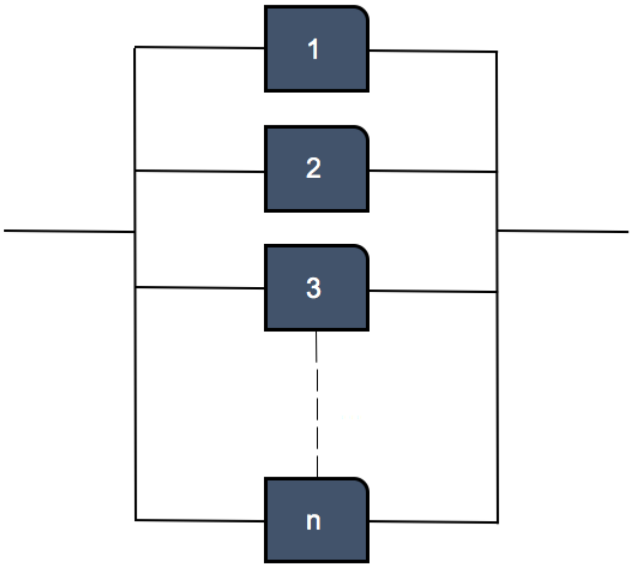

Figure 2-4: Active Parallel Connection for Reliability and Availability. [7]

For this case *n* number of simultaneously operating units form an active parallel system, requiring the assumption that the independent units are all actives, performing the same task/function and each one has autonomy to fulfill the role, noticing that in case of failure of any unit, another one can fulfill the activity, without any latency. [7]

Therefore, in the diagram of Figure 2-4 each block denotes a unit, and based on the logic presented above at least one of the units must work normally for the fulfill the activity and the system has a successful operation.

With the purpose of calculate the Reliability and Availability of systems presented in the Modelling Development Part of this thesis document, an Active Parallel Connection formed for independent and non-identical *n* units can be equate using the simple application of probability and statistical knowledge in Equation (20). For unsuccessful operation happens, all units must fail, so it is necessary to remove from one the probability that all units fail, that is equated as the multiplicand of the failures F_i of each component, (the simply explanation for that is based on Equation (3) and it application of the complementary event property between Reliability and Probability of Failure).

$$R_P(t) = 1 - \big(1 - R_1(t)\big)\big(1 - R_2(t)\big) \dots \big(1 - R_n(t)\big) = 1 - \prod_{i=1}^{n} \big(1 - R_i(t)\big) = 1 - \prod_{i=1}^{n} (1 - e^{-\lambda_i t})$$

(20)

$$A_p(t) = 1 - \prod_{i=1}^{n} (1 - A_i(t))$$

(21)

2.1.4.3. “M out N” Parallel Connection:

For this case *n* number of simultaneously operating units form a *“m out n”* Parallel Connection that can be also represented by diagram in the Figure 2-4, but now supposing that the independent units may even perform the same task/function but each one has not autonomy to fulfill the role, being necessary at least *m* among *n* numbers of units to accomplishment of the function.

Using the theory behind the combinations of events together with the Binomial Theorem from probability and statistical knowledge, it is possible to achieve the equations for Reliability and Availability of *m* among *n* units: [4]

$$R_{moutn}(t) = \sum_{i=m}^{n} \frac{n!}{i!\,(n-i)!} \big(R(t)\big)^{i} (1 - R(t))^{n-i} \tag{22}$$

$$A_{moutn}(t) = \sum_{i=m}^{n} \frac{n!}{i!\,(n-i)!} \big(A(t)\big)^{i} (1 - A(t))^{n-i} \tag{23}$$

2.1.5. Inspectability

The last parameter to be discussed in the RAMI Analysis is the Inspectability, that can be simplify as the system ability to undergo inspection actions for check essential parameters and functions of a unit, being one characteristic of a Maintainable Design.

The Inspectability action should be set in the design phase, trying to aim at simplifying the monitoring of the unit, having as output a testing and failure diagnostic. Therefore, Inspectability is opposed to inspection (similar with the behavior of Maintainability and maintenance), once increasing the Inspectability of a system decreases simultaneously the time for inspection for the same system.

The system must be subjected to a functional checkout, being for some systems impossible to have full non-destructive testing, making necessary to weigh between Inspectability and Maintainability. [8]

Considered as a separate part of RAMI action, the Inspectability is a determinant tool for systems that use inspection actions, used to achieve a design that minimize the time spend in maintenance. Therefore, together with accessibility and standardization parameters, but with a preventive character, the Inspectability parameter applied in the design phase can improve the Maintainability of these systems.

Furthermore, both Maintainability and Inspectability are influenced by accessibility and standardization parameters, once make a system with better ability to undergo inspections depends about the convenience to access certain areas and it is difficult to make testing and failure diagnostic of a system with lesser extent of standards.

Another time, the case of ITER PPR System must be noticed, by the fact that the access to areas next to Plasma is difficult and the improvement in Inspectability is not an appropriate choice for components in this situation.

2.2. RAMI Procedure for ITER PPR System

After introduced the parameters, mathematical background and application for RAMI Analysis modelling and calculations, the focus now is exactly to define the RAMI procedure/process.
As explained at Section 2.1., this specific analysis tool, classified as technical risk control strategy, was stablished for IO, being a new interpretation of Maintenance and Safety study presented in literature, with the objective to be an apparatus for continuous commitment in guide the system to meets the project requirements in terms of the Reliability, Availability, Maintainability and Inspectability, with possible utilization in different engineering systems. [2]

At this thesis document, the process defined is focused on the development of a Functional Analysis (FA) of the ITER PPR at system and sub-system level. Modelling the system and using the Reliability measure of the components involved in the execution of PPR final objectives, together with the identification of their failure criticality and on the definition of risk mitigation actions the procedure intend to achieve the Availability requirements proposed for the project. The procedure is divided into 5 main stages:

- System Functional Analysis (FA);
- Reliability Block Diagrams (RBD);
- Failure Modes, Effects and Criticality Analysis (FMECA);
- Risk mitigation actions;
- RAMI Results.

Understand the divisions of the Project/System in study is the first step to achieve the final goal of RAMI Analysis. It can be possible through the FA of the System in development, being the PPR System the focus in this thesis document.

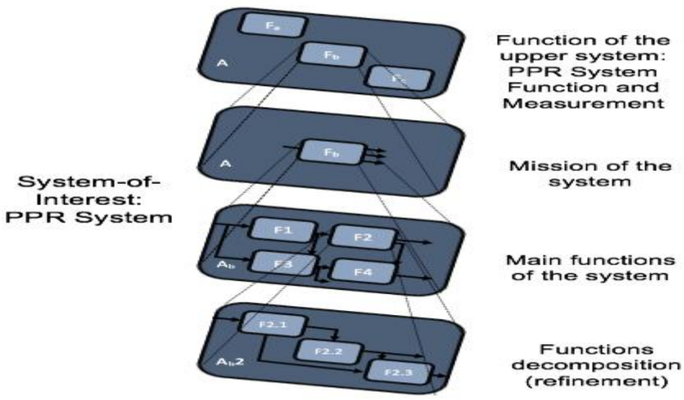

Figure 2-5: Functional Breakdown, comprising the Top-down description of the system and sub-systems level, applied to PPR System.

The first part of FA procedure is the creation of a top-down description of the System and it Sub-Systems levels, from the main functions to the basic functions performed by the components. An application of this first step, called of Functional Breakdown, is illustrated at Figure 2-5, for the PPR System case.

The intention of this first part consists in delimit the objectives of the upper system, what is consists in a Measurement activity and a main Function for the PPR System case, what was detailed in Chapter 3. To achieve these final objectives there are different missions to be accomplish, for each mission certain main functions are necessary. In a final view, these main functions can be decomposed in different small functions, that can be attribute for certain components.

With the hierarchy delimited for the PPR System and it objectives, it is possible to understand the whole System as activities performed by Sub-Systems (Gaps) composed by an agglomerate of components, performing smaller functions to achieve at the end the final objectives of the system. Using the sub-division and attributing for each lower level function one component, the System FA can be completed, as illustrated at Figure 2-6.

The objective of the FA consists in identify all basic functions that the system must perform to meet the requirements and objectives of the System, having as output a list of the critical components associated with these functions.

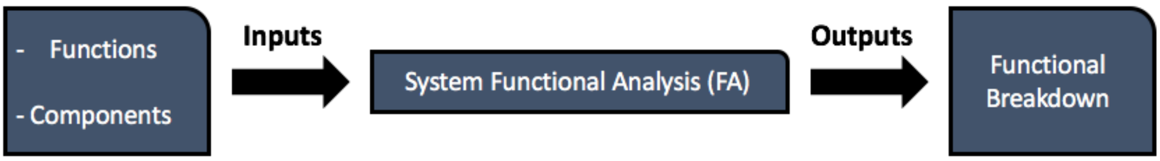

Figure 2-6: System Functional Analysis (FA) procedure.

Receiving a complete list of critical components resulting from Functional Breakdown it is possible to make the second stage of RAMI Analysis, the Reliability Block Diagrams structuring of the System, with scheme illustrated at Figure 2-7.

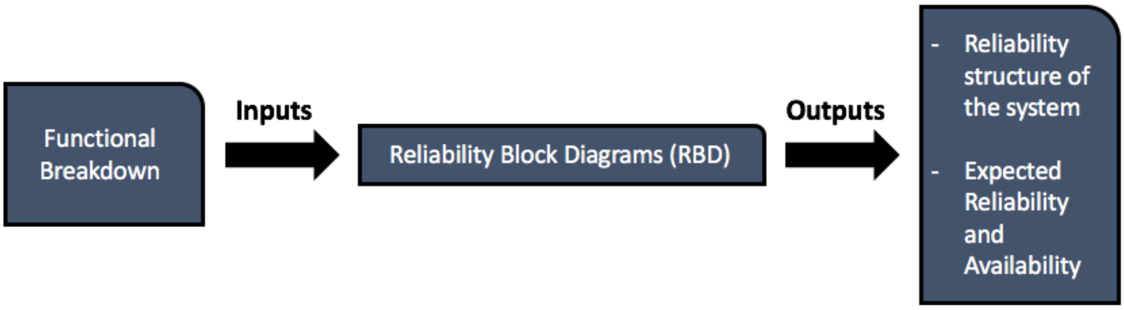

Figure 2-7: Reliability Block Diagrams (RBD) operation to model the System.

This stage consists in a schematic representation of the system using the reliability logic through an RBD, having as objective determine if each connection is operating or failed, given the information whether each block is in operating or failed state.

The blocks can be viewed as a "switch" that is closed when the block is operating and open when the block is failed.

The system is considered operational if a path of "closed switches" is found from the input to the output of the diagram.

The possible logics can be called as connections, and was already explained in this Chapter, at Section 2.1.4., showing the Series, Active Parallel and "*m* out *n*" Parallel connection, the basic ones that are present in the PPR case.

The output given for this stage consist in RBD for each Sub-System inside the whole structure, making possible plot structure representations creating a logic hierarchy for the System. With these representations, it is feasible to achieve expected Reliability and Availability measures of the Sub-Systems and correspondent System.

With the System organized in a logic structure and with first calculations for Reliability and Availability starts the third stage of the RAMI Analysis, the FMECA, a process with the intention to develop criticality charts composed of all the Failure Modes (FM), their causes and effects, occurrence of causes and severity of effects.

Illustrated in Figure 2-8, the FMECA have four main phases:

- Identification of all FM for the components that accomplish each basic function.
- Identification of the causes and effects of each FM on the overall functions.
- Qualitative assessment of the frequency of Occurrence of causes and Severity of effects.
- Make a criterion of Prioritization of Risks.

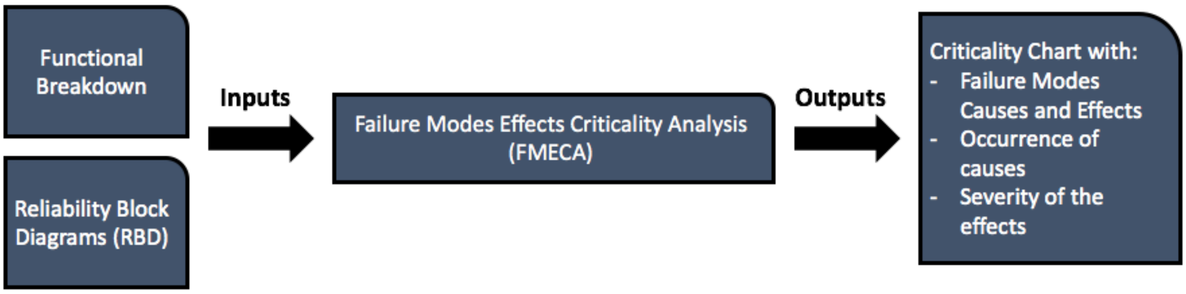

Figure 2-8: Failure Modes Effects Criticality Analysis (FMECA) structure to achieve the Criticality Chart.

Resuming, the FMECA stablish in each line of a table: one basic function that need to be done by the System, for this function is attributed one component, for this component a certain number of possible FM, for each FM one effect (impact to operation) with Severity scale and in the end the cause (root cause, failure mechanism) with Occurrence scale.

An essential step of FMECA consists in the creation of a criterion to quantify and classify risks, with a selection between them to be prioritized for the Maintenance and Safety team, trying to be aware nearly the problematic components.

The criterion needs a parameter to quantify risks to be possible to classify them, being in this case the Criticality of each FM the chosen, once the Criticality is a basically a measure used to rank the dangerous FM for the whole operation, having two components: Occurrence and Severity.

Both Severity and Occurrence measures are qualitative assessment scales, so, for this thesis document merely interest the measures for the ITER operation.

The key parameter for scaling the Severity is the impact on the Availability of the ITER machine, with the amount of unexpected maintenance time introduced by a failure, scaled in accordance with the MDT.

Six Severity classes are defined as detailed in the Table 2-1.

Value	Description	Meaning
1	Weak<1h	Unavailable less than 1 hours
2	Moderate<1d	Unavailable between 1 hour and 1 day
3	Serious<1w	Unavailable between 1 day and 1 week
4	Severe<2m	Unavailable between 1 week and 2 months
5	Critical<1y	Unavailable between 2 months and 1 year
6	Catastrophic>1y	Unavailable more them 1 year

Table 2-1: Qualitative judgment from the Severity rate scale of ITER Components, made by ITER operation. [ITER internal documents] [2]

These Severity graduations from 1 to 6 must be applied just for PPR System components that can stop the whole ITER machine with failure. If the failure does not stop the ITER operation (stopping just the PPR System for instance), the Severity 1 must be applied, a decision take by RAMI team once the main concern of ITER operation is the whole ITER machine and not the PPR System device (the information about the stop in whole ITER machine was stablished by designers at this phase of work). Therefore, for all components just with Severity bigger than 1 (i.e. all components considered with possibility of stop ITER operation) is already necessary a separable evaluation.

The second factor to be aware is the Occurrence, quantify by the expected number of failure per unit of time.

If supposed the MTBF of components fit the exponential distribution explained at Section 2.1.1., the expected number of failures is simple given by Equation (24). [2]

$$N[0,t] = \lambda_i \text{ x t}$$

(24)

Equation (24) gives the expected number of failures N from time 0 to t, with λ_i representing the failure rate of the component (for a specific FM cause), and *t* defines the time interval [0, t].

Six occurrence classes are defined as detailed in the Table 2-2.

Value	Description	Meaning	
1	Very Low	λ_{risk} < 5e-4/y	λ_{risk} < 5.7e-8/h
		MTBF>2000 years	
2	Low	5e-4/y < λ_{risk} < 5e-3/y	5.7e-8/h < λ_{risk} < 5.7e-7/h
		200 years < MTBF < 2000 years	
3	Moderate	5e-3/y < λ_{risk} < 5e-2/y	5.7e-7/h < λ_{risk} < 5.7e-6/h
		20 years < MTBF < 200 years	
4	High	5e-2/y < λ_{risk} < 5e-1/y	5.7e-6/h < λ_{risk} < 5.7e-5/h
		2 years < MTBF < 20 years	
5	Very High	5e-1/y < λ_{risk} < 5/y	5.7e-5/h < λ_{risk} < 5.7e-4/h
		10 weeks < MTBF < 2 years	
6	Frequent	λ_{risk} > 5/y	λ_{risk} > 5.7e-4/h
		MTBF < 10 weeks	

Table 2-2: Qualitative judgment from the Occurrence rate scale of ITER Components, made by ITER operation. [2]

Once the Criticality is composed by qualitative measures, the Criticality is also qualitative, being possible to create different equations with expression formed by Occurrence and Severity in distinct ways. ITER operation uses a linear equation to quantify the Criticality, presented below in Equation (25). [2]

$$Criticality = Severity \ x \ Occurrence$$

(25)

The Equation (25) shows the Criticality as simple product of Severity and Occurrence, with coefficient 1 for both, giving the impression that the two parameters have the same degree of importance. For Criticality Matrix of FMECA both have the same impact for criticality calculation, giving to a component the degree of Risk from 1 to 36. However, trying to better frame the requirements, the Severity measure has a special consideration in this RAMI operation made for PPR System, once the main requirement for the ITER operation consider the ITER machine operation priority, therefore, the failures that cause damage for Availability of whole ITER machine must be avoid. This special consideration makes all components that can stop the ITER machine (judge by design at this stage of project) a component considers as critical.

With two scales already explained and the Criticality parameter defined, the procedure now needs a Criticality Level graduation, also qualitative, interesting for this study just the ITER classification of Criticality Levels, that can be found in Figure 2-9, together with the Criticality Zones at Figure 2-10.

Level	Actions
LOW	Minor Risks, corresponding actions are considered "optional", Criticality is 1 than 7
MEDIUM	Medium Risks for which actions are only "recommended", Criticality is between 7 and 13
HIGH	Major Risks calling for "required" actions, Criticality is higher than 13

Table 2-3: Criticality Levels for ITER operation. [2]

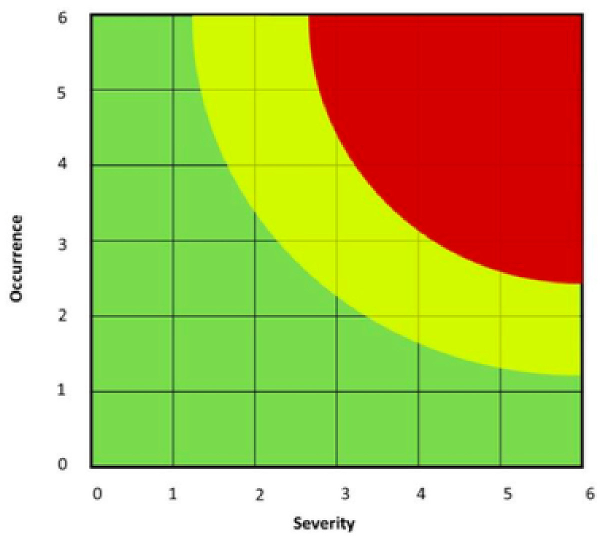

Figure 2-9: Risk Zones for Minor, Medium and High Risks. [2]

As denoted in Figure 2-9, the ITER operation defined three levels of Risks, classified as Minor, Medium and High Risks, with respective Low, Medium and High levels of Criticality. The Risks Zones are illustrated at Figure 2-10, plotting the components in different zones in accordance with the Risk that presents for ITER machine, being the yellow and red zone areas to be avoid, once represent alarming components. [2]

The Criticality Levels graduation together with the concern in stop the ITER machine can guide the RAMI team and designers to divide the problematic components, that can be a hazard for the ITER machine operation, prejudicing the Availability of ITER operation. Therefore, components that failure can stop the ITER machine (designer's judgment) and Components with Medium and Major Risk graduation must be taken to the next step of RAMI, once these components have recommended or required improvement actions.

The next and fourth part of RAMI Analysis is the procedure of Risk Mitigation Actions study, illustrated at Figure 2-11.

At this stage, the RAMI team define risk mitigation actions to reduce the risk level associated to the FM identified in FMECA. These actions are distinguished by the way they reduce the Criticality Level, either by reducing the Severity, introducing more protection actions, or reducing the Occurrence, introducing more prevention actions, of the failure modes, and also by the development phase of the project in which they are related to (design, test, operation or maintenance).

Figure 2-10: Risk Mitigation Actions procedure to achieve new configurations.

Table 2-4 shows for the different phases in project actions examples that can reduce the Occurrence or the Severity of certain FM, removed from Maintenance and Safety literature. [8]

Effects / **Project Phase**	**Protection** (decrease Severity)	**Prevention** (decrease Occurrence)
Design	Implement risk-containment provisions to avoid cascading failures	Implement redundancy to reduce the Risk of losing the function
Test	Apply specific tests to ensure	Apply specific test in simulated

	Maintainability of components that require a long time to repair	operating conditions to check the reliability of the component
Operation	Prepare specific training and procedures to allow falling back to a safe degraded mode in emergency	Interlock operations of sensitive components with a safety check to avoid damage
Maintenance	Keep spares on-site so that time to repair is shortened	Increase the frequency of inspections and preventive maintenance operations

Table 2-4: Examples of Risk Mitigation Actions for each category and effects. [5]

With the actions taken new Criticality Charts can be done, with possible new Reliability Block Diagrams if the structure was modified.

Finally, changes in at least one category (design, test, operation, maintenance) of at least one component modify the results for Reliability and Availability for the components and consequently for all following hierarchy. Therefore, the fifth and final part for RAMI Analysis is the RAMI Requirement procedure, represented at this thesis document for one Final Availability Model.

The final step receives as inputs the Functional Breakdown organized hierarchically in RBD structures (made by components with following failure modes) and the final parameters for Reliability (MTBF) and Maintainability (MDT), both with possible modification done by Risk Mitigation Actions. So, is possible to achieve as outputs the values for Availability and Reliability for the Sub-Systems and System's objectives.

The Final Availability Model procedure is the unique RAMI Requirement for this RAMI Analysis, being a final value of Availability to be achieve, given by ITER operation, the only objective to be accomplish by the RAMI team and designers. This requirement for Availability was completely explained at Section 3.3 of this study and the Final Availability Model procedure illustrated at Figure 2-11.

The RAMI Requirements definition step delimit for the RAMI Analysis procedure targets to be base for comparison and achieve with modifications in any phase of project. These targets are often complex and composed by terms of Availability, Reliability, Maintainability, Inspectability, Test and Validation of RAMI Performance, Spares and Standardization, etc. However, for this thesis document just the Availability requirements was used to be compared with Analytical and Simulation activities.

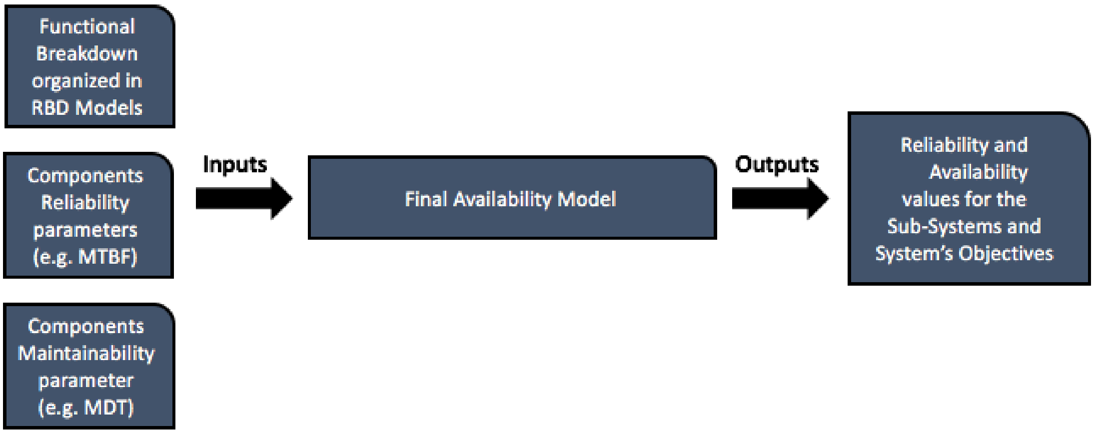

Figure 2-11: Final Availability Model procedure to achieve the Final Reliability and Availability values for the System.

2.3. Discrete Event Simulation Background

Intending to complete the analytical results achieved by use RBD models coming from RAMI Analysis procedure explained in the Section 2.2. together with analytical equations explained in the Sections 2.1.1. until 2.1.4., the simulation is a different effort to accomplish trustful results for the procedure, making a parallel deeper study based on the stochastic nature of the problem under analysis. Therefore, Section 2.3. has as objective to present the theoretical background behind the simulation approach chosen to be applied, being the Availability the parameter in study for be accessed, considering its stochastic nature and deriving its confidence interval that can be compared with the explicit requirement imposed for the system. It is necessary to determine the variable for the simulation, and how the analysis intend to study a model consistent with reality, the time to failure, still related with the failure rate, is the variable of the study, once in a component operation, the failure do not happen between mean values of time, as average result MTBF. Therefore, for this analysis the MDT is considered as a constant.

After World War II period and the Manhattan Project, the Monte Carlo Method (MCM) was developed as a result of the discussions between Stan Ulam, John von Neumann and Henrico Fermi. Using statistical sampling techniques for extract information from stochastic problems, modeled using an algorithm for generating uniformly distributed pseudo-random numbers, the method is often used, applied for simulate physical, biological and mathematical systems, normally with problems that cannot be represented precisely, having a statistical behavior, and/or difficult or impossible other approaches to solve (analytically). At this thesis document the MCM is the concept behind the generation of a Discrete Event Simulation (DES) for the PPR System operation, with consequent effect in ITER operation. [9]

Used as a class of computational algorithms that combine iteratively pseudorandom sampling to create simulation, the MCM basically solves any problem having a probabilistic behavior, once by the Law of Large numbers (from probabilistic theory) the average of results achieved by performing the same practice/experiment a large number of times should be close to the expected value of the random variable in study, and will tend to become closer and converge as more trials are performed. In the other words, simulating the reality for components life during the time of operation, it is possible to achieve multiple results for the random variable Availability once the simulation runs repeatedly, so theoretically, the average of results extracted from simulation converges to the expected value of the random variable in study (Availability), having as told before the advantage of having not just point results, but a confidence interval, besides the average and standard deviation results.

To achieve trustful results (small confidence interval with more reliance) for this confidence level to complement and be a base of comparison with analytical equations, the simulation needs an appropriate procedure/algorithm, a certain large enough number of iterations n and an effective randomness technique to create pseudorandom numbers to emulate components consonant with reality.

But the first step is to describe the simulation type. The DES, as the name suggest, is a simulation that models the operation of a unit as a discrete sequence of events in time. Being a complex procedure it requires precision of different aspects of simulation to achieve reliable results. Having an organized procedure of development, definition of modelling techniques and of activity blocks (or classes), run an appropriate number of iterations and then a trustful algorithm are steps to be set, being the activity blocks and algorithm created and just explained in the following Section 4.3., where the simulation is found. [5]

As every simulation activity, the DES development needs an organized and delimited process to be started. Describing a general procedure for one simulation, it can be theoretically composed by: [10]

- Type of simulation definition.
- Problem definition with all the variables set.
- Choice of a mathematical model that fits to the situation and mold the reality of problem. Being this step broad in number of modelling techniques, being the definition based in information about the problem. Two examples of techniques that are usually applied for Risk Engineering models:
  - Time-driven simulations:
    - Suitable for cases that have events happens at each step of time, i.e. the simulation has a variable recording the current time, being necessary to check after each increment to see which events may happen at the current time point, handle those that do. Usually simulations of this type use fine elements method to construct a simulation occurring with a continuous time.
  - Event-driven simulations:
    - Normally used in events that are not guarantee to happen at regular intervals of time, do not having a good bound on this time step. So, this simulation makes the time increment “jump” until the next event happens. This is the typical definition of simulations used for discrete event

simulation (DES), being the already introduced Monte Carlo Method one of the famous examples to be applied. In the Risk Engineering case the events causing “jumps” in the time are the failure and the repair.

- Implementation of the chose model.
- Computation of partial (for iterations) and final results.
- Interpretation of Results, leading for confidence intervals.

After explained the logic behind the procedure, the Table 2-5 delimits for each step of procedure the specification for the RAMI Analysis of PPR System choice of simulation.

Procedure Step	Specification for PPR System RAMI Analysis
Type of Simulation	As already introduced, this thesis document addressed the Discrete Event Simulation for the analysis of Availability.
Problem Definition and Variables set	Create a simulation that emulate the components, Sub-Systems and System’s Objectives operation through the use of a randomness factor to be applied in the failure rate, where each basic unit (component) is represented, at each step of time, as operational or not, with operational life represented by a Boolean Signal. Combining this Boolean Signal through logic gates creates a stochastic way of measure Availability, the parameter of interest.
Mathematical Model	As already introduced, the Mathematical Model required to be frame for a Discrete Event Simulation needs to be an Event-Driven Simulation, being the Monte Carlo Method (applying Inverse Transform Method made using pseudorandom numbers) the model for this thesis document.
Implementation	Modelling one component and after stablishing the connections, being possible to use a Synchronous or Asynchronous cases.
Computation	Simulation gives at the end of iterations results for all hierarchical units in form of Boolean Signals representing the operation. The integration of the signal’s graphs guide for the wanted parameter for the simulation, Availability (available time divided by total time).
Interpretation	The results for achieve are registered for each simulation and values of average, standard deviation and confidence intervals can be set, making a deeper investigation of system safety.

Table 2-5: DES Procedure for PPR System case.

Therefore, after decided as a discrete event, event-based Monte Carlo Method, there are two possible models to be set, Synchronous or Asynchronous.

About the modelling techniques both Reliability, Availability in Risk Engineering problems can be analyzed using this kind of computational approach defined at Table 2-5, because in this thesis document the failure of any unit is considered a stochastic or random process (as already explained before in this Chapter), being a collection of random variables, therefore, having a statistical behavior.

For instance, the possible failure event of any unit has a random probability distribution, if the Useful Life approach, explained in the Section 2.1.1., is considered (match with the databases giving constant MTBF). Therefore, it is impossible to predict or calculate precisely the chances or times of failure, although they could and should be modelled analytically and statistically (by simulation) to create a complete safety analysis.

At the Synchronous case, System's internal clock synchronize all the states changes happen in the system operation, so the events of transition (failure and repair) can happen at the same time in different components, being the existence of overlapping events possible. For example if considered a System modeled like a Series Connection (Section 2.1.4.), that must present two overlap failures in different components, with downtimes computed just one time for the upper hierarchy Availability, once just one clock exist. Should be noticed that in the Synchronous case, the components are modeled as in the Analytical Model, with independent operation between them, once the operation of one component do not interfere in the other operation.

In the other model, Asynchronous, events occur asynchronously once each separate unit in the system has the own clock, which in the same case cited before, the clock of rest of system must stay stopped while the increment of time for failure is computed for a certain failed component in Series Connection.

Therefore, completely defined, it is finally possible to develop a DES, where PPR System's Main Objectives, Sub-Systems and components operations are modeled as working in a series of discrete time events, being ordered steps, separated by a computational sample time, chosen at simulation start moment as a separation unit between two iterations, normally chose in units representing real time units, such as seconds, minutes and hours represented by sample times of 1, 60, 3600, respectively. Being the use of operation lifetimes in accordance with the ITER time scenarios used (see Section 3.1.1.), 11680 and 116800 hours' missions.

For this thesis document, the random events, generated through Synchronous and Stochastic Simulation (the Section 4.3. and Chapter 6 have the explanation about the choice for Synchronous), are generation and load of times to failure, not more constant (as MTBF) but rather random, at a correct time of replacement, using the failure rate of component as weight for time to failure generation. The state of each unit is given at each instant step in simulation by a Boolean Signal, but possible changes in state (failure and repair) are just loaded in chronological separated steps, being a classic example of a two-state system classified as "markovian", explained at Section 2.1.3. So, resuming, the DES for components life modelling "jumps" in the modeled time of simulation directly to events failure or repair, explaining classification as Event-Based.

Besides the fact that Useful Life Model is used for components life, suggesting random failures of them in this period, exist other fact that connect the components life to a stochastic process, both are assumed memoryless. This means, once one component back from failure situation (by repair or replacement), it must be recognized as new and perfectly operational). Therefore, the Monte Carlo Method (Event-Based Simulation) is a correct mathematical model for the PPR System.

The number of trials to achieve reliable results should be chosen accordingly with the confidence interval desired, but for this thesis document, due to long time spend in simulation, the iterations stop to be done when results added for average calculation for Availability achieve stabilization.

Looking for good alternative to simulate the procedure explained through activity blocks used for easier programming, without a done library, use the MATLAB software together with the Simulink tool is the common choice, making possible to develop in the software workflow all the simulation treated until here in a flowchart of pre-programmed activities, in form of blocks.

3. ITER PPR System

3.1. ITER Operation and PPR System Background

The Chapter 3 is dedicated for definitions and explanations about ITER operation and PPR System useful characteristics for this thesis document and for applications of initial steps of RAMI procedure explained at Section 2.2.

The first Section (3.1.1.) starts introducing the ITER operation Scenario, i.e. the activity times for the ITER machine operation, the following sections present a background of last RAMI and Functional Analysis documents used as input for this new study, and finally shows the new interpretation of FA, Functional Breakdown, RBDs and FMECA, which are the initial inputs for the new RAMI Analysis. The following Sections was done in accordance with the ITER project, with information extracted from ITER official internal documents, with possible simplifications to frame to a thesis document. [2,11,12]

3.1.1. ITER Operation Scenario

ITER is designed and will be constructed and operated to fully optimize the available time, 24 hours/day, 365 days/year. Figure 3-1 shows the relevant periods for the planned ITER's operation scenario. It is anticipated that machine operation will be carried out in long periods separated by maintenance periods (such as an 11-day continuous operation and a 3-day break for routine maintenance), corresponding to a cycle, with a major shutdown of a few months for maintenance/upgrades (8 months are currently envisaged) and/or further installation after a long plasma operation period (16 months are currently envisaged). Three 8-hour shifts are envisaged as a basis for planning during the operation. The third shift will be used either for plasma operations, test, conditioning or routine maintenance. The operating scenario totalizes 20 years of operation, having at the end 116800h operational hours, and will use 4 global operation states: Plasma Operation State (POS), Test and Conditioning State (TCS), Short Term Maintenance (STM) and Long Term Maintenance (LTM). [2]

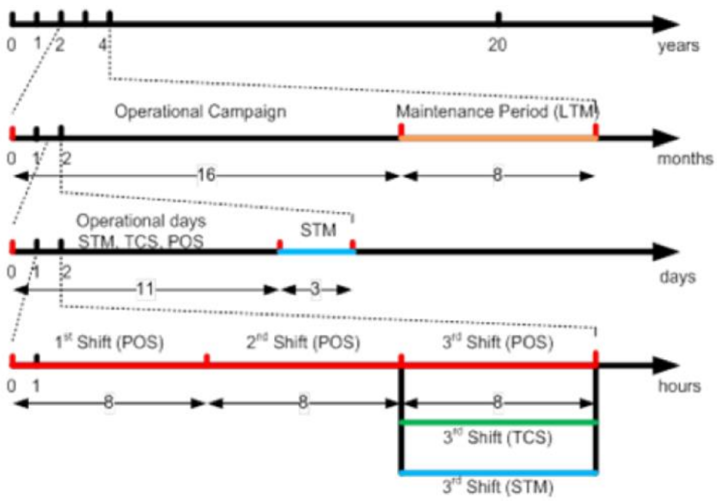

Figure 3-1: Planned operation scenario for ITER machine. [2]

3.1.2. PPR System Basic Background and Previous Documents

One Functional Analysis and one full RAMI analysis were established in earlier phases of PPR design, made by ITER operation, where a complete Functional Breakdown describing the system was made, plotting a full FMECA, RBD's and analytical calculations to achieve Reliability and Availability measures for the System's Objectives. This initial works on PPR system are the main source of information and RAMI inputs for this thesis document, but the reading of that first contacts with PPR system it is not required for understand this new study.

Trying to reflect the updated design of the PPR system, including engineering design solutions, new components and new assumptions, a new interpretation of Functional Analysis was made, including new Functional Breakdown, FMECA and RBD representations, made using new Schematics that was presented at sequence of this study. So, a new RAMI iteration is the theme for this thesis document, in order to estimate updated values for Reliability and Availability of PPR's main objectives (measurement and function) under the stipulated operating conditions. Based on the achieved results, recommendations in the sphere of design, test, operation and/or maintenance can then be proposed according to their potential to reduce the failure risk levels and improve the operational Availability of the system.

Chapter 3 intend to define and explain the PPR System dispositive and it purpose/objective. The first Section 3.1.1. resume the times scenarios to be use in the documents assumptions and calculations, now in Section 3.1.2. the objective is to briefly describe the PPR System intentions, physical operation and first sub-division, what can be detailed at Section 3.2.1., 3.2.2. and 3.2.3 with the explanation about the PPR System Functional Analysis.

The Plasma Position Reflectometry (named inside ITER operation as with a code name PBS 55F3) provides information for plasma operation and for establishing performance characteristics, these activities are fulfilling through two separate actions (define in theoretical part as System's Objectives): Electron Density Profile Measurement and Plasma Position Function, both explained next.

The PPR system is being designed to operate in O-mode using FM-CW in the frequency range 15 – 75 GHz, covering the specified density range from 0.3 to $7x10^{19}$ m^{-3}. The measurements are carried out at four toroidal/poloidal locations, known as Gap 3, Gap 4, Gap 5 (containing Gap5(A) and Gap5(B)) and Gap 6, showing next in Figure 3-2.

All considerations about ITER operation and assumed design of PPR System for RAMI actions was considered as official at the date of this thesis document.

These reflectometry channels are merely the first sub-division of the PPR System, being the PPR Sub-Systems, containing five channels in total, as the Gap 5 includes 2 active parallel reflectometry channels, Gap 5(A) and Gap 5(B), which are essentially identical (at this design iteration): the only difference between the two is in the number of Mitre Bends components involved (that can be better understood with the RBD presented next). [2]

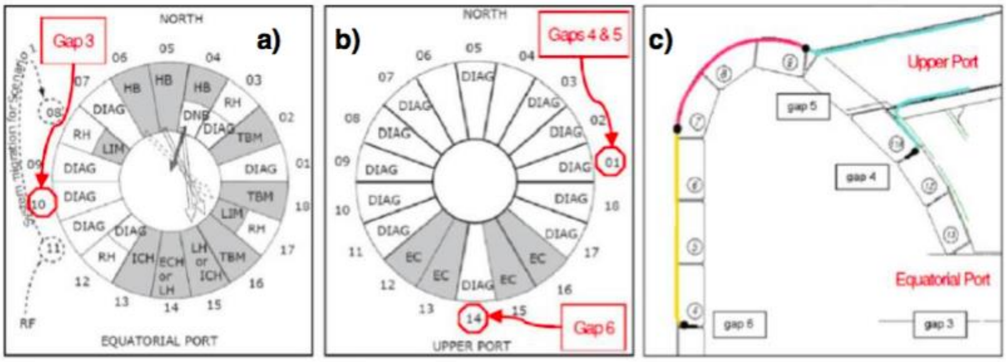

Figure 3-2: Location of gaps: (A) equatorial port; (B) upper ports and (C) proposed waveguide routing in the vacuum vessel. [2]

It makes the PPR System device a collection of channels installed in different locations of the ITER Building, each one with the objective of collect from Plasma one measurement.

Figures 3-3 until 3-6 shows the new Schematics of PPR's Sub-Systems: Gap 3, Gap 4, Gaps 5 and Gap 6 reflectometry channels, respectively, being until this design phase the best physical representation of division of the physical System (PPR) until the project achieve final design models. These new Schematics bring a new perspective for the FA and Functional Breakdown, guiding the RAMI team to a better perception of the System, made in the sequence.

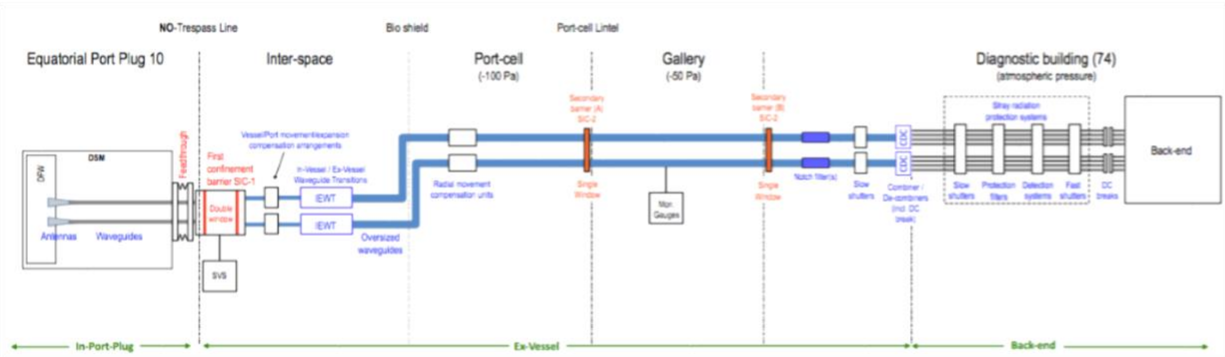

Figure 3-3: Schematic of PPR's Gap 3 (in-Port-Plug) system. [11]

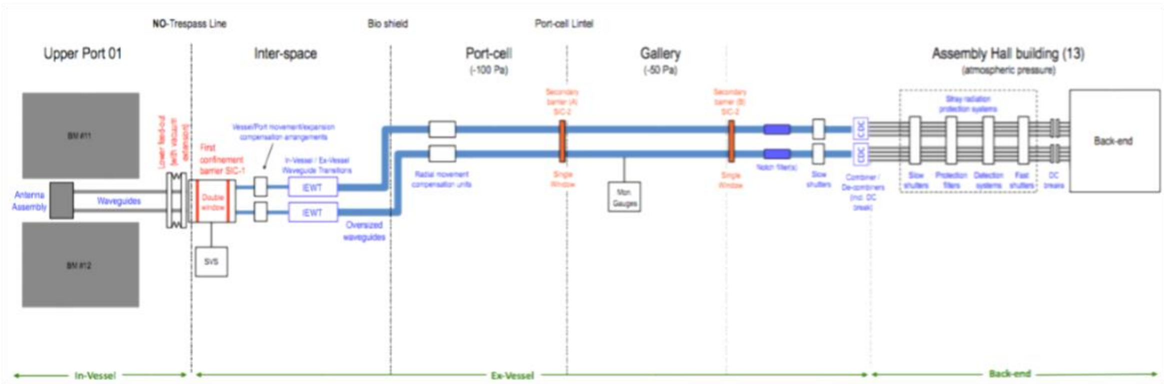

Figure 3-4: Schematic of PPR's Gap 4 (In-Vessel) system. [11]

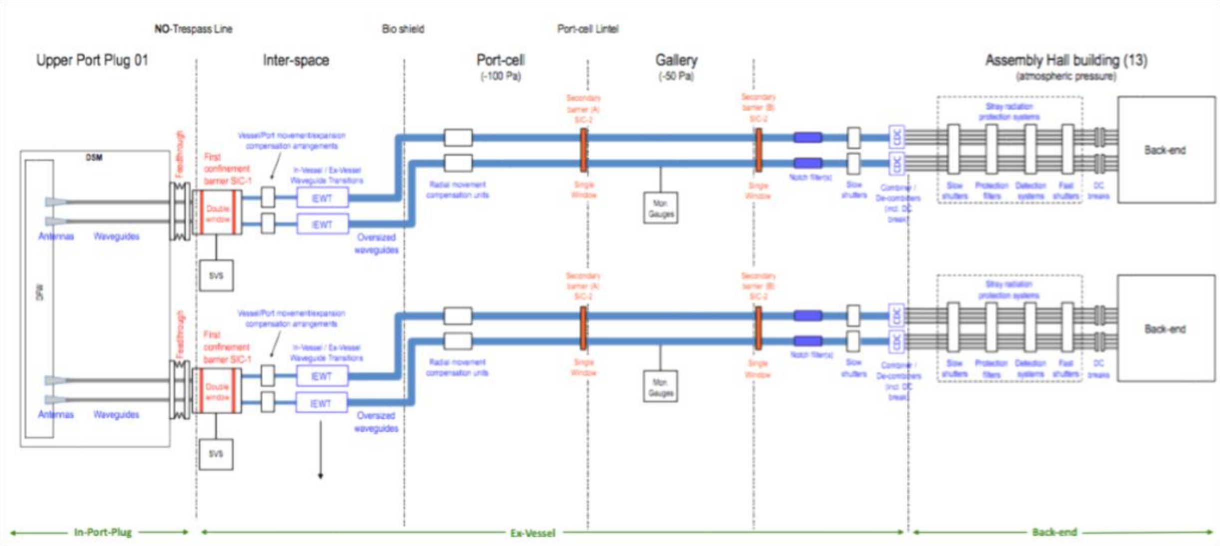

Figure 3-5: Schematic of PPR's Gap 5 (in-Port-Plug) system. [11]

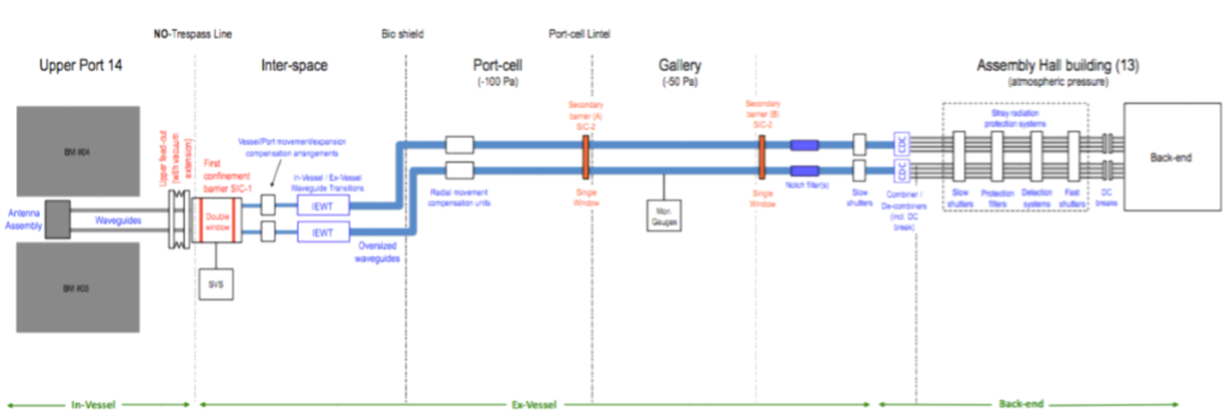

Figure 3-6: Schematic of PPR's Gap 6 (In-Vessel) system. [11]

3.2. Functional Analysis, Functional Breakdown and FMECA New Approaches

3.2.1. Functional Analysis and Functional Breakdown New Approaches

The schematics from Figures 3-3 until 3-6, presented at Section 3.1.2. and placed in Annex, were the base for a new perspective approach for Functional Analysis, being the best solution to understand the components that form the consequents Sub-Systems (Gaps), whose union create the whole PPR System. This sub-division can be easier understood looking for Figure 3-2 that explain the System divided in channels, compounds practically for the same kind of components, but with different locations at the ITER Building and quantities. The Schematics are the best option for representation until the project achieve a final technical design drawings for the Gaps, used together with the FA information to achieve a breakdown of critical components associated with each basic function. [11]

For the analysis presented in this thesis document, the Functional Breakdown of the system resulted in a re-organization of the main functions defined and in the addition of new sub-level functions, to better accommodate the adopted distribution of diagnostic components into Sub-Systems.

To achieve an intelligent visualization of the System operation, its used the Figure 2-5 found at Section 2.2. of this document, together with the theoretical background explained in the same section, for divide the Whole System with Main Objectives in small basic functions did by basic units (components).

The primary function of the PPR System is to provide measurements of plasma edge density as a function of the distance from the wall at four defined locations known as Gaps, this is a deeper explanation about the measurement did by each Gap (Electron Density Profile Measurement) cited at Section 3.1.2., guiding the Whole System to provide for ITER the main action, the Plasma Position Function.

Looking deeper inside the Sub-Systems, achieving the basic functions did by components, they could be divided in four basic functions (At the functional level of basic functions, it was decided to separate two of them in the last FA. The basic function “To launch and detect mm-wave signals to/from the plasma” was split in two different basic functions, already cited at this section, being: 1) “To generate/detect mm-wave signals”; 2) “To route mm-wave signals to/from the plasma”): [12]

- To generate/detect mm-wave signals;
- To route mm-wave signals to/from the plasma;
- To provide services and features to support the basic functions;
- To provide measurements of density profile and plasma position.

Once all components at each Gap can accomplish his own basic functions, the first main objective for the system can be done, being the Electron Density Profile Measurement the measure analyzed for each Gap of PPR System when a signal emitted from the Back-End part of each Gap reach the plasma inside the Tokamak machine and returns to the Back-End.

Accomplishing these measures in the four possible locations it is possible to achieve the Main Objective of PPR System, the Plasma Position Function, providing for engineering a safety parameter for control the Plasma inside Tokamak.

The Functional Breakdown of the system was already thoroughly reviewed in the last FA. This revision has resulted in a re-organization of the basic functions defined and in the addition of new sub-level functions, to better accommodate the adopted distribution of diagnostic components into Sub-

Systems.

In some cases, it was decided to increase the number of sub-level functions to provide a higher level of detail in the description of the different Sub-Systems elements, once the design can evolve and guide the PPR System to have Gaps truly different. [12]

For the definition of the System Architecture options and selection of the best candidate (for which the last Functional Analysis at sub-system level was performed), the PPR Sub-Systems (Gaps) has been initial split in four major sub-divisions, considered as Gap parts:

- In-Port-Plug (Front-End components for both Gap 3 and Gap 5);
- In-Vessel (Front-End components for both Gap 4 and Gap 6);
- Ex-Vessel (waveguides, transitions, confinement barriers, combiners/de-combiners and stray radiation protection);
- Back-End (microwave sources, acquisition & control systems and software packages).

At this exact level of the PPR Sub-Systems (Gaps), the major changes introduced by the last FA, did by ITER operation, consist of the merge of the In-Port-Plug (the location next to Plasma for Gap 3 and Gap 5 where the Antennas components are connected) and In-Vessel (the location next to Plasma for Gap 4 and Gap 6 where the Antennas components are connected)) Front-Ends (although in different locations, they perform the same function). Being for instance just three main sub-divisions inside the PPR System, that was considered for division for following RBDs of the System. The sub-divisions are:

- Front-End.
- Ex-Vessel.
- Back-End.

However, the introduction of new components acting as divisors inside the Gaps, result in a five basic functional blocks division for each Gap, as follows:

- Front-End;
- Ex-vessel transmission lines;
- Confinement barriers;
- Back-End;
- Acquisition & Control system.

The components added at last design change, acting as devisors are:

- Confinement barriers: consists of the primary confinement barrier (between primary vacuum and interspace), the secondary barrier A (between Port-Cell lintel and the Gallery) and the secondary barrier B (between Gallery and the Diagnostics (Gap 3) and Assembly (gaps 4, 5 and 6) buildings.

- Acquisition & Control System: consists of the microwave and electronics instrumentation (located at the Diagnostics and Assembly Hall buildings) required to emit/receive microwaves, to perform signal conditioning, to acquire data, to perform RT data analysis, and to communicate with Control, Data Access and Communication (CODAC) and Plasma Control System (PCS) for gap measurements.

For each of the channels (Gaps 3, 4, 5, and 6), the PPR diagnostic elements have been distributed into the five functional blocks division cited, which are listed and described in Table 3-1. [12]

PPR Functional Blocks inside the Sub-Systems (Gaps)	**Description**
Front-End	The diagnostic Front-End comprises the antenna assembly to launch/receive the mm-wave signal to/from the plasma and the In-Vessel/In-Port-Plug waveguide transmission line (TL) to route the signal to/from the antennas to vacuum vessel feedouts (for in-vessel systems) or feedthroughs in the port-plug closure plates (for in-port-plug systems). Noticing that the name feedthroughs was generically applied for this thesis document.
Ex-vessel Transmission Lines	Ex-vessel transmission lines are used to route the signal to/from the vacuum vessel to the diagnostic buildings where the instrumentation is located. There is one TL per antenna (10 in total: two TLs for Gaps 3, 4 and 6 and four TLs for Gap 5). The TL is made up of various oversized waveguide components (straight sections, mitre bends, mode filters, DC breaks, etc.), which are not only used to transmit the signal (low loss TL), but also to maintain the polarization and mode purity of the transmitted signal. The TL also includes: waveguide transitions to couple the in-vessel/in-port-plug waveguides with the ex-vessel waveguide TL system (IEWT); combiner/de-combiner to split the signal (15 – 75 GHz) into the four fundamental frequency bands used by the Back-End sub-system (using waveguide tappers or Quasi-Optical (QO) technology); alignment and calibration associated components (thermo-couples, supports, etc) and all the intermediate support elements to fix the waveguides to existing support structures.
Confinement Barriers	The confinement barriers sub-system includes all components that contribute to provide vacuum containment that ensures tritium confinement, including components related to vacuum measurements. According to the Preliminary Safety Report, there must be two confinement barriers in the PPR system: First confinement barrier (safety classification SIC-1) close to the vacuum vessel and Second confinement barrier (safety classification SIC-2) between the Gallery and the rest of the buildings. But for this thesis document the component related to barriers was considered with different actuations for each Gap, once each

	Gap actions and structure can cause damage for the barriers. After the accident at the Fukushima nuclear power plant in Japan, safety requirements were revised at ITER operation. As a result of this revision, the Second Confinement barrier for the PPR system is made up of two more barriers close to building penetrations: one in the Port Cell lintel (Second-A confinement barrier), and a second one between the Gallery and Diagnostics areas (Second-B confinement barrier). The secondary window assemblies have been identified as Hardware Core Components.
Back-End	The Back-End comprises all the specific diagnostic instrumentation (RF & IF components and associated electronics units) for mm-wave signal emission and detection. There are four receivers/emitters per ex-vessel TL since four frequency bands are required to cover the diagnostic frequency band (15- 75 GHz). The sub-system also includes all the waveguide components (rectangular waveguides at fundamental frequency bands) required to connect the RF instrumentation to the ex-vessel TL sub-system (up to the combiner/de-combiner) and all components required to protect the instrumentation from stray radiation (notch filters, slow shutters/switches, fast pin diodes, etc.). All components are located in the diagnostic areas. The analysis software packages for off-line and real-time measurements are formally included in this sub-system.
Acquisition and Control System	System to: 1. Digitize and store raw data with specified quantity and temporal resolution (different systems for off-line and real time (RT) processing) 2. Control and monitor the working status of all relevant components (launched/received power, frequency sweep, stray microwave radiation protection system, thermo-couples, calibration, etc.) 3. Interface to relevant networks (CODAC, CIS, PCS) for diagnostic operation.

Table 3-1: List and description of the Basic Functional Blocks inside each PPR Gap. [12]

Therefore, considering the whole PPR System such as explained with two main objectives (measurement and function) and using this actions for split the Sub-Systems in Basic Functional Blocks, it is time now to further look for the existing PBS (Plant Breakdown Structure) of the PPR System and the location of the Front-End (the part closer to the plasma, one of the main difference between the Gaps) and Back-Ends of the various Sub-Systems, that are shown in Table 3-2, being basically the resume of physical locations of first and last part of PPR Sub-Systems in the ITER Building.

The Table 3-2 introduce the PBS number (numerical code for a System, Sub-System inside the IO), the PBS node (the short name for the System and Sub-System, adopted for this thesis document), the full name and description, besides the Front-End and Back-End location.

Such as told before, the Front-Ends of Gaps 3 and 5 are located In-Port-Plug with the Antennas installed inside apertures in the diagnostic first wall. For Gaps 4 and 6, the Front-Ends are located In-Vessel with the Antennas installed between two (poloidally) consecutive blanket modules. [2]

PBS number (code in IO)	PBS node (shorts name)	Full Name and Description	Front-End Location	Back-End Location
55F300	PPR system	Plasma Position Reflectometry (PPR) system	--	--
55F303	PPR, Gap 3	Plasma Position Reflectometry, Gap 3. Equatorial view, LFS	In-Port-Plug EPP#10	Diagnostic building 74
55F304	PPR, Gap 4	Plasma Position Reflectometry, Gap 4. Oblique view/LFS	In-vessel/in-port UP#01	Assembly Hall building 13
55F305	PPR, Gap 5	Plasma Position Reflectometry, Gap 5. Top view	In-Port-Plug UPP#01	Assembly Hall building 13
55F306	PPR, Gap 6	Plasma Position Reflectometry, Gap 6. Equatorial view, HFS	In-vessel/in-port UP#14	Assembly Hall building 13

Table 3-2: Reflectometry Channels (Gaps) positions in ITER building. [2]

The full Functional Breakdown for ITER PPR System in accordance with the FA did at this section is illustrated at Annex 1. The image did by ITER operation delimit for the whole System from Main Objectives until the basic ones.

One complete new output for Functional Breakdown of the ITER PPR System is needed in this new iteration of RAMI analysis, trying to achieve a realistic analysis for this phase of design, doing a new interpretation of FA, exposed at this section. The work presented already did a top-down description of the System and Sub-Systems performed, besides the hierarchical identification of functions.

This new output is presented at the following Section 3.2.2.

3.2.2. New Functional Breakdown outputs for PPR System

Using the Table 3-1 and 3-2, the Schematic Figures 3-3 until 3-6, the Annex 1 and all the information presented at this Section 3, it is possible to make a new list of critical components, addressed to all the determined basic functions.

After the flow-down of the primary functions of the PPR System to the Sub-System level in order to identify the basic functions related to each basic function of the PPR Gaps, a complete list of the critical components (for all Gaps, being different components type and number depending of the Gap in focus) outputted by the new Functional Breakdown interpretation related with the ITER PPR System Measurement and Function that were considered for this RAMI analysis is:

- Antenna to route microwaves;
- Antenna supports/holders to withstand loads;
- In-port-plug waveguide to route microwaves;
- In-port-plug waveguide supports to withstand loads;
- In-vessel waveguide to route microwaves;
- In-vessel waveguide supports to withstand loads;
- Feedthrough;
- First Confinement Barrier SIC-1;
- Vessel/Port movement/expansion compensation arrangements;
- IEWT to transmit microwaves;
- Ex-vessel waveguide to route microwave signals;
- Ex-vessel transmission lines (TL) support to withstand load (Interspace);
- Ex-vessel transmission lines (TL) support to withstand loads (Port-Cell and Gallery);
- Mitre bend in interspace to route microwaves;
- Mitre bend outside interspace to route microwaves;
- Radial movement compensation units;
- Secondary Barrier (A) SIC-2;
- Secondary Barrier (B) SIC-2;
- Notch Filter;
- Slow Shutter;
- Spurious operation of Fast Shutter;
- Combiner/De-Combiner (CDC) to combine/de-combine microwave signals;
- Protection Filters;
- Detection System (Stray Sensor);
- Pin switches of the fast shutter;
- DC breaks;
- Radio Frequency (RF) source to generate microwaves;
- Receiver or and associated electronics to detect;
- Data Acquisition (DAQ) system;

- Back-End supports/holders;
- Local Controller;
- Control Software.

The First Confinement and Secondary Barriers are components that belong to the Safety Important Class (SIC) from ITER, and as so shall be dealt with in an independent RAMI analysis by ITER operation. [2]

For Secondary Barrier, a simulation studies already done and reported in a separated RAMI Analysis made by ITER operation, allow gathering the required data to include in the present analysis of the reflectometry channels. However, there is not yet sufficient information about First Confinement Barrier. [13]

Also, there is not yet information that allows to characterize the reliability behavior of Feedthroughs, Vessel/Port movement/expansion compensation arrangements, Radial movement compensation units, Notch Filters and Slow Shutters.

These components were considered as "Transparent Units", that means, with no considered failure rate associated, what needs to be review for upcoming RAMI iterations.

Already having all the components that accomplish the basic Functions, the FMECA Analysis can start, guiding the system for the problematic components.

3.2.3. FMECA

Looking from the Tables 2-1 and 2-2 for Severity and Occurrence scales, and being aware of the background of FMECA, presented on topic 2.2. of the Theoretical Part of this thesis document, it's possible to develop here the analysis for this iteration of RAMI, having as input the output list of components from Functional Breakdown made for this study, at Section 3.2.2.

Applying the scales (qualitative judgment) for Severity and Occurrence, related in the Theoretical Part, and knowing from Equation (25) that the Criticality is a parameter calculated from multiplication from Severity and Occurrence, the new measurement it is made and classified in accordance with the following Table 3-3, plotting an aware and qualitative classification for each component of PPR System.

The Table 3-3 cited is just the Criticality Matrix, looking for implement the rules for the components listed as critical.

The components marked by red letters in the table was considered as possibly problematic, and for these components a separate analysis need to be done, noticing that besides Criticality, a Severity bigger than 1 is enough to consider a problematic component (i.e. component considered for the designers, at this stage, as capable of stop ITER operation).

Therefore, the Antenna supports/holders to withstand loads, In-Vessel waveguide to route mm wave, First Confinement Barrier SIC-1, IEWT to transmit, Secondary Barriers (A) and (B) SIC-2 and CDC to combine/decombine mm-wavesignal are considered for the Criticality Matrix, Table 3-3, as the components with possible Impact to ITER Operation. This study is the principal focus of RAMI Analysis, once the RAMI Requirement presented at the Section 3.3. was clear about the importance that the PPR System do not present damage for the ITER machine operation, having a parameter in Availability to be achieved by RAMI team and designers.

FMECA Table for PPR System							
Name of Component	λ [1/h]	μ [1/h]	MTBF [h]	MDT [h]	Severity [1-6]	Occurrence [1-6]	Criticality [1-36] for ITER Operation
Antenna to route mm wave	1.04E-05	4.63E-04	9.62E+04	2160	1	4	4
Antenna supports/holders to withstand loads	2.28E-07	2.31E-04	4.39E+06	4320	5	2	10
In-port-plug waveguide to route mm wave	1.04E-06	4.63E-04	9.62E+05	2160	1	3	3
In-port-plug waveguide supports to withstand load	2.28E-07	4.63E-04	4.39E+06	2160	1	2	2
In-vessel waveguide to route mm wave	1.04E-06	1.71E-04	9.62E+05	5,840	5	3	15
In-vessel waveguide supports to withstand load	2.28E-07	1.71E-04	4.39E+06	5,840	1	2	2
Feedthought					1	1	1
First Confinement Barrier SIC-1					1	1	1
Vessel/Port movement/expansion compensation arrangements					1	1	1
IEWT to transmit	1.04E-07	6.94E-04	9.62E+06	1440	4	2	8
Ex-vessel waveguide to route mm signal	1.04E-07	6.94E-04	9.62E+06	1440	1	2	2
Ex-vessel TL support to withstand load(Interspace)	2.28E-08	6.94E-04	4.39E+07	1440	1	1	1
Ex-vessel TL support to withstand load(Port-Cell and Gallery)	2.28E-08	2.08E-02	4.39E+07	48	1	1	1
Mitre bend in interspace to route mm wave	1.14E-06	6.94E-04	8.77E+05	1440	1	3	3
Mitre bend outside interspace to route mm wave	1.14E-06	2.08E-02	8.77E+05	48	1	3	3
Radial movement compensation units					1	1	1
Secondary Barrier (A) SIC-2	1.66E-08	1.71E-04	6.03E+07	5840	5	1	5
Secondary Barrier (B) SIC-2	1.66E-08	1.71E-04	6.03E+07	5840	5	1	5
Notch Filter					1	1	1
Slow Shutter					1	1	1
Spurious operation of Fast Shutter	4.40E-07	5.00E-01	2.27E+06	2	1	2	2
CDC to combine/decombine mm-wavesignal	1.04E-07	4.17E-02	9.62E+06	24	3	2	6
Slow Shutter					1	1	1
Protection Filters	2.28E-08	4.17E-02	4.39E+07	24	1	1	1
Detection System(Stray Sensor)	1.00E-06	4.17E-02	1.00E+06	24	1	3	3
Pin switches of the fast shutter	1.14E-04	4.17E-02	8.77E+03	24	1	5	5
DC breaks	5.71E-07	2.08E-02	1.75E+06	48	1	3	3
RF source to generate mm-waves	2.00E-07	4.17E-02	5.00E+06	24	1	2	2
Receiver or and associated electronics to detect	1.00E-07	4.17E-02	1.00E+07	24	1	2	2
Data Acquisition system	1.14E-05	4.17E-02	8.77E+04	24	1	4	4
Data processing software	1.71E-05	4.17E-02	5.85E+04	24	1	4	4
Back-end supports/holders	2.28E-08	2.08E-02	4.39E+07	48	1	1	1
Local Controller	1.10E-06	4.17E-02	9.09E+05	24	1	3	3
Control Software	1.71E-05	4.17E-02	5.85E+04	24	1	4	4

Table 3-3: Criticality Matrix of FMECA for PPR System, with critical components write in red.

3.3. Project Requirements for PPR System and ITER Operation

This section is a summary of the RAMI requirements applicable for the PPR system that come from ITER operation through conditions to be followed. The numbering of requirements in ITER operation and in PPR system it is not final as it is still a project and a system under development when the present report is issued. Therefore, the project requirements such as RAMI analysis need to be an iterative process, having to be updated according to design development. [2]

Other design, operational and maintenance requirements, beyond Reliability, Maintainability, Inspectability, Tests and validation of performance and Spares and Standardization requirements need to be included in those applicable documents for also to be considered for PPR system. However, for the aim of this thesis document only the Availability ones are shown and considered, once the PPR system already have an overall value of Availability to be verified and achieved.

Availability Requirements of PPR system extracted from ITER operation requirements for PPR System: [2]

1. REQ-156 extracted from ITER operation requirement for PPR system:
The maintenance and/or replacement of PPR system equipment shall minimize the impact on ITER operation.

That is one of important requirements for all diagnostic Systems, showing that the ITER Availability is priority and the failures impacting the ITER machine operation must be avoid.

2. REQ-157 extracted from ITER operation requirement for PPR system:
The inherent availability of the PPR system shall be compatible with the overall 98.58±0.20% allocated to the whole Diagnostics system.

That is another important requirement to be used as base of comparison for Analytical and Simulation results.

Therefore, based on all the RAMI Analysis described in the Chapter 3, the intention now it is to present the RBDs for model the System Structure and start the two different approaches to achieve results.

4. RAMI Approaches and Models

This section presents the RBD models for PPR System and the Input Database explaining the two approaches used for achieving the final RAMI results: the Analytical and the Discrete Event Simulation.

The explanations and knowledges about PPR System from Chapter 3 and theoretical background for RAMI described in Literature Review (Chapter 2) are used as basis for Chapter 4.

4.1. Reliability Block Diagrams (RBD)

The RBD approach uses the functional breakdown output (list of components for the Sub-Systems) as a basis but concentrates on the reliability-wise relationships linking the function-blocks (components that perform each basic function). Diagrams describing the multiple levels in a hierarchy consistent with the functional breakdown, together with the input data fed to the lowest level blocks (components), allow to compute the resulting Reliability and Availability for the upper levels (Sub-Systems, Gaps), up to the main Measurement and Function of the PPR System or to the whole ITER Operation. These input data consist in the Reliability parameter, Mean Time Between Failures (MTBF), and maintenance parameter, Mean Down Time (MDT), which were obtained from ITER Reliability databases, previous experience, tacit knowledge compiled on other scientific devices/environments, and assumptions made following the personal experience of the RAMI Analysis. [4]

4.1.1. RBDs for the Reflectometry Channels (Sub-Systems, Gaps)

The RBD to evaluate the Reliability and Availability analysis of the different reflectometry channels (Gap 3, Gap 4, Gap 5(A), Gap 5(B) and Gap 6) of the ITER PPR System are presented in Figure 4-1 to Figure 4-4, where the order of representation was chosen now according with the Front-End position of each Gap, making the Gap 3 and Gaps 5 and consequently the Gap 4 and Gap 6 stay always represented next each other in this study, what was better explained in the last part of this Section (4.1.1.), after the representation. Each Gap is composed by two reflectometry lines used for diagnostics purposes. As already introduced, the signal is issued from Back-End region of each Sub-System and travels all the structure through one emission line, until reaching the Plasma, and then comes back through another receiving line.

According to the system design it was assumed that all components in the Back-End, Ex-Vessel and In-Port Plug/In-Vessel are in series. Most blocks in the RBDs include more than one elementary component. In case one block consists of similar components (typically for the emission and reception segments of the reflectometry channels) their number is presented below each block, and the set has a series Reliability wise relationship. However, in the Back-End sub-division, Reliability blocks (Stray Radiation Protection System, Back-End, and Local Control System) present a more complex architecture in terms of lower level components and Reliability relations among them. The RBD for the Back-End sub-division involving their components is presented in Figure 4-5 to Figure 4-7.

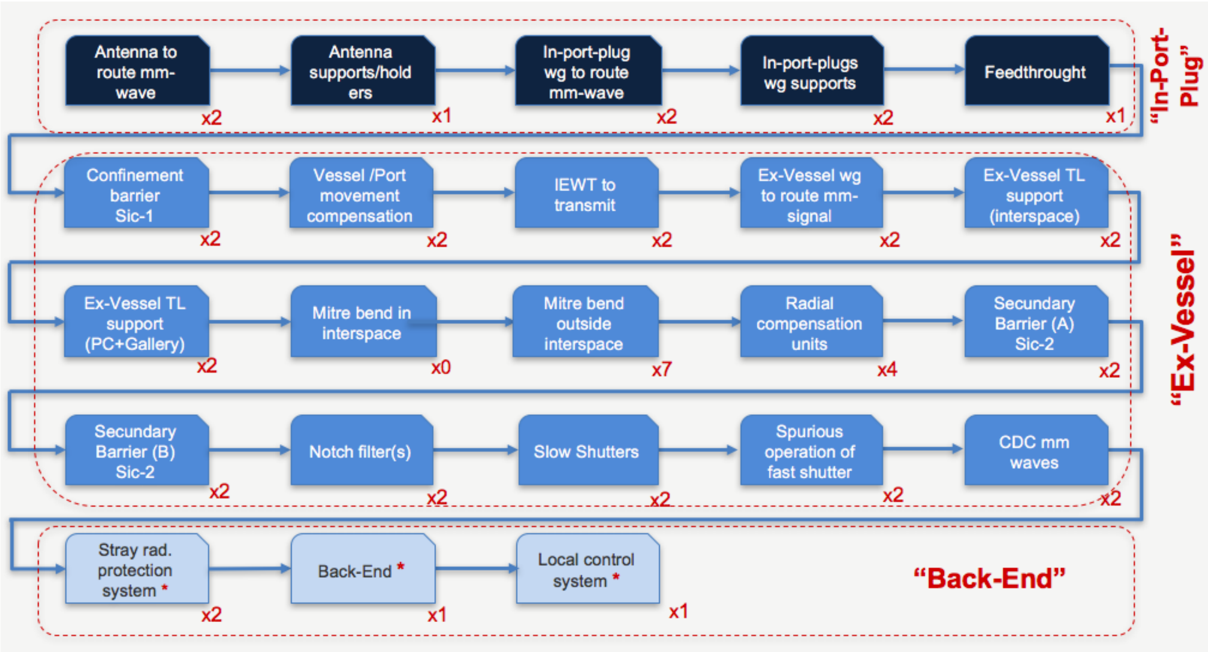

Figure 4-1: RBD of reflectometry channel Gap 3.

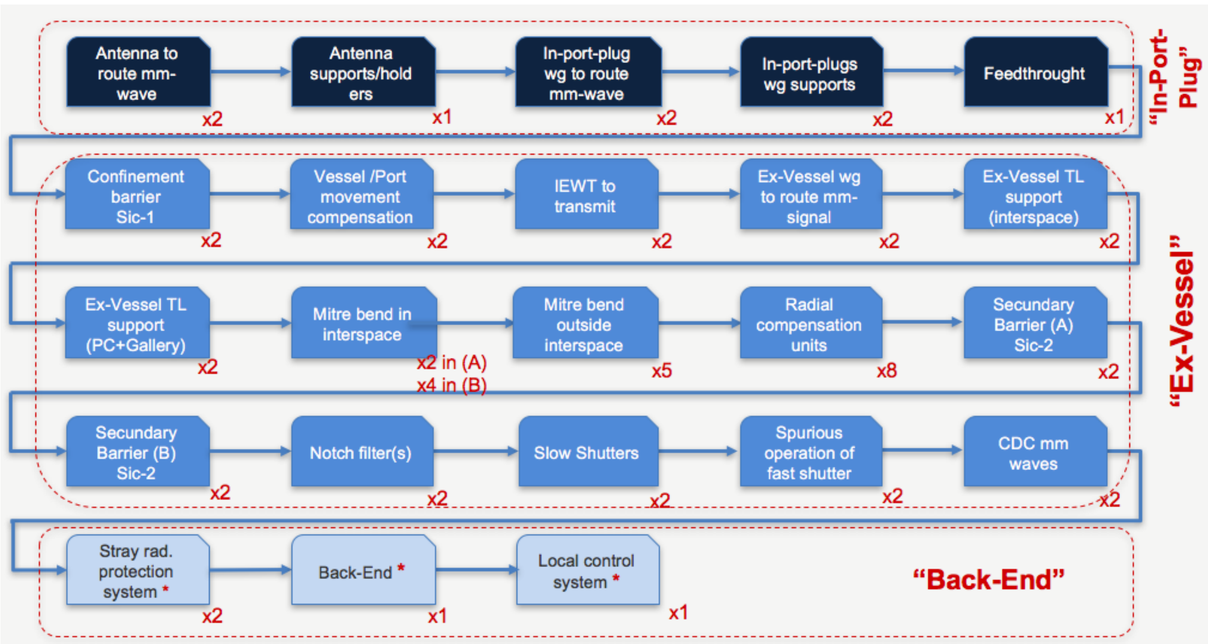

Figure 4-2: Generic representation for RBD of reflectometry channel Gap 5(A) and Gap5(B).

Should be notice that the Gap 5 has here represented just one RBD, but as explained before, the Gap 5 has a redundancy in active parallel, and the representation differ just in number of the component 'Mitre bend in interspace', what is exposed in the Figure 4-2, with two numbers presented below component's block, indication that in Gap 5(A) are present two Mitre bends in interspace and in Gap 5(B) 4 of them.

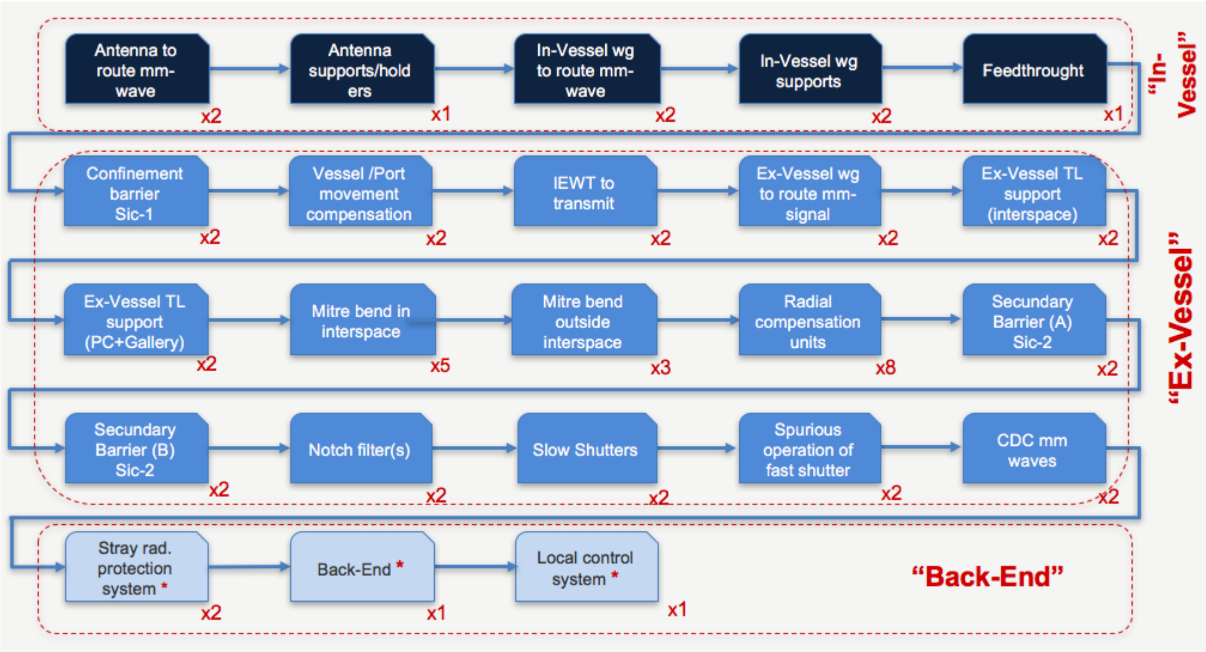

Figure 4-3: RBD of reflectometry channel Gap 4.

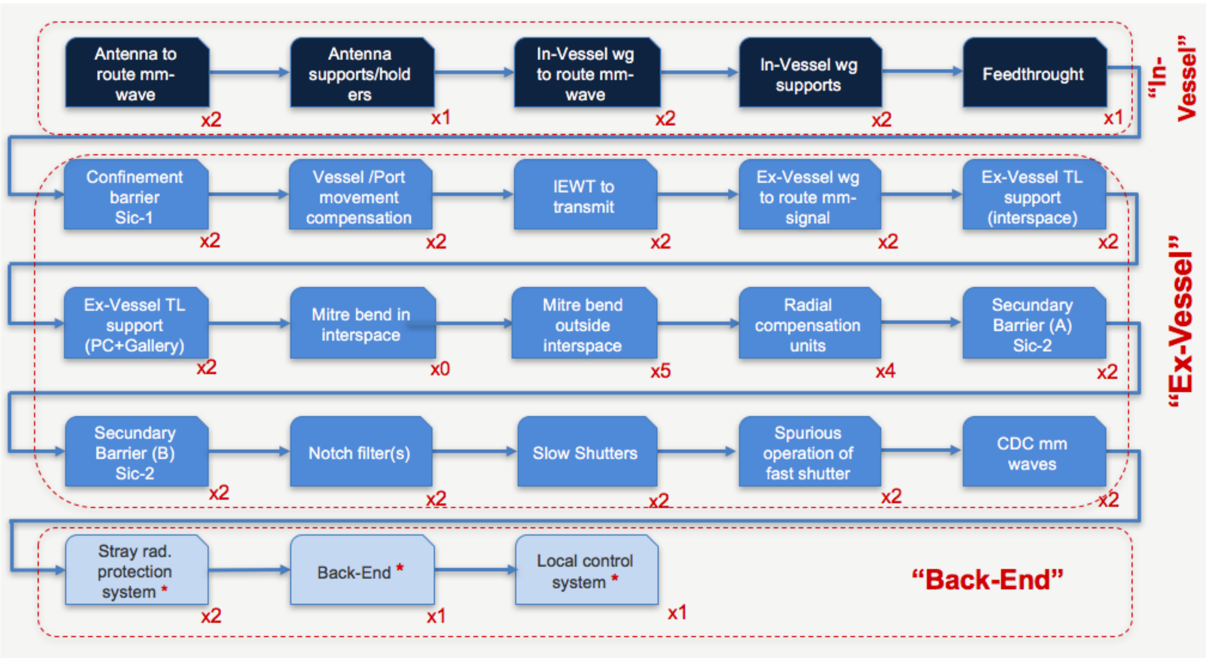

Figure 4-4: RBD of reflectometry channel Gap 6.

It should be noted that even if the RBD of the Stray Radiation Protection System represents its components in a parallel arrangement, if fact the requirement that the four parallel lines of 5 components in series must be operational (4 out of 4 Active Parallel connection) for Stray Radiation

Protection System to be considered available, results and logics converge in a classical series connection between all components (Figure 4-5).

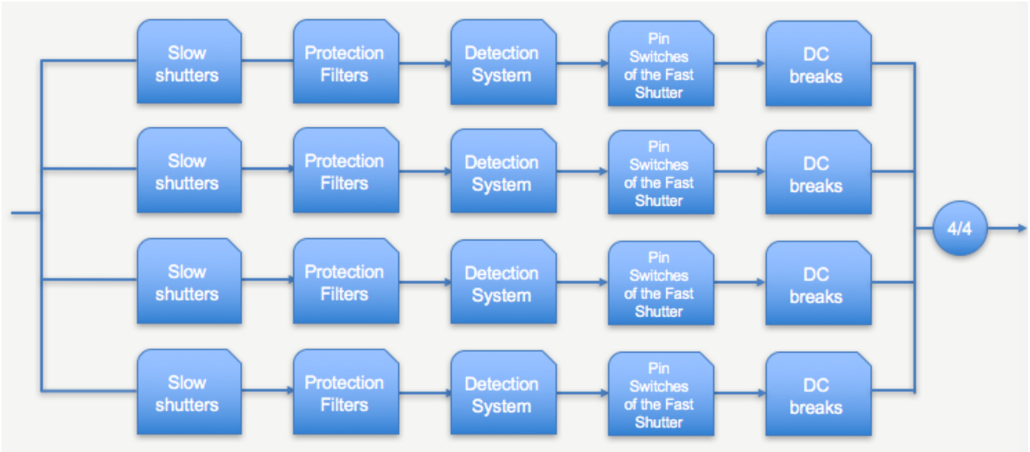

Figure 4-5: RBD of Stray Radiation Protection System.

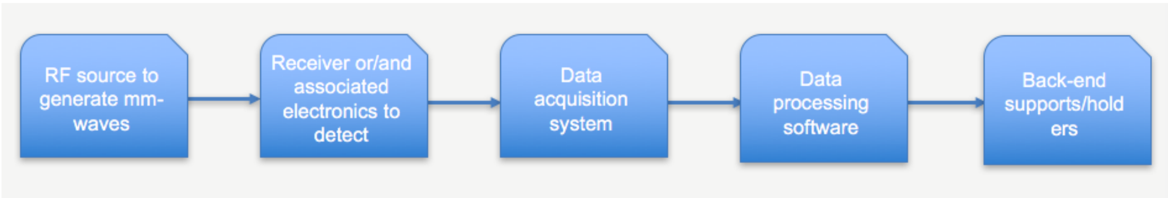

Figure 4-6: RBD of Back-End.

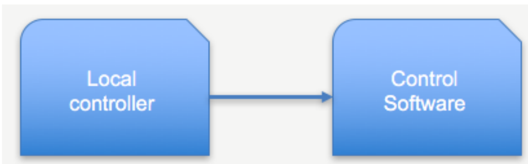

Figure 4-7: RBD of Local Control System to Control and Monitor.

In summary, all reflectometry channels have a quite similar architecture, being the main difference among them the Front-End location and the specific number of some components. In Gap 3 and Gap 5 antennas components are connected and located in the In-Port-Plug, and in Gap 4 and Gap 6 they are in In-Vessel, that is the purport for the order of representation. In addition, Gap 5 has a redundancy of 1 out of 2, meaning that it is composed by two independent reflectometry lines (Gap 5(A) and Gap 5(B)) and for it be considered available only one of the lines must be operational, resulting in Active Parallel connection. Note again that between Gap 5(A) and Gap 5(B) there is just a difference related with the number of Mitre bends, related on Figure 4-2, below the component 'Mitre bend in interspace.

4.1.2. RBDs for the Electron Density Profile Measurement and Plasma Position Functions (Main PPR System's Objectives)

Considering that the purpose (objective) of the ITER PPR System is to provide Electron Density Profile Measurements and based on these measurements allow performing the Plasma Position Function, the higher level RBD for these measurements and position function are presented in Figures 4-8 and Figure 4-9.

In fact, each Gap can provide an Electron Density Profile Measurement arising from one distinct location in the plasma, meaning that to have '*m* measurements out of the 4' possible ones, only *m* Gaps must be operational: the RBD presented below on Figure 4-8 considers a "*m* out 4" Parallel condition for the measurement case.

However, to ensure that the Plasma Position Function is available to guarantee the position of Plasma inside the Tokamak machine, all the 4 measurements must be provided. This means that Gap 3, Gap 4, Gap 5 and Gap 6 have to present their measurements, and in the corresponding RBD this function is represented by a series of Gaps with a redundant active parallel for Gap 5, in Figure 4-9.

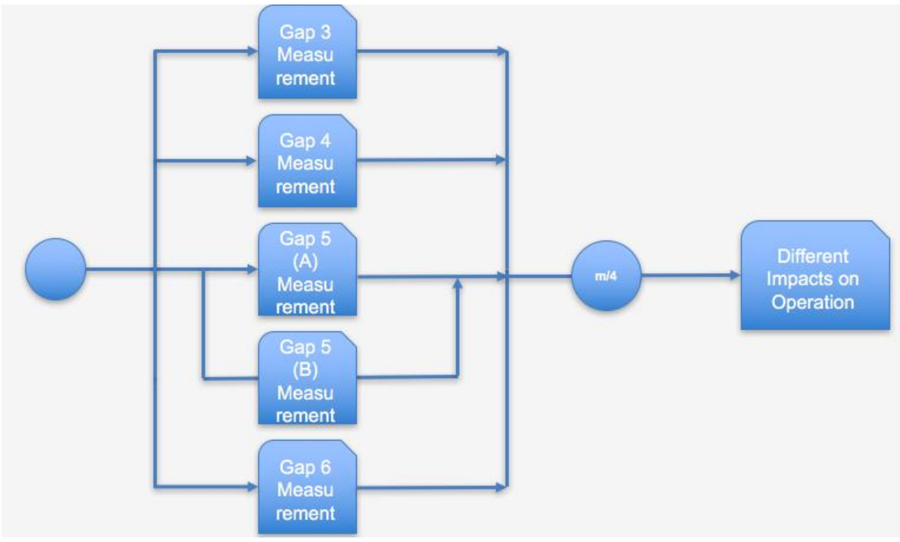

Figure 4-8: RBD of Electron Density Profile Measurement.

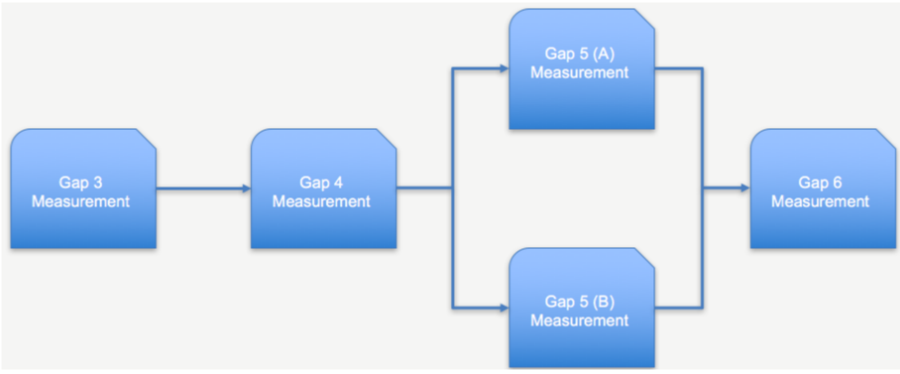

Figure 4-9: RBD of Plasma Position Function.

4.1.3. RBDs for the Impact on ITER Operation

Since the impact on ITER operation of a failure or any maintenance and/or replacement of the PPR System equipment is intended to be minimized (RAMI Requirements, presented in section 3.3.), the components whose failure can result in a potential break of all ITER operation were identified. This identification took placed gathering the judgments of the design team involved in the PPR system development, what was confirmed by FMECA presented at Section 3.2.3., leading to the following critical failures: the arcing or contact between antennas and modules, possible achieved by failure on Antenna Support Holders; In-vessel Waveguides failure; First Confinement Barrier (SIC-1) failure; IEWT failure; Secondary Barriers (A) and (B) failure (SIC-2); and CDC failure. Figure 4-10 presents the RBD designed to estimate the potential impact of these failures on ITER operation. All the identified components were considered in a series connection, reflecting that a failure of any of them determines a stoppage on ITER operation, such as previous sections, the number of components for each block it is designed below the block, where all the components are in series connection. Notice that the Secondary Barrier components was placed together in the RBD, once they are similar and have the same Input Data, presented next (totalizing 4 barriers per Gap, 20 at total PPR).

Such as explained in the Theoretical Part of this study., the Failure Modes, Effects and Criticality Analysis contribute for RAMI analysis giving the components with a combination between Severity and Occurrence that can cause problems for operation, what is the interest of this topic about the impaction in ITER operation.

Should be noted that in the previous RAMI analysis, made by ITER operation, only two failures were considered as having influence on all operation: the “arcing between antenna and blanket module” and “failure of antenna supports/holders”. However, in this new iteration of RAMI Analysis, it was considered that the arcing between two components are a phenom/risk and not a failure of a component, meaning that it is not in the scope of this analysis. So, a new analysis became necessary.

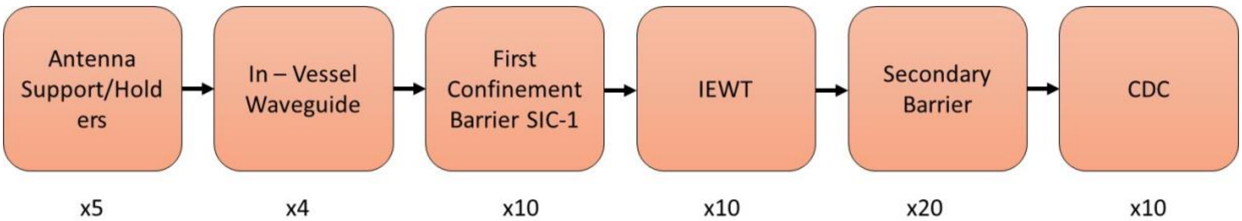

Figure 4-10: RBD of Impact on the ITER operation.

4.1.4. Input Data

In order to assess the reliability/failure behavior of the components and the maintenance capabilities of the ITER PPR system, input data was collected from different available databases, essentially from the last RAMI analysis made by ITER operation ([2]), the ITER databases and one separate RAMI analysis made for the Secondary Barriers([13]). Table 4-1 presents the data collected for each elementary component (all failure modes were considered): the name of the component; the failure rate λ_i; the repair rate μ_i; the MTBF (= 1 / λ_i); the MDT (= 1 / μ_i); and the location (sub-division) of the component in the PPR system.

Reliability and Maintainability Data Base for all units in ITER PPR System					
Name of Unit	**Failure Rate λ [1/h]**	**μ [1/h]**	**MTBF [h]**	**MDT [h]**	**Location on ITER**
Antenna to route mm wave	1.04E-05	4.63E-04	9.62E+04	2160	In-port-plug/In-vessel
Antenna supports/holders to withstand loads	2.28E-07	2.31E-04	4.39E+06	4320	
In-port-plug waveguide to route mm wave	1.04E-06	4.63E-04	9.62E+05	2160	
In-port-plug waveguide supports to withstand load	2.28E-07	4.63E-04	4.39E+06	2160	
In-vessel waveguide to route mm wave	1.04E-06	1.71E-04	9.62E+05	5,840	
In-vessel waveguide supports to withstand load	2.28E-07	1.71E-04	4.39E+06	5,840	
Feedthought					
First Confinement Barrier SIC-1					Ex-vessel
Vessel/Port movement/expansion compensation arrangements					
IEWT to transmit	1.04E-07	6.94E-04	9.62E+06	1440	
Ex-vessel waveguide to route mm signal	1.04E-07	6.94E-04	9.62E+06	1440	
Ex-vessel TL support to withstand load(Interspace)	2.28E-08	6.94E-04	4.39E+07	1440	
Ex-vessel TL support to withstand load(Port-Cell and Gallery)	2.28E-08	2.08E-02	4.39E+07	48	
Mitre bend in interspace to route mm wave	1.14E-06	6.94E-04	8.77E+05	1440	
Mitre bend outside interspace to route mm wave	1.14E-06	2.08E-02	8.77E+05	48	
Radial movement compensation units					
Secondary Barrier (A) SIC-2	1.66E-08	1.71E-04	6.03E+07	5840	
Secondary Barrier (B) SIC-2	1.66E-08	1.71E-04	6.03E+07	5840	
Notch Filter					
Slow Shutter					
Spurious operation of Fast Shutter	4.40E-07	5.00E-01	2.27E+06	2	
CDC to combine/decombine mm-wavesignal	1.04E-07	4.17E-02	9.62E+06	24	
Slow Shutter					Back-end: Stray radiation protection system
Protection Filters	2.28E-08	4.17E-02	4.39E+07	24	
Detection System(Stray Sensor)	1.00E-06	4.17E-02	1.00E+06	24	
Pin switches of the fast shutter	1.14E-04	4.17E-02	8.77E+03	24	
DC breaks	5.71E-07	2.08E-02	1.75E+06	48	
RF source to generate mm-waves	2.00E-07	4.17E-02	5.00E+06	24	Back-end: Back-end
Receiver or and associated electronics to detect	1.00E-07	4.17E-02	1.00E+07	24	
Data Acquisition system	1.14E-05	4.17E-02	8.77E+04	24	
Data processing software	1.71E-05	4.17E-02	5.85E+04	24	
Back-end supports/holders	2.28E-08	2.08E-02	4.39E+07	48	
Local Controller	1.10E-06	4.17E-02	9.09E+05	24	Back-end: LCSCM
Control Software	1.71E-05	4.17E-02	5.85E+04	24	

Table 4-1: Components Reliability and Maintainability Input Data for elementary components of PPR System. [2,13]

The Input Data was made removing for different references the λ_i and MDT of the components/failure modes, and after applying the equations remembered at this section, but fully explained at the Chapter 2. [2,13]

The numbers of components involved are not listed because they are different depending on the Gap, which is clearly looking for RBDs for the Gaps (Figures 4-1 until 4-4). It should be noted that Reliability and Maintainability data is not presented for some components (Feedthroughs, First Confinement

Barrier, Vessel/Port movement/expansion compensation arrangements, Radial movement compensation units, Notch Filter and Slow Shutter), such as explained at Section 3.2.2., once an estimation of λ_I and MDT is not yet available. In these cases, a null failure rate was considered for the following analysis, meaning that these components become transparent in the analysis. In a following iteration, this must be reconsidered, and appropriated values should be collected or estimated for these components (possible uncertainty analysis).

4.2. Analytical Model

4.2.1. Reliability and Availability Analytical Calculations

In this topic was explored an Analytical approach to quantify values for System's Reliability and Availability, being this analytical solution one application of all information described in the Theoretical Part of this thesis document.

The Analytical solution is structured by the RBDs hierarchy developed at sections 4.1.1., 4.1.2. and 4.1.3., respectively for Sub-System formed by components connection (lower hierarchy level); System Main Objectives (upper hierarchy levels), Measurement and Function formed by Sub-Systems (Gaps); and Impact to ITER Operation. Using with the Reliability and Maintainability data collected for the essential components of PPR System, presented in Table 4-1, it is possible to estimate the Reliability and inherent Availability of ITER PPR System, together with the time scenarios presented at Section 3.1.1. and the equations found in the Theoretical Part of the document, essential the Equations:

1. (10) and (12) inside the Table 4-1 to have the parameters need for calculation.
2. (8) and (13) for the Reliability and Availability calculations for each basic component.
3. (18), (19), (20), (21), (22), (23) for the connection calculations: between components inside the Sub-Systems; between the Sub-Systems to form the System Main Objectives; and between components to form the Impact to ITER Operation analysis.

4.2.2. Assumptions

A collection of assumptions was required to model this RAMI analysis, used for the procedure described at last Section 4.2.1. to achieve results for the Reliability and Availability measured in different profiles.

These assumptions can be separated for parts and adapting for this study. The following sub-topics are the essentials assumptions needed for the PPR System model.

4.2.2.1. Design, function and measurement assumptions:

The design, function and measurement assumptions about the PPR system are as follows the RBD presented at Section 4.1.2. and is a representation of all the background behind the PPR System presented at Chapter 3, with two extra assumptions to be consider: [2]

1. Each reflectometry channel (Gap, Sub-System) of the PPR system was considered as fully independent. The components are considered with independent operations too, once the operation of one unit (Gap and/or one component) can not interfere in the other one operation. The failure of one Gap or one component can stop the operational “line/network” of a RBD logic but the operation of each unit is assumed separated and independent, without interference between operations.
2. Independent control of each channel is assumed.

4.2.2.2. Operation scenarios assumptions:

The operation scenario defined for ITER operation is described in Section 3.1.1., and the time is used in hour unit, with two extra assumptions: [2]

1. The duty cycle (ratio of the operating time of the component compared to the total operating time of the PPR system) was assumed 100% for all components, i.e. all components are considered with operational time equal to PPR System, without standby operations or delays considerations.
2. This thesis study updated the operation scenarios once in the preliminary RAMI analysis did by ITER operation was assumed for a mission of 20 years (ITER lifetime), 116800 hours of work, do not neglecting the pauses for shut downs anymore, such as was performed in the last RAMI procedure (considering 20-year continuous operation of 175200h).

4.2.2.3. Maintainability and down time assumptions:

Several assumptions were made about the mean down time (time for which the capability of providing the measurements is off), the thesis document’s measure for Maintainability, MDT, associated to the different FM of components. [2]

The assumptions intend to explain the use of MDT as measure for Maintainability instead of MTTR.

These assumptions are the explanation of data found in Table 4-1 for Reliability and Maintainability Data Base.

The full premises presented in ITER documents is not necessary for purpose of this thesis study. Being the data presented in Table 4-1 a compact of theoretical requirements and definitions of ITER, already enough for calculations. Extra information about residual radiation doses and specific details of components are not included at this study, but some examples of considerations are presented next for illustration.

Some Maintainability parameters are explained based on the location of component. Also, is present a Logistic Time note that is important for explain the use of MDT as measure for Maintainability, and notes for Repair/Replacement and Start-up times.

1) Cooling time, access time and down time by areas:

Basically, the MDT is assumed in accordance with the location of the component, so the assumption was divided by area.

A) In-vessel and port-plug areas:

- Antennas may be repaired during the 8 months of shutdown period. The Antennas are delicate components, once they are the Plasma closest components, being able to be repaired just in the programmed shutdowns.
- For measurements availability analysis, it is considered that a failure of the antenna would imply a minimum of 3 months of down time (one month of cooling, one month for replacement, and another month for re-start time). That is the reason for the time of 2160 hours for MDT for component "Antenna to route mm wave".
- In-vessel waveguides will be designed to endure the lifetime of ITER without maintenance. Therefore, they are considered not maintainable at this stage of PPR design, so the failure of an in-vessel waveguide would prevent the measurement of the corresponding channel for the rest of ITER lifetime. As an exercise, in the sensitivity analysis, it is considered a case which the in-vessel waveguides are maintainable. It must be considered that a failure event affecting the in-vessel waveguides cannot be completely dismissed, and a solution in terms of corrective maintenance should be foreseen for the design team for next iterations of the project, at least to continue ITER operation. So, a total of 3 months' down time (2160 hours) was assumed for the waveguides inside the port-plugs ("In-Port-Plug waveguide to route mm wave" and his support "In-Port-Plug waveguide supports to withstand load"), if the repair/replacement requires the port-plug to be taken to the hot cell. It might be possible to reduce this down time if the repair/replacement can be performed in-situ, and will be analyzed for next RAMI iterations.

B) Port Interspace area:

- Access time to Port Interspace is considered as 1 month after shutdown (conservatively), although the project requirement is to have less than 100 µSv/h 12 days after shutdown, so that some restricted work is possible before that. That is the location where it is situated the components "First Confinement Barrier SIC-1", "Vessel/Port movement/expansion compensation arrangements", "IEWT to transmit", "Ex-Vessel waveguide to route mm signal", "Ex-Vessel TL support to withstand load (Interspace)" and "Mitre bends in interspace to route mm wave".

C) Port-cell and gallery area:

- Port Cell and Gallery are considered to be accessible 24 hours after shutdown, as the project requirement is to have less than 10 µSv/h (radiation measure) 24 hours after shutdown.
- That is the location where it is situated the components "Ex-Vessel TL support to withstand load (Port-Cell and Gallery)", "Mitre bends outside interspace to route mm wave", "Radial movement compensation units" and "Secondary Barrier (A) SIC-2". There was addiction of 24 hours in the MDT of this components for get access to them.

D) Diagnostic area:

- Diagnostic area is considered to be always accessible, as the project requirement is to have less than 0.5 µSv/h at any time.
- That is the location of the components used for analysis of Plasma, majority of Back-End components.

2) Repair/Replace time:

- Repair/Replacement time depends on the component and task involved. If the task can be performed manually, estimation is done according to design information, manufacture data if available, and taking into account allowance for access times and working with Personnel Protection Equipment. If a remote task (e.g. on port plugs) is needed, the process time scale is in the order of a month.

3) Logistic time:

- Logistic time refers mainly to the necessary time to have all the means needed for the repair/replacement activities available. The availability of spares is frequently a critical point and may have a strong impact on the MDTs, and therefore on the PPR System availability.
- The initial assumption for the present analysis has been that spares are available on-site for all the components of the PPR system. However, this assumption will have to be revisited when the design is further developed in terms of the detail design of components. Special attention will have to be put in the "ad-hoc" designed components, for which the difference between having spares or not may introduce significant differences on the PPR System availability. When component information is available, sensitivity analysis will have to be performed to assess the impact or having spares or not on the system availability.
- This last assumption is the explanation about the use of MDT instead of MTTR for this actual analysis.

4) Start-up time:

- Start-up time is the time for re-starting operations once the repair, replacement and installation activities have finished. It includes the process to reach all the needed conditions (vacuum, etc.) before operation and depends on the location and the type of failure. For heavy maintenance activities requiring clearing of Port-Cell, access to Port-Cell interspace or extracting a Port-Plug, a start-up time of 1 month is considered as a generic value. For failures in the Port-Cell, Gallery or Diagnostic Areas not implying loss of vacuum or any other major issue, a much shorter re-start process (from immediate to some hours depending on the type of failure) is assumed.

4.3. Discrete Event Simulation: Synchronous Model

Using as theoretical background the Discrete Event Simulation (DES) Background (presented at Literature Review at Section 2.3.) and having as objective to emulate the PPR System and consequent Impact to ITER Operation Analysis, the DES get as input the RAMI parameters, i.e., Reliability (failure rates, λ_i) and Maintainability (mean down times, MDT) parameters from Table 4-1;

mission time scenarios from Section 3.1.1.; the RBD models (describing the hierarchy/connections between components) presented at Sections 4.1.1., 4.1.2. and 4.1.3.

Then, this simulation classified as discrete in time, Event-Based and Synchronous uses the basic procedure of Monte Carlo Simulation Method for modelling the collection of PPR System components: [5]

- Define the objective parameter and the variable for simulation:
  As already described at Section 2.3., the Availability is the parameter to be accessed, considering its stochastic nature and deriving its confidence interval, through a deeper analysis made for the variable time to failure, still related to failure rate, but passing now for a different overview, adding a stochastic/random behavior for the time to failure instead the mean value used in Analytical Model (MTBF). So, the MDT is considered as a constant input.
- Delimit a domain for possible events:
  Define all lower units (components) with failure chances, to be emulate, in other words, establish all the hierarchy of project, the Systems' Objectives (Impact to ITER Operation, Electron Density Profile Measurement and Plasma Position Function), Sub-Systems (Gap 3, Gap 4, Gap 5(A), Gap 5(B), Gap 6) and separate components.
  Two assumption should be noticed:
    - The called "Transparent Units" or components with no associated failure rates (do not interfere to Availability Analytical calculation), at this phase of project, must be removed from simulation, once they are considered as having no failure chances. So, 49 components for the Analysis of Impact to ITER Operation and 346 components for the measurement and function analyses are considered.
    - The units at Synchronous Simulation have a similar behavior that in Analytical Models of PPR System, due to fact that components are considered as operational independents, memoryless and possible failures having a stochastic/random behavior, but in simulation the components are not considered with a mean overview. The operational independent behavior leads to this Simulation Model with only one individual clock to govern all operation, with one failure do not affecting the others, enabling overlap of failures.
- Generate events randomly:
  As already explained in Section 2.3., the Monte Carlo Method works for problems with a stochastic/random behavior.
  So, for attribute possible failure facts, it is necessary to define a new parameter for measure the expend time until the failure, the denominate pseudorandom time to failure (TTF) for each component's life, with the failure rate of the component used as a weight factor, but considering a random factor (represented by a random generation number).
- Perform deterministic judgments of component states based on the events (Event-Based

Simulation):

First, defining the two events and two states for the domain:

- There are just two possible events: failure/repair.
- There are just two possible states: operational/non-operational.

Failure or not failure conditions, characteristic from the “Two-state Markovian Analysis” (see Figure 2-2), create a Boolean Signal for each component, showing the activity, where signal equal to 1 means operational state and equal to 0 means non-operational/failure state.

The simulation being Discrete and Event-Based just “jump” until the next event that generates state change.

- Access the objective parameter for each hierarchical level:
  Count the occurrence number of a specific component state among total observation or, in this case, just integrating the area from the Boolean Signal Graph and comparing with the total mission time, gives an Availability measure with a stochastic profile (with the same theoretical thinking presented in Equation (14)).

Each iteration is operational time run, performed by the algorithm (in form of blocks in Simulink) sample time by sample time. For each iteration was simulated the total two scenarios of time: 116800h for the Impact to ITER Operation and 11680h for the Effect to Electron Density Profile Measurement and Plasma Position Function (more components lead more computational time expend). In simulation, one hour is the sample time (=1). Remembering that the simulation just iterates over the sample time, but the Boolean Signal and consequent unit state can just change when the simulation achieve the next event.

After collect results from certain number of different runs, statistical inference was used to estimate the confidence intervals for the performance parameter (Availability). Being the DES procedure leaded to stop when the average of Availability of numerous measures stabilize.

Used from the *Simulink toolbox* of MATLAB, the already pre-programmed block Uniformly Pseudorandom Number Generator, is used for input in each component model, being this block the tool for generation of random events, presented next. [10]

Applying the procedure initially for modelling one component, and then applying for superior hierarchical relationships (Sub-Systems and System), the Simulation can start to run iteratively.

4.3.1. Modelling one Component

To fit the PPR System as a Simulation Model, the first step is modelling one individual component. So, the procedure intends to apply the model for all components and stablish hierarchical relationships between them.

The inputs for all components model:

- The Failure Rate λ: constant characteristic of each component, expressed in the hour^{-1}, considered as the constant time rate that a component has failures, used as a weight coefficient factor to create the new variable TTF.

- The MDT: constant characteristic of each component, expressed in hour(s), considered as total time required either to restore system to a given performance level or to keep it at that level of performance, still used as a constant value.
- The mission time: constant duration of the mission, expressed in hour(s), as mentioned in the Section 3.1.1.

Using the λ as coefficient weight for each component, together with the use of a pseudorandom number (pre-programmed block), it's possible to generate pseudorandom times to failure (TTF), as occur in real life, with random distribution of failures.

For modelling one component's life it's necessary to use the different and "random" TTF, just at correct instant of simulation, that was explained in the sequence as the time of replacement.

4.3.1.1. Inverse Transform Method and the Time to Failure Random Variable

The first step to model one component is determine the new variable TTF value, being necessary the mathematical tool from MCM, the Inverse Transform Method. [5]

The "Two-states Markovian processes" are considered with exponential distribution for Cumulative Distribution Function (CDF) F(t) (also called Cumulative Failure Distribution, CFD, that represent the cumulative Failure Probability), its Probability Density Function (PDF) f(t) and for Reliability Function R(t).

In a time-homogeneous system or Useful Life Approach the failure rate λ(t), described as the transition rate (see Figure 2-2) or also called as hazard function of the process (the rate with the component changes the signal for 1 to 0) is assumed as a constant (λ), explained at Section 2.1.1. Therefore, by Analytical calculations (Equation (10)) it is possible to achieve an average value for time to failure (MTBF or MTTF).

The new random variable pretended, TTF, $\in [0, \infty[$, is said to be exponentially distributed if its CDF $F_{TTF}(t)$ and PDF $f_{TTF}(t)$, can be modelled by the equivalent Equations: [5]

$$F_{TTF}(t) = 1 - e^{-\lambda \times t} \quad \text{and} \quad f_{TTF}(t) = \lambda \times e^{-\lambda \times t}$$

(26)

Using the complementary Equation (3) from section 2.1.1. and applying the Inverse Transform Method, it's possible to load one TTF value, just applying one of the following equivalent equations, achieved by manipulation of $F_{TTF}(t)$ of Equations (26):

$$TTF = -\frac{1}{\lambda} \times ln(1 - F_{TTF}) \quad \text{or} \quad TTF = -ln(1 - F_{TTF}) \times MTBF$$

(27)

Where λ and MTBF are constant inputs from RAMI Database (Table 4-1) and the CFD F_{TTF} is the failure accumulate chance (probability), being the failure a stochastic event and the variable F_{TTF} a number contained at [0,1]. A random number generator can be used to describe the chance of the component failure. This generator is resulting from the Neumann method for randomize numbers (used in first approaches of MCM), applied in computation, represented in *Simulink toolbox* using the pre-programmed block Uniform Random Number, shown in Figure 4-11 as one of the inputs for the component model, together with a constant failure rate (λ). Figure 4-11 is an example for the Antenna to route microwaves component:

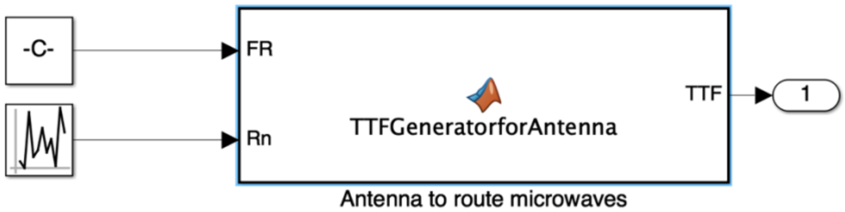

Figure 4-11: MATLAB Simulink – *TTFGenerator* example for the Antenna to route microwaves component.

So, using the failure rate as a weight coefficient factor, different for each component, together with a pseudorandom number, the programmed block "*TTFGeneratorforComponent*" (illustrated at Figure 4-11 example for Antenna example) generate for each component's life one different and random time to failure, using one of Equations (27), occurring this generation at each sample time.

Looking for Figure 4-12, graphs of Reliabilities versus Mission times are plotted for two different components, being the red line the representation of a component with a two times bigger failure rate than blue line, leading to a Reliability curve tending faster to zero, with less chances to be reliable at a certain time t. So, for this component represented by a red line and a certain random Cumulative Failure Function Value, that is complementary with R, both contained in ([0,1]), the curve assigned one certain value of time (for example). Therefore, for one random F_{TTF} number and curves made in accordance with the failure rate, one time can be assigned for the curve. This curve is plotted to explain the Inverse Transform Method relation between Reliability and time, and that components with bigger failure rates tend to have lower assigned times for one certain random number F_{TTF}, that is the reason for failure rate be a weight coefficient factor.

So, the Equation (27) is programmed inside the block "*TTFGeneratorforComponent*", represented in Figure 4-11 for Antenna example, being a computational way to achieve a pseudorandom time to failure, TTF using the inverse relation between time and Reliability.

Should be noticed that each "*TTFGeneratorforComponent*" receive as input one "seed" parameter, being through this seed number that the Uniform Random Number block works generating pseudorandom number between one interval chose (at this case an interval chose as [0,1]. This seed must be different for each case to guarantee a better randomness.

So, already introduce the variable, one certain component starts the simulation creating the first TTF, and at time equals to TTF_1 value the component fails, then, the repair operation starts and just finish in a simulation synchronized time equal to TTF_1 + MDT, being this simulation time the time of returning of the component to the working state, being the exact instant to load a new TTF. This process is illustrated at Figure 4-13, achieving the Boolean Signal of operation for the certain component. This initiated Boolean Signal is the final output for each component, showing for each sample time in the mission time horizon if the unit is operational (signal 1) or non-operational (signal 0). [14]

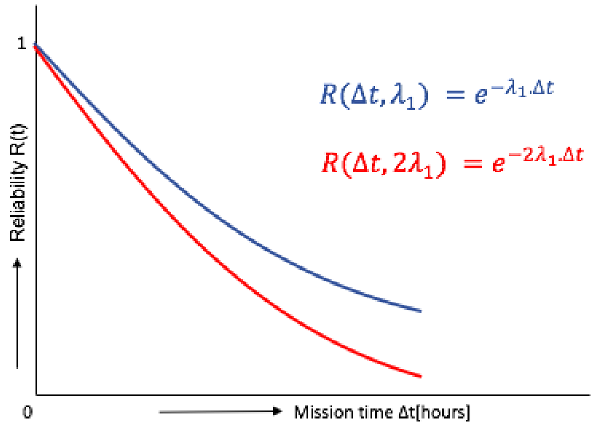

Figure 4-12: Graph of Reliability versus Mission time for two components with 2 times failure rate relation, representing the exponential behavior of the Reliability in accordance with failure rate, in the Useful Life Model.

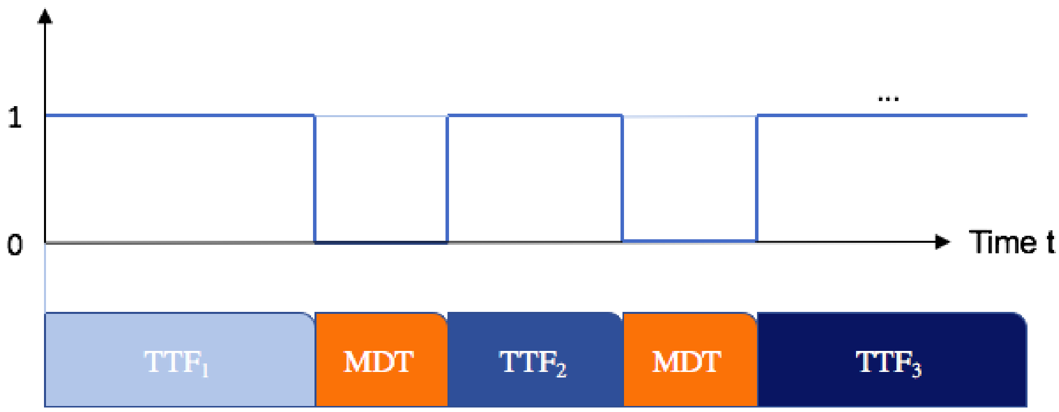

Figure 4-13: Component Boolean Signal showing different Time to Failure (TTF) generated.

Each component has now a generator (represented by a Simulink block) to generate continuously pseudorandom TTF, and when the simulation time arrives to this TTF, the component change the state to non-operational.

However, remain now the simulation understands the correct time to load new TTF, the exact instant explained as the simulation time of returning to the working state for a component, the called Time of Replacement (ToR).

4.3.1.2. Synchronous Model Procedure for Simulation

The pre-programmated blocks Uniform Random Number generate for each sample time of simulation one R value, creating through Equation (22) a new TTF at each 1 hour. The ToR, illustrated at Figure 4-14, is parameter formed by sums of TTF random values with constants (MDT), therefore, another random variable.

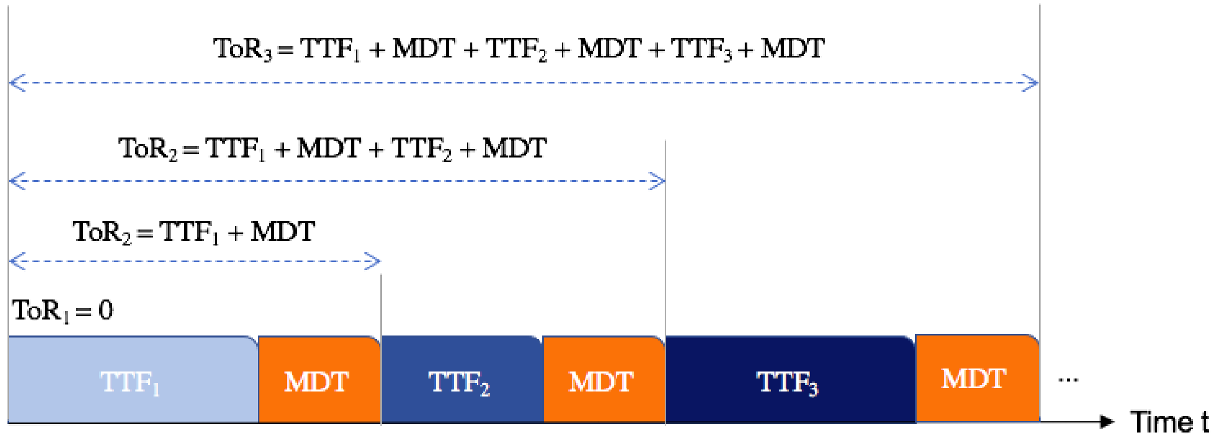

Figure 4-14: Time of Replacement (ToR) illustration.

It represents the simulation times at which the component become ready to operate (again), with the Boolean Signal returning to 1 (or in the initial instant starting in 1), being visible that at start of operation the $ToR_1 = 0$, since every component is considered to start Available. After starts in 0 the ToR is incremented to the times of return from the repair condition (changing states from 0 to 1 in a constant repair rate).

So, explaining the simulation procedure (algorithm) for the showed example of Antenna Waveguide to route microwaves, at Figure 4-15, it was possible to develop an algorithm to model all components.

The simulation starts with the mission time choice, being 11680h (16 months scenario) for the Antenna Waveguide to route microwaves case. Component starts with operational state, Boolean Signal equals to 1(consequent ToR_1 is initiated as 0).

- For each sample time, one TTF_i is generated by "*TTFGeneratorforAntenna*", illustrated at Figure

4-11, being the block hierarchically located inside the structure of Component Simulation Model for the Antenna case, illustrated at Figure 4-15.

- The first TTF_1, randomly generated, is loaded.
- The simulation "jumps" until the time that the simulation time reaches the TTF_1 value. This "jump" action characterize the Discrete Event/Monte Carlo/Event-Based Simulation.
- At the simulation time equals to TTF_1 the component Antenna Waveguide to route microwaves change the state from 1 to 0, becoming non-operational, with Boolean Signal equals to 0.
- The simulation loads the MDT parameter, making the ToR_2 be equal to TTF_1 + MDT. Meaning that the components now considered broken will be read to operate again at simulation time equals to TTF_1 + MDT.
- The simulation "jumps" again for the simulation total time equals to ToR_2, so at this instant the component changes back for operational condition and then a new TTF value is loaded, at this case TTF_2.
- So, the simulation "jumps" again and the procedure repeats iteratively until the simulation clock reaches the initial chose mission time.

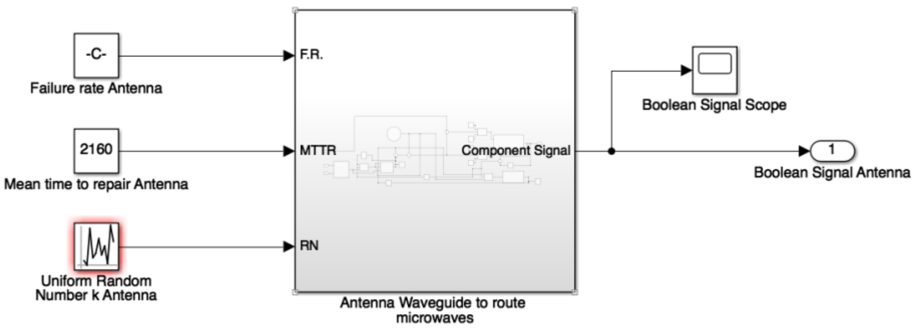

Figure 4-15: MATLAB Simulink – Component Simulation Model Example for Antenna Waveguide to route microwaves.

The whole iteratively procedure of simulation, explained for the Antenna Waveguide to route microwaves, is inside the block structure showed at Figure 4-15. The iterative procedure composed by blocks instead algorithm is illustrated at Figure 4-16.

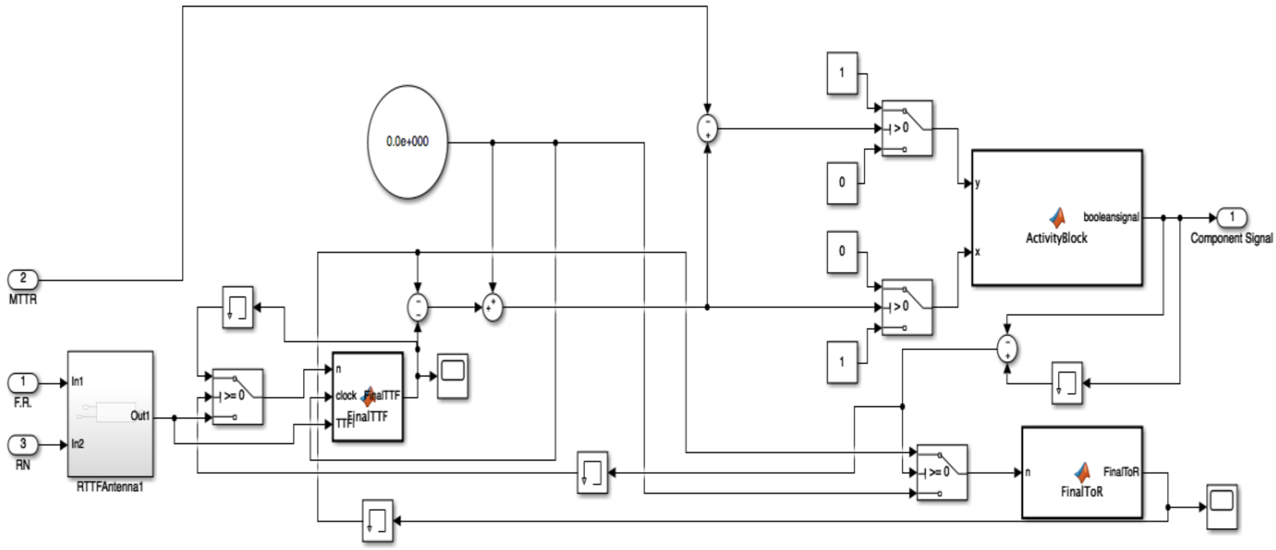

Figure 4-16: MATLAB Simulink – Example of application of the DES procedure for the Antenna to route microwaves case.

With input RAMI input parameters already explained, and the algorithm made for a general component case, the last explanation for one component model are the four programmed blocks and their functions inside the structure, that use switches and delays blocks from MATLAB to increment parameters:

- ToR at the correct time, done by block "*FinalToR*";
- Loading at the simulation time equals to recent ToR value, one TTF value, done by block "*FinalTTF*";
- This TTF values are constantly generated by a block "*TTFGeneratorforAntenna*", equal the illustrated at Figure 4-11, but just used for FinalTTF when simulation time achieve the next replacement value.
- The "*ActivityBlock*" make the actual TTF with the last ToR sum and compare at each sample time this value with the clock. If the next failure event was achieved, i.e. if the actual TTF summed with anterior simulation time that the component become read to operate (ToR) achieved the clock time, the component is said to be non-operational and the "*ActivityBlock*" changes the outputted Boolean Signal from 1 to 0. Just when the clock achieves a value bigger than the sum of actual TTF with the last ToR and the loaded constant MDT, it is supposed that the "*ActivityBlock*" changes the Boolean Signal back to 1, and the component returns to the operational state, loading a new TTF.

  These operations can be better understood by the Equations (28) and (29), being the representation of failure and repair instants achieved, respectively.

$$simulation\ clock > TTFactual + ToRanterior \tag{28}$$

$$simulation\ clock > TTFactual + ToRanterior + MDT \tag{29}$$

4.3.2. Modelling the System Hierarchy

Based in the hierarchy on RBD for System's Objectives and Sub-Systems, presented at Section 4.1.1., 4.1.2., 4.1.3., the Simulation connect the components of the two separate simulations to be done, the Impact to ITER Operation (49 components); Electron Density Profile Measurement and Plasma Position Function (346 components).

The connections rules are simple. Each component modeled with the rules explained at Section 4.3.1. are connected in series, active parallel or "*m* out *n*" parallel with another component. The connections are made using the Boolean Signal outputted from each component's simulation model.

For the signals of two components in a series connection, one AND logical gate must be used. For the case with two components in active parallel connection, a OR logical gate must be used. This operation creates an upper hierarchy Boolean Signal for the connections. Being possible to apply these rules until reach the bigger hierarchy for the System. For the "*m* out *n*" parallel case of Electron Density Profile Measurement, blocks Relational Operators are used to use logical operations and check how many Gaps are available at each iteration.

The following Figures 4-17, 4-18 shows the two-separate upper hierarchy for the two DES: the Impact to ITER Operation and the Electron Density Profile Measurement/Plasma Position Function Analysis.

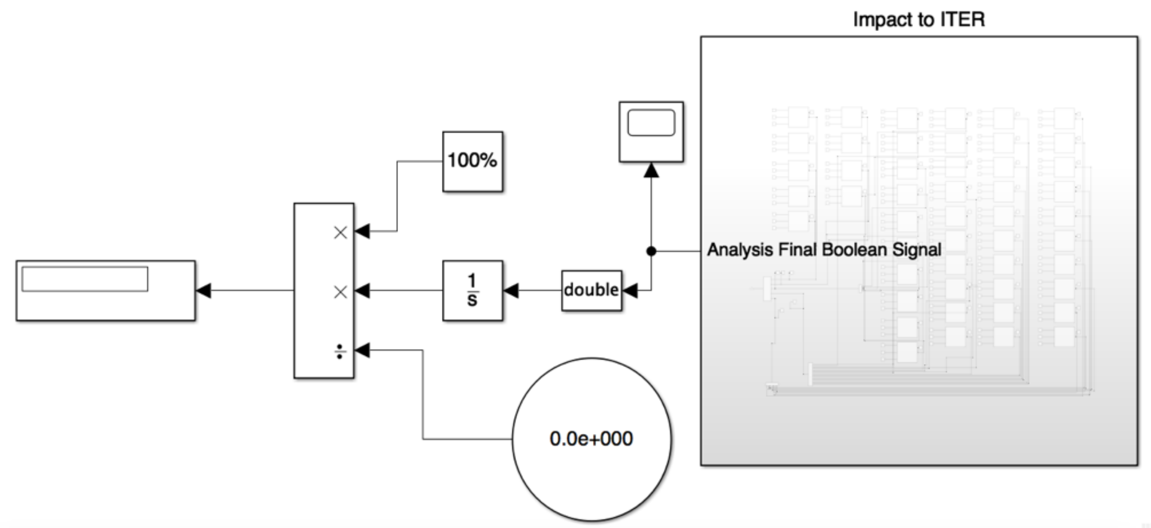

Figure 4-17: MATLAB Simulink – Impact to ITER Operation upper hierarchy of Simulation Modelling (totalizing 49 components).

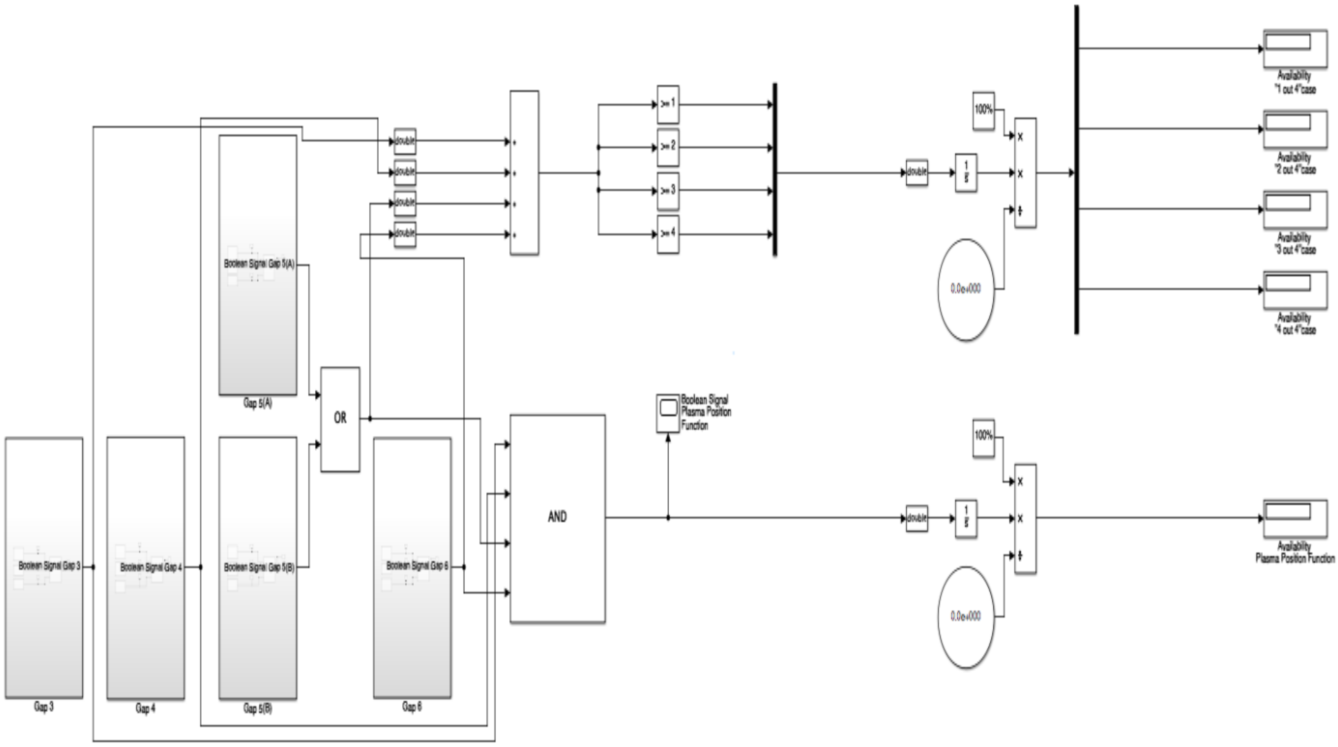

Figure 4-18: MATLAB Simulink – Electron Density Profile Measurement/Plasma Position Function Simulation Modelling, composed by Gaps (totalizing 346 components).

Inside the Impact to ITER Operation there is a structure containing the 49 components (illustrated at Figure 4-19) considered as critical, all in a series connection, making all the components Boolean Signal be gathered for the same AND logical gate, achieving one final Boolean Signal for the analysis.

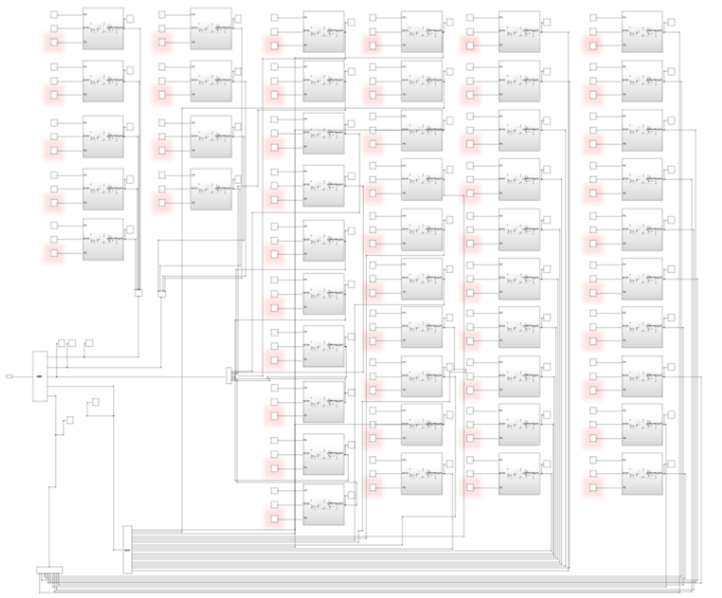

Figure 4-19: MATLAB Simulink – Components Connection for Impact to ITER Operation Simulation Modelling

Inside the second simulation for the Electron Density Profile Measurement/Plasma Position Function, 346 components are in structure inside Gaps, that are still divided in the three major divisions: In-Port-Plug/In-Vessel, Ex-Vessel and Back-End, depending of the Gap, being an example for Gap 3 (In-Port-Plug Back-End) at Figure 4-20.

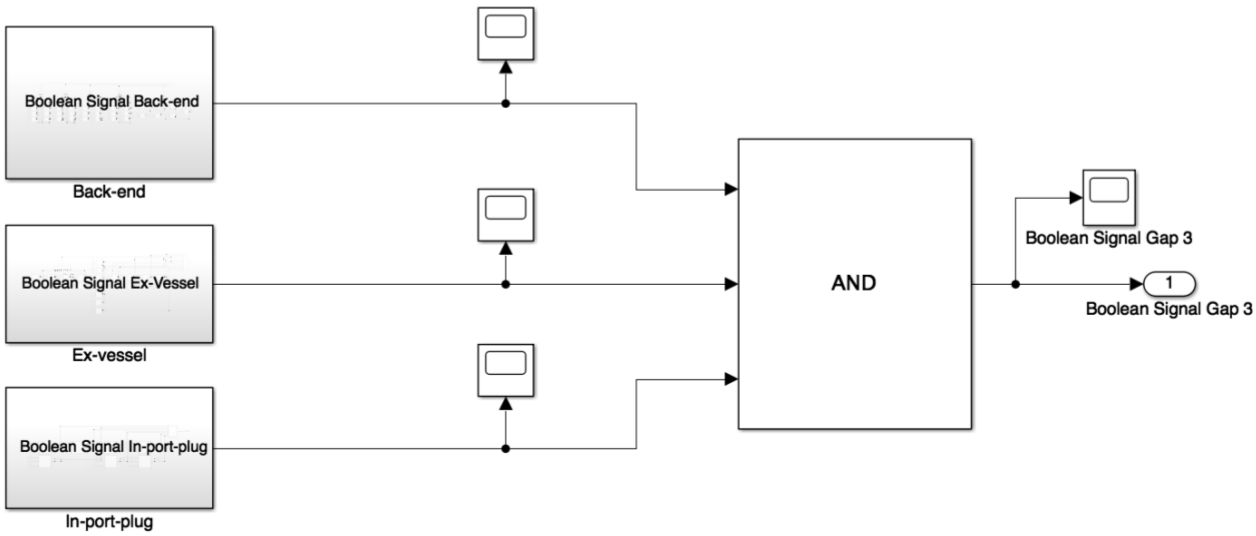

Figure 4-20: MATLAB Simulink – Gap 3 Connection for Simulation Modelling

Looking for PPR System as a complex collection of components, is supposed that the Synchronous Simulation is the good answer to model and guide this analysis, once the components MDT is small in order of magnitude comparing with the components MTBF or the simulation random times (TTF). Therefore, the chances of overlapping are lower in the PPR System case, having Analytical and Synchronous Models Approaches great chances of convergence, being unnecessary the development of a complex Asynchronous Model.

5. RAMI Results

5.1. Analytical Results

This section presents the analytical results of the new RAMI Analysis for PPR System. It begins by the impact of failures of the PPR system on the ITER operation (Impact on ITER Operation Analysis) and evolves to Electron Density Profile Measurement and Plasma Position Function, the sequence it is chose by the order of importance for ITER operation, being the ITER machine Availability the priority.

The results of Reliability and Availability for each Sub-System (Gap) of ITER PPR System are not presented in totality, once the separately values do not have a requirement at this phase of RAMI Analysis. But for exemplification and comparison between Gaps, just the Availability for all Operation (20 years, 116800 operational hours) is organized at Table 5-1 for each Gap.

Availability A (20 years; 116800h)				
Gap 3	Gap 4	Gap 5(A)	Gap 5(B)	Gap 6
92.71%	91.12%	92.41%	92.11%	91.86%

Table 5-1: Availability for each Sub-System (Gap) on ITER PPR System.

Doing an analysis for these results and looking for RBDs presented in Section 4.1.1. and Input Data at Table 4-1, it is reasonable to understand the reason for closer values for Availability, once the structures of components are similar. But, looking deeply to understand the lower Availability for Gap 4 and Gap 6, it is notorious behind the small differences that In-Vessel Waveguides and Supports have almost 3 times the MDT of In-Port-Plug Waveguides and Supports for Gap 3 and Gap 5, although the same function and failure rate. This MDT guide a bigger impact in the analytical calculation of Availability for these Gaps.

5.1.1. Impact on ITER Operation

This analysis consists in a regular series connection between six reliability blocks as presented and explained in Figure 4-10. Note that each Reliability block is composed by specific series of similar components belonging to the different Gaps, with the quantity of components indicated above the blocks. The impact to the Reliability and Availability of ITER Operation determined by the PPR System is presented in Table 5-2.

Reliability			Availability	
R (11 days, 264h)	R (16 months; 11680h)	R (20 years; 116800h)	A (16 months; 11680h)	A (20 years; 116800h)
99.80%	91.39%	40.63%	97.16%	96.79%

Table 5-2: Results for Analysis of Impact to whole ITER operation.

As expected the results of Reliability decrease when time evolves: the reliability within a timeline of 11 days is high, but in the mission time of 16 months it significantly reduces and for life time of the ITER operation the reliability is only 40.63%. It means that the probability of achieving a life of 20 years without any failure in the PPR System affecting the ITER operation is only 40.63%. The Availability results reflect this and are not accordance with the requirement for Availability presented in requirement REQ-157 of Section 3.3., in which is mention that the Availability shall be compatible with the overall 98.58±0.20%, and impact on ITER operation should be minimized.

5.1.2. Effect on the Electron Density Profile Measurements

The effect of failure events on the Electron Density Profile Measurements was performed, considering a "*m* out 4" parallel condition for the Gaps, with one redundancy in Gap 5 (there are 4 kinds of Gaps, with Gap 5(A) and 5(B) representing a redundancy in parallel, totalizing 5 reflectometry channels, see Figure 4-8). Table 5-3 presents the results achieved for the Reliability and Availability of the measurements for the different time scenarios. Figure 5-1 plots the evolution of measurements Availability with the parallel condition.

	Reliability			Availability	
	R (11 days, 264h)	R (16 months; 11680h)	R (20 years; 116800h)	A (16 months; 11680h)	A (20 years; 116800h)
"1 out 4" condition	99.93%	0.00%	0.00%	100.00%	100.00%
"2 out 4" condition	98.12%	0.00%	0.00%	99.94%	99.94%
"3 out 4" condition	84.01%	0.00%	0.00%	98.09%	98.02%

"4 out 4" condition	42.67%	0.00%	0.00%	77.51%	77.13%

Table 5-3: Results for ITER PPR System Electron Density Profile Measurement.

The results show a relevant dependency of Reliability and Availability with the number of reflectometry channels that must be available for the measurement operation. However, the damage in the results is only significant when 3 or 4 out of 4 Gaps have to be operational for the measurement operation.

It also should be noted that the Reliability becomes zero for a time line of 16 months (and consequently for 20 years). Nevertheless, the effect of time evolution in the Availability of measurement operation is almost worthless, as the MDT of components are significantly lower when compared with their MTBF (see Table 4-1).

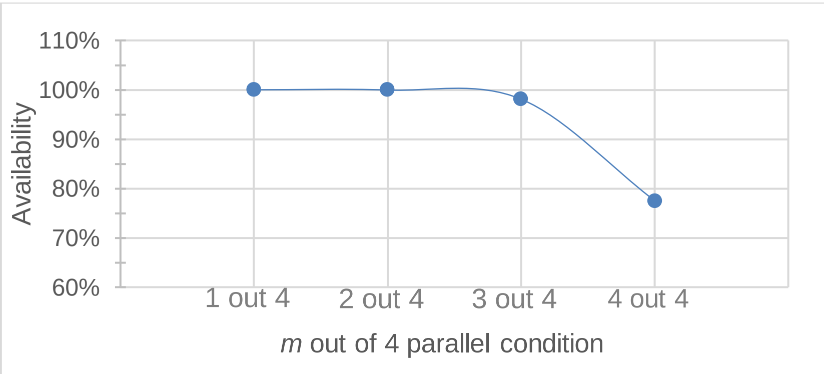

Figure 5-1: "*m* out 4" parallel analysis for Availability of the Electron Density Profile Measurement in a mission period (16 months).

5.1.3. Effect on the Plasma Position Function

The effect of failure events on the Plasma Position Function performed, considering a series sequence of the Gaps with a parallel arrangement in Gap 5 (see Figure 4-9) was studied. Table 5-4 presents the results achieved for the Reliability and Availability of the function for the different time lines.

Reliability			**Availability**	
R (11 days, 264h)	**R (16 months; 11680h)**	**R (20 years; 116800h)**	**A (16 months; 11680h)**	**A (20 years; 116800h)**
42.67%	0.00%	0.00%	77.51%	77.13%

Table 5-4: Results for ITER PPR System Plasma Position Function.

It should be noted that the results achieved for Plasma Position Function are equal to the ones obtained in the “4 out 4” reflectometry channels in the Electron Density Profile Measurement, as expected, once a “4 out 4” active parallel connection has a convergence to values of a series connection, for Reliability and Availability, what can be understand looking for equations presented for the connections at section 2.1.4.

This extremely results of Reliability and Availability in the PPR Plasma Position Function are a consequence of unexpected high values of the failure rate of Pin switches of the fast shutter components. Their failure rate is 1.14E-04 failures per hour. Besides it the single component with a failure rate in the 10^{-4} order of magnitude (all the other have significantly lower failure rates), it is worth remembering that each Gap have 8 Pin switches of the fast shutter in a series connection, inside the Stray Radiation Protection System, leading to a high damage in the function Reliability.

The effect of Pin switches of the fast shutter components in the Reliability and Availability of the PPR System brings the opportunity for a separated analysis of this component, looking for solutions to increase their performance. The Preventive Maintenance is actually a practice based on Literature, presented at Table 2-4, where for the Maintenance phase of the project is programmed inspections and replacements to resolve problems of possible failures. Is used together with applications of redundant components in design phase for concern about the occurrence of a failure (Prevention Actions).

5.1.4. Pin switches of the fast shutter and Stray Radiation Protection system separate analysis

The Reliability and Availability of elementary Pin switches of the fast shutter was calculated (Table 5-5) for decreased failure rates, according with the individual judgments of the design experts that only can explain a so high failure rate based on extremely severe operating conditions which is not the case on the PPR System, for this mechanical actuation component.

Failure Rate λ [1/h]	Reliability			Availability	
	R (11 days, 264h)	R (16 months; 11680h)	R (20 years; 116800h)	A (16 months; 11680h)	A (20 years; 116800h)
1.14E-04	97.04%	26.41%	0.00%	99.73%	99.73%
1.14E-05	97.70%	87.53%	26.41%	99.97%	99.97%
1.14E-06	99.97%	98.68%	87.53%	100.00%	100.00%

Table 5-5: Reliability and Availability for an elementary Pin switches of the fast shutter for decreasing failure rates.

Also, the Reliability and Availability were calculated at Table 5-6 for the Stray Radiation Protection System, considering decreasing values of failure rate of the Pin switches of the fast shutter.

Remembering that each block Stray Radiation Protection System is composed by four series in parallel connection (see Figure 4-5).

Failure Rate λ [1/h] of Pin switches of the fast shutter	Reliability			Availability	
	R (11 days, 264h)	R (16 months; 11680h)	R (20 years; 116800h)	A (16 months; 11680h)	A (20 years; 116800h)
1.14E-04	88.51%	0.45%	0.00%	98.89%	98.89%
1.14E-05	98.64%	54.49%	0.23%	99.87%	99.87%
1.14E-06	99.71%	88.01%	27.88%	99.97%	99.97%

Table 5-6: Reliability and Availability for the Stray Radiation Protection System for decreasing failure rates of Pin switches of the fast shutter.

For the same decreased failure rates of the Pin switches of the fast shutter, and assuming its preventive replacement every 6, 3 or 1 month(s), Table 5-7 presents the lower Reliability achieved for an elementary Pin switches of the fast shutter over the 16 months of the mission or the 20 years of the ITER operation life time (or in any period higher than the replacement interval).

Failure Rate λ [1/h] of Pin switches of the fast shutter	Minimum Reliability		
	6 months	3 months	1 month
1.14E-04	60.69%	77.91%	92.01%
1.14E-05	95.13%	97.53%	99.17%
1.14E-06	99.50%	99.71%	99.92%

Table 5-7: Reliability of an elementary Pin switches of the fast shutter for decreasing failure rates and different preventive replacements.

Table 5-8 presents the integrated effect of a higher value of the Pin switches of the fast shutter failure rate together with its preventive replacement on the Reliability and Availability of the Electron Density Profile Measurement and Plasma Position Function of the PPR System.

Pin switches of the fast shutter Component			Electron Density Profile Measurement "1 out 4" Situation		Plasma Position Function	
Failure Rate λ [1/h]		Preventive Replacement	Reliability		Reliability	
			16 months	20 years	16 months	20 years
Current Value	1.14E-04	6 months	3.06%	0.00%	0.00%	0.00%
		3 months	20.85%	0.00%	0.00%	0.00%
10^{-1} the λ	1.14E-05	6 months	72.19%	0.01%	0.47%	0.00%
		3 months	80.08%	0.01%	1.01%	0.00%
10^{-2} the λ	1.14E-06	6 months	85.84%	0.01%	1.86%	0.00%
		3 months	86.51%	0.01%	2.01%	0.00%
Failure Rate λ [1/h]		Preventive Replacement	Availability		Availability	
			16 months	20 years	16 months	20 years
Current Value	1.14E-04	6 months	100.00%	100.00%	77.51%	77.13%
		3 months	100.00%	100.00%	77.51%	77.13%
10^{-1} the λ	1.14E-05	6 months	100.00%	100.00%	82.43%	82.02%
		3 months	100.00%	100.00%	82.43%	82.02%
10^{-2} the λ	1.14E-06	6 months	100.00%	100.00%	82.93%	82.53%
		3 months	100.00%	100.00%	82.93%	82.53%

Table 5-8: Effect of “Pin switches of the fast shutter” failure rate and Preventive Maintenance on the PPR System reliability and availability.

The Reliability values for the PPR System have significantly increased if preventive replacement of Pin switches of the fast shutter is implemented and a smaller failure rate is considered. The Reliability of the Electron Density Profile Measurement (in "1 out 4" Situation) increases from 0.00% (in a case with the actual failure rate for the component and no preventive maintenance, see Table 5-3) to more than 80% for the 16 months of a mission (example with lower failure rate and with preventive maintenance of Table 5-8), and the Reliability of the Plasma Position Function increases from 0.00% to near 2% in the same time line. However, due to the effect of the remaining components for the life time of ITER operation, Reliability although larger is still almost 0%.

It should be noted that the replacement policy of the Pin switches of the fast shutter has no influence on the Availability. In fact, components failure rates are modeled as constants, in the called Useful Life approach presented at section 2.1.1. and the components instantaneous availability is given for Equation (13), so by a deeply look for equation together with the Input Data Table 4-1, it is plausible to understand that the Availability is negligible affected because the order of magnitude of the repair rate is already far higher than the failure rate.

For easier representation, the Availability was just represented by the “1 out 4” case, being trivial the fact that in cases with “2, 3, or 4 out 4” measurements, the Reliability and Availability values are smaller.

5.2. Synchronous Simulation Model Results

This section presents results for the developed Synchronous DES of PPR System. It is presented by the same order done in Section 5.1., selected to accomplish the priority order for ITER operation.

To make the confidence interval for the system Average Availability, the Central Limit Theorem from Statistic must be used, meaning that if these averages are the sum of stochastic system availability at each run, it is also random variables and its distribution follows a normal distribution.

5.2.1. Simulation Results Stabilization

The first result to be presented for the simulation consists in a graph of results stabilization for Average Availability, illustrated at Figure 5-2, where the blue points represent each iteration Availability result, and the orange points the Average of Availability calculated at the iteration, with the requirements set in two lines (upper and lower).

Doing the Average of Availability values outputted from DES, iteration by iteration, the graph was a tool used as stop criterion, being the values presented for iteration 18 until iteration 25 designations that even if the outputs next were out of range of average (for example the values for Availability at iterations 19 and 25, respectively 85% and 94.98%), the average stays stabilized. It is easier to understand the stabilization looking for the amplification of graph from Figure 5-2, illustrated in Figure 5-3, showing that since iteration 17 the Average Availability stays between 98 and 99%, do not changes more than 1%.

Doing the DES for more trials until reach a number of iterations that stabilize the average and enable to develop a good confidence interval. Although, the weakness of the Monte Carlo Method with the computing time expended, 25 measures of Availability were done, sufficient for stabilize the two separate simulations. This weak is truly perceptive when we deal with large complex systems like this, with large number of components and iterations (DES developed having 49 components in the Impact to ITER Operation Analysis and 346 in the Plasma Position Function, besides the mission simulation times chose respectively for both as 116800h and 11680h).

Noticing that the Electron Density Profile Measurement and Plasma Position Function simulations for the operational time of 20 years (116800h) lasted almost 1 day long (about 20 hours) of computational time to be run in a computer with Intel 7 and 8Gb of RAM memory.

For the same reason the Impact to ITER Operation Analysis, with less components (49, once there is no Data for the First Confinement Barrier), ran for 116800h of simulation time, corresponding to all ITER Operation lifetime, while for the Plasma Position Function, with 346 components, just was possible to run 11680h of sample time, equivalent of 16 months' operation.

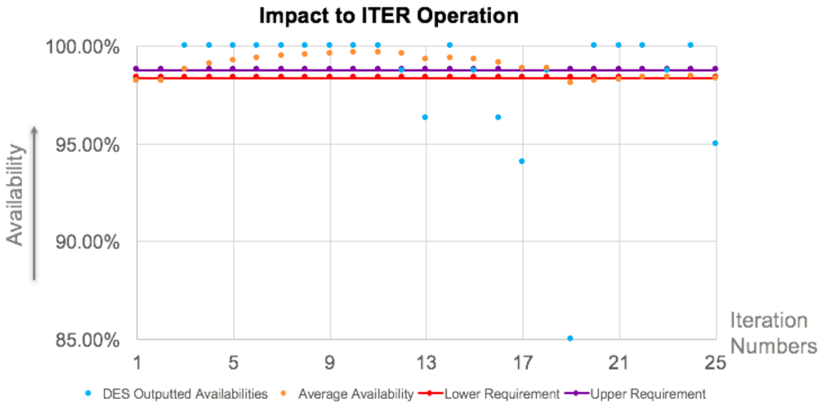

Figure 5-2: MATLAB Simulink – Results stabilization for Availability outputted from DES made for the Impact to ITER Operation Analysis.

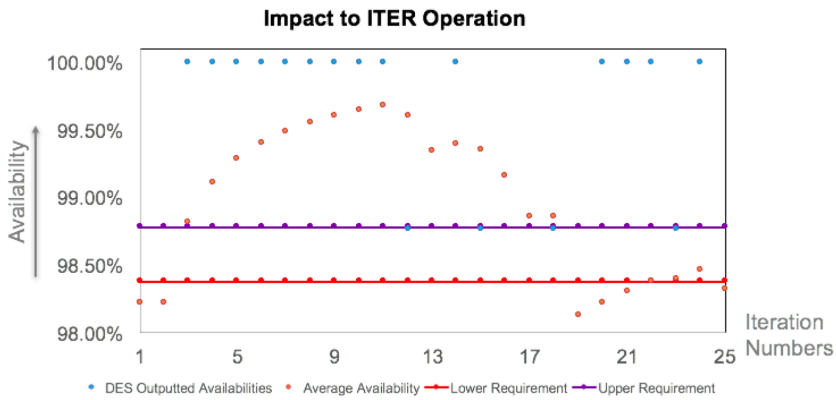

Figure 5-3: MATLAB Simulink – Amplified version of graph presented in Figure 5-2.

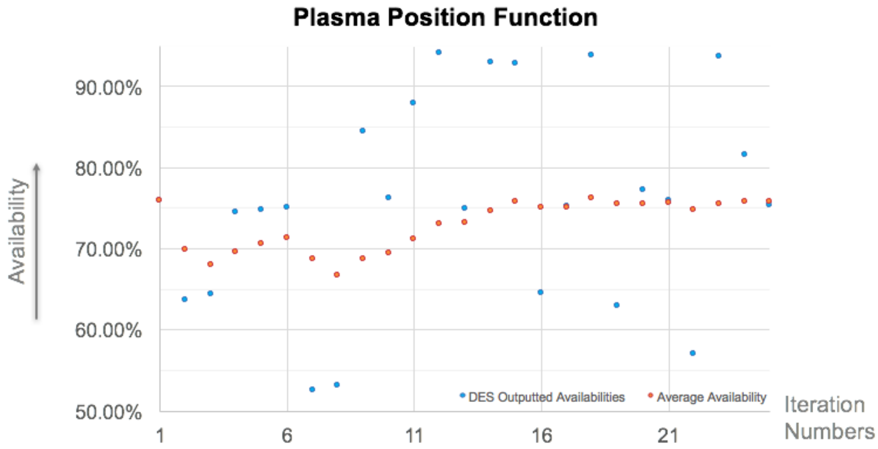

Figure 5-4: MATLAB Simulink – Results stabilization for Availability outputted from DES made for the Plasma Position Function.

5.2.2. Impact on ITER Operation

Using the 25 values for Availability collected from Synchronous DES made for Impact to ITER Operation Analysis and doing the Average, Standard Deviation and 95% Confidence Interval of the measures:

Availability for Impact to ITER Operation from DES		
Availability (Simulation sample time: 116800h)	**Standard Deviation (Simulation sample time: 116800h)**	**Maximum and Minimum from 95% Confidence Interval (Simulation sample time: 116800h)**
98.33%	3.20%	[92.06% ; 100.00%]

Table 5-9: Availability Results for DES made for Impact to ITER Operation.

The Availability Average result are not in accordance by a slim margin with the requirement for Availability presented in requirement REQ-157 of Section 3.3., in which is mention that the Availability shall be compatible with the overall 98.58±0.20%, therefore like in the Analytical Model, the Impact on ITER Operation should be minimized, even in this simulation procedure, where 14 of 25 simulations for Impact to ITER Operation Analysis does not present any failure, achieving 100% of Availability. Looking for the standard deviation and the consequent confidence interval, the system may or not stay in accordance with the requirements, but even for more trials of simulation, the average value do not tend to converge for the requirement.

Should be noticed that the DES Average Result achieved of 98.33% with the following Standard Deviation of ±3.20% stays close for the Analytical Results of 96.79 achieved using Instantaneous Availability Equation (13), “for the same operation time” of 116800h. The statistical resulting for a Synchronous simulation converges to the Analytical Availability how expected, because both (analytical calculation and Synchronous Simulation) gives the possibility of overlap failures, computed in an erroneous way for the System Availability. But as mentioned at Section 4.3., the Synchronous Simulation is enough for the PPR System case, once the small MDT in comparison with the MTBF complicates the probabilities of overlapping, discarding the necessity for an Asynchronous Simulation.

5.2.3. Effect on the Electron Density Profile Measurements

Using the 25 values for Availability collected from DES made for Effect to the Electron Density Profile Measurements Analysis and doing the Average, Standard Deviation and the Confidence Interval of the measures:

Availability for DES			
	Availability (Simulation sample time: 11680h)	**Standard Deviation (Simulation sample time: 11680h)**	**Confidence Interval of 95% (Simulation sample time: 11680h)**
“1 out 4”	100.00%	0.00%	[100.00% ± 0.00%]
“2 out 4”	99.96%	0.06%	[99.96% ± 0.12%]
“3 out 4”	97.72%	4.21%	[97.72% ± 8.25%]
“4 out 4”	75.77%	12.34%	[75.77% ± 24.19%]

Table 5-10: Availability Results for DES made for Effect to Electron Density Profile Measurements Analysis.

The values of Average Results from DES converges again to the Analytical Results achieved using Instantaneous Availability Equation (13), for the same “time” of 11680h. The Average Availabilities for “3 out 4” and “4 out 4” of 97.72% and 75.77%, respectively, are a little lower from the Analytical values of 98.09% and 77.51%, but with standard deviation and confidence interval the values stay close.

5.2.4. Effect on the Plasma Position Function

Using the 25 values for Availability collected from DES made for Effect to the Plasma Position Function Analysis (that is the same simulation that ran for Effect to the Electron Density Profile

Measurements Analysis) and doing the Average, Standard Deviation and Confidence Interval of the measures:

Availability Confidence Interval for DES		
Availability **(Simulation sample time: 11680h)**	**Standard Deviation** **(Simulation sample time: 11680h)**	**Confidence Interval of 95%** **(Simulation sample time: 11680h)**
75.77%	12.34%	[75.77% ± 24.19%]

Table 5-11: Availability Results for DES made for Effect to Plasma Position Analysis.

Again, the result of Average Availability for DES stay close to the Analytical one, 77.51%, but for this function, equally for the “4 out 4” case for the Effect in Electron Density Profile Measurement, the standard deviation and confidence interval stay too big, due to a simulation with variable results, what can be seen at Figure 5-4, guiding the possible necessity to more trials.

The results presented in Synchronous Simulation gives the same values for Availability for Electron Density Profile Measurement in the “4 out 4” parallel case and the Plasma Position Function series case, compatible with the theory of series and parallel connections presented at Section 2.1.4.

5.2.5. Simulation Failures Detection

For the Impact to ITER Operation Analysis, from 25 iterations ran it were observed, like already cited, 14 iterations with no failure (having 100% of Availability). However, over the 25 iterations were observed failures in the different critical components, being 5 failures of IEWT, 4 failures in the In-Vessel Waveguides, 3 failures in Antenna support/holders, and 1 failure for both CDC and Secondary Barrier. Therefore, there are no evidences of a major critical component, once the failures happen in all the blocks presented in the Impact to ITER Analysis (see Figure 4-10, noticing that First Barrier Confinement was out of scope for simulation). Nevertheless, should be given a warning around the In-Vessel Waveguide component, once this component presented 4 failures in 25 iterations ran, having a huge MDT considered of 5840h to affect the Availability (being just truly repairable during the LTM, at this design phase, so the failure of a waveguide would significantly reduce the usefulness of the measurement for the ITER life time, what was not considered at this RAMI Analysis, once a MDT of 5840 hours was used to check this hypothetical scenario).

Some images were collected from the Synchronous Model Simulation with the function of show and exemplify some results on display of simulation together with the consequent Boolean Signals and component failure identification.

The Figure 5-5 and 5-6 show the display and the Boolean Signal, respectively, for the Impact to ITER Operation Simulation.

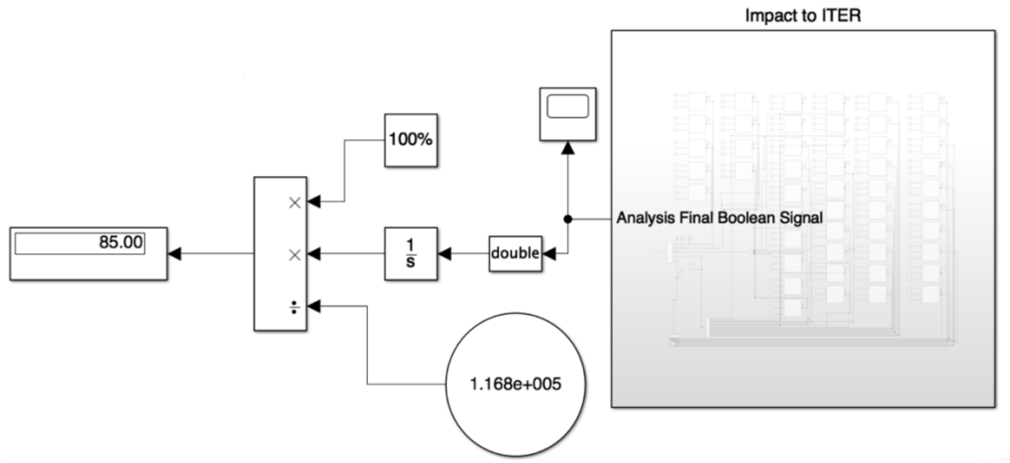

Figure 5-5: MATLAB Simulink – Display showing the worst iteration (just 85% of Availability). for the Impact to ITER Operation Analysis, with 116800h run.

The three failures of the worst iteration (iteration number 19) of DES for Impact to ITER Operation are represented in Figure 5-6, being at this iteration warning two failures in the In-Vessel Waveguides already related, and one in the Secondary Barrier (A) SIC-2, achieving critical 85% of Availability for the Analysis.

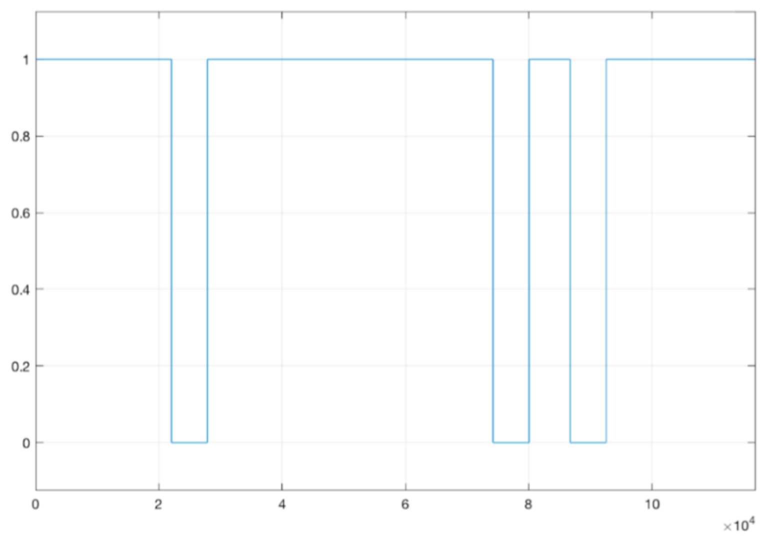

Figure 5-6: MATLAB Simulink – Final Boolean Signal outputted from the Impact to ITER Operation Analysis, having two failures in the components In-Vessel Waveguides and one failure in the Secondary Barrier (A) SIC-2, with 116800h run.

Figure 5-7 illustrated the Synchronous Simulation for Effect to the Plasma Position Function and Electron Density Profile Measurements Analysis, showing the display with results and the Boolean Signal for 11680h operation made for the Plasma Position Function.

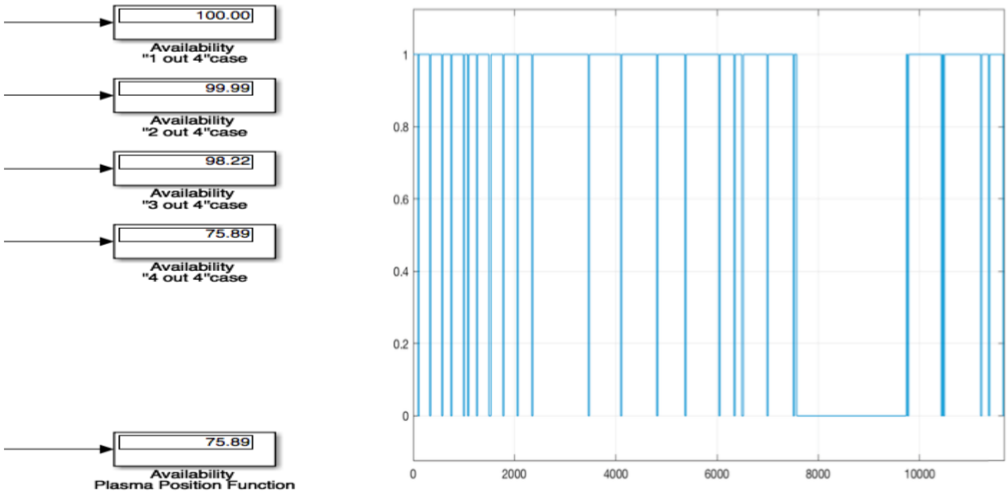

Figure 5-7: MATLAB Simulink – Display for Effect to the Plasma Position Function and Electron Density Profile Measurements Analysis, showing the Final Boolean Signal for Plasma Position Function, noticing numerous number of failures in Pin Switches of the fast shutter, with a 11680h run.

Figure 5-7 shows for the Boolean Signal one notable downtime, being one Antenna Waveguide component failure with MDT of 2160h. A huge number of failures with a small MDT was noticed, being several failures in the Pin switches of the fast shutter components, compatible with the remarkable small Reliability (26.41% for 16 months' scenario) presented for this component, already guiding for a separate analysis.

Figure 5-8 shows for the same iteration done for Figure 5-7 a Boolean Signal for the Gap 6, showing the Antenna Waveguide failure at that Sub-System, besides some failures for the Pin switches of the fast shutter.

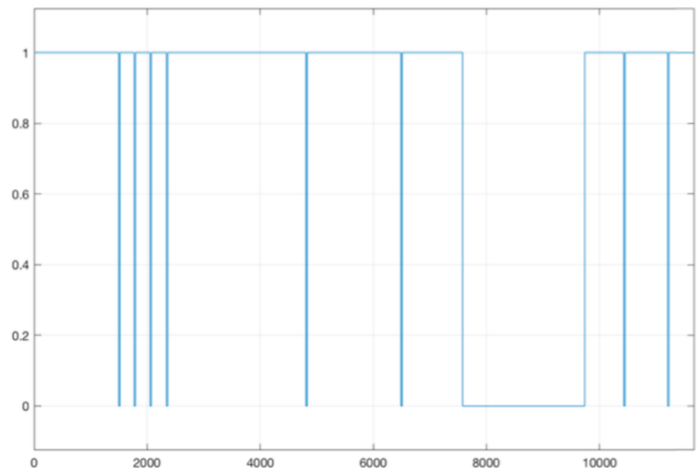

Figure 5-8: MATLAB Simulink – Final Boolean Signal for Gap 6 in the same iteration of simulation in Figure 5-6, for 11680h run.

6. Conclusions

6.1. Conclusion

The Reliability Analysis of the PPR System was made considering the potential impact on ITER Operation, the effect on Electron Density Profile Measurement and the effect on the Plasma Position Function, with regards based on ITER operation proposition that the ITER machine Availability is the major focus of the project, so the whole operation interests and must stand out in front of other lower Systems.

An availability of 97.16% for 16 months of mission time and of 96.79% for the ITER operation life cycle was achieved for the ITER machine due to critical failures on the PPR System, calculated by an Analytical Approach. These values are not in accordance with the diagnostic Availability requirements (that is stablished as 98.58±0.20% in REQ-157 of Section 3.3.). This means that mitigation actions are needed specially driven for the components on the PPR System that directly can affect the ITER operation (Antenna Support/Holders, In-Vessel Waveguides, First Confinement Barrier, IEWT, Secondary Barriers and CDC). It should be noted that achieved Availability for ITER operation is the result of the Reliability of the different elementary components involved, which is quite high, together with the number of similar elementary components, which accounts for 59 components (see Figure 4-10, with no Data Available for First Confinement Barriers, being actually 49 components affecting the ITER operation). With the same components, a Synchronous Simulation was modeled for the Impact to ITER Analysis guiding for 25 iterations of simulation, achieving for the ITER operation life cycle one Average Availability of 98.33% with 3.20% of standard deviation, guiding for a confidence interval of [98.33%±6.27%]. The simulation confirms the possible necessity for mitigation actions to reduce the impact of PPR System on ITER operation, being even possible that the system achieves the requirement due to the confidence interval. At this stage design actions should be driven not only to increase the Reliability of the components but essentially to the reduction of the number of components involved in the impact of ITER operation. A special warning was given for the In-Vessel Waveguide component, that presented 4 failures in the 25 iterations ran, having a huge impact of unavailability caused by a MDT of 5840h.

In the case of Electron Density Profile Measurement, due to the very high level of redundancy (five redundant reflectometers, Gap 3, Gap 4, Gap 5(A), Gap 5(B) and Gap 6, are considered as able to provide this measurement), the Availability results are very similar to the ones calculated for the case of the analysis of the expected impact of PPR system on ITER availability (99.94% of Analytical Availability and 99.96% for simulation Average Availability to take until 2 measurements for all ITER operation life cycle, showing that the damage in the results is only significant when 3 or 4 out of 4 Gaps have to be operational for the measurement operation.), and therefore they are in line with the general requirement for diagnostics, what is confirmed for the Synchronous Simulation results plotted at the Table 5-10.

In the case of the Plasma Position Function, the Analytical Availability Results stays around 77%. This is mainly due to the fact that all gaps are needed to provide a useful input to the ITER plasma position and control system (PCS), and therefore every failure of a single component would lead to the failure of the measurement. Besides that, the In-Vessel Waveguides are only repairable during the LTM period, so the failure of a waveguide would significantly reduce the usefulness of the measurement for the ITER life time, what was not considered at this RAMI Analysis, once a MDT of 5840 hours was used to check this scenario, once the designers are concerned about this components with no maintenance during the operations of 16 months. The simulation leads for closer results (with Average Availability around 75%) and proves the worry about the Plasma Position Function.

Hence, in the case that this measurement is essential for the operation of ITER (which is not the case assumed in the present report), then design measures should be implemented in order to increase substantially the level of Reliability and Availability up to the general objective for this kind of measurement in ITER. Probably the implementation of redundancy (within PPR system or other reflectometers), and other design improvements would be needed. More trials on the simulation are another good choice to achieve a better (small) confidence interval for this Function.

A sensitivity analysis was performed on the influence of Pin switches of the fast shutter on the Reliability and Availability results of the Stray Radiation Protection System and on Electron Density Profile Measurement and Plasma Position Function, as it is a component with the higher failure rate and a high number of them are involved in a series connection. Also, the potential effect of its preventive replacement was analyzed. Results show that a significant increase in the Reliability is obtained. Although the high number of different components involved and their Reliability characteristics highly constraint the sensitivity of the PPR System to the Pin switches of the fast shutter. Event with these components with a null failure rate, the Reliability of the Plasma Position Function is 2.16% for the 16 months of mission time, and for the Electron Density Profile function is 87.17% for the same time frame (1 out of 4 measurements condition), showing that the Pin Switches of the fast shutter is not the unique problematic component affecting Reliability. Another time the Synchronous Simulation confirms the Analytical Results, showing a lot of failures in this specific component during a 16 month' operation for one iteration of simulation, what was illustrated at Figure 5-6.

Further iterations of the analysis are needed not only to accommodate the design evolution, but also to increase the accuracy and representativeness of the components input data and specially to include the missed Reliability and Maintainability data of some of the components.

6.2. Future Work

The initial assumption of the analysis has been that spares are available on-site for all the components of the PPR system, using values of MDT as the same value of MTTR. However, the Availability of spares may have a strong impact on the MDTs, and therefore on the Availability results. Further analysis is needed in order to better determine the effect of spare components and its viability, being a possible future work analysis.

Sensitivity analysis will have to be developed to show what the impact could be if assumptions about the fabrication or delivery time are made. This should be taken into account both for "out-of-the shelf" components, as may be the case of some electrical components of the reflectometer Back-Ends, and especially for diagnostic-specific components such as the antennas, IETW, CDC, waveguides, and some Back-End components.

Another possible future works for the project might be new developments of DES:

1. One Asynchronous modelling for the stochastic behavior of time to failure.
2. Create a new simulation made considering a stochastic behavior of the time to repair.
3. Make another simulation focus on the Reliability of the System instead of the Availability.

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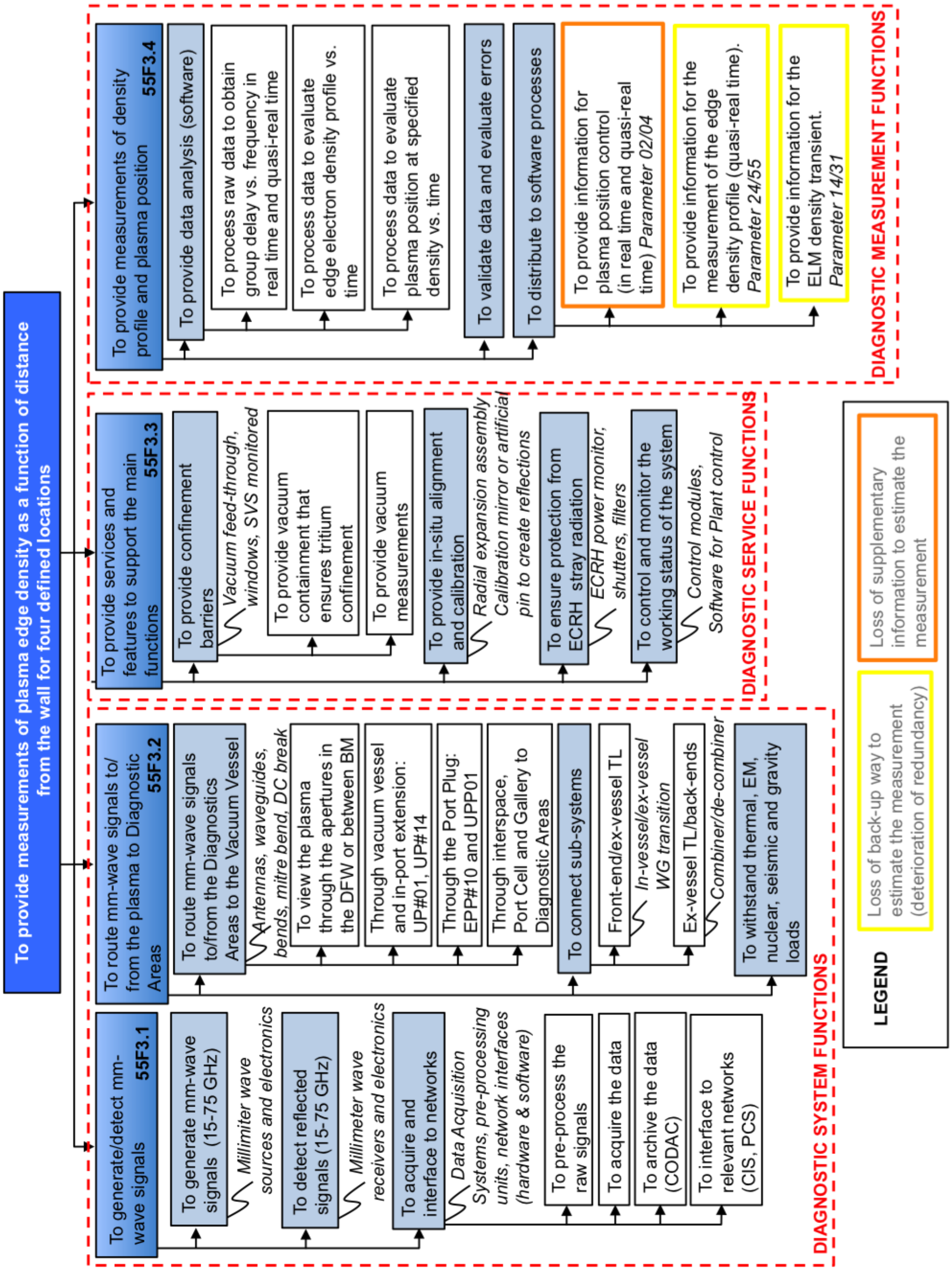
Annex A



Annex A: Functional breakdown of the PPR system. [12]