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João Santos de Oliveira

ASSESSING THE IMPACT ON THE RELIABILITY OF THE INCREASE OF RENEWABLE PENETRATION WITH WELL-BEING ANALYSIS

THE CASE OF PORTO SANTO

Dissertation within the Masters in Electrical and Computer Engineering, Energy Masters Degree supervised by Professor Doctor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes and presented to the Department of Electrical and Computer Engineering of the Faculty of Sciences and Technology of the University of Coimbra

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Faculdade de Ciências e Tecnologia
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Dissertação no âmbito do Mestrado Integrado em Engenharia Eletrotécnica e de Computadores, Área de Especialização em Energia orientada pelo Professor Doutor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes e apresentada ao Departamento de Engenharia Eletrotécnica e de Computadores da Faculdade de Ciências e Tecnologia da Universidade de Coimbra
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ORIENTADOR

Professor Doutor Álvaro Filipe Peixoto Cardoso de Oliveira Gomes

PRESIDENTE DO JÚRI

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FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE D COIMBRA

“Sempre parece impossível até que seja feito”

Nelson Mandela

"Este trabalho teve o apoio da Fundação para a Ciência e Tecnologia (FCT) e do Fundo Europeu de Desenvolvimento Regional (FEDER) via COMPETE – Programa Operacional Competitividade e Internacionalização (POCI), no âmbito dos projetos T4ENERTEC (POCI-01-0145-FEDER-029820) e UID/MULTI/00308/2013."

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Abstract

One of the most important parameters in the evaluation of any electrical system it's its reliability. With the increasing penetration of highly variable and intermittent renewable energy sources (solar and wind) and, also, the reduction of conventional sources and the predictable increasing demand, improving or even keeping up the reliability indexes will be a challenging task. This will be even more demanding in small isolated power systems as the ones seen in many small islands.

Taking this into account, a software tool was developed using the MATLAB environment, capable to perform Chronological and Non-Chronological Monte Carlo Simulations combined with the Well-Being Analysis (WBA) for assessing the reliability of power systems independently of the existing technologies. This analysis sorts the system in 3 distinct states, Healthy State, Marginal State and Risk State. WBA is used because conventional analysis only assesses the success and the failure - healthy or risk state -, while an intermediate state - marginal - gives a more suitable review and, therefore, should be considered.

The tool (for the Chronological Method) can work with existing generation and/or demand data, or it can be created using system generator's data (Capacity Outages and respective probabilities) combined with information regarding resource availability, maintenance, among others. For the Non-Chronological method, the Capacity Outage Probability Table (COPT) is created using the generators' capacity outages and respective probabilities, previously mentioned, and then, with a N number of simulations the WBA is completed.

The tool was tested and validated using the Roy Billinton Test System (RBTS) where the indexes for the base values are calculated and compared, with a load increase of 5% per year later added.

Finally, this tool will be applied in studies regarding the electrical system of the island of Porto Santo, Madeira, Portugal, where some variables of the installed capacity of conventional power sources, in this case thermal diesel, and the increased of solar and/or wind power in the system, will be tested. Concluding that the Capacity Credit (CC) is null for the intermittent sources.

Keywords: Reliability, Well-Being Analysis, Monte Carlo Simulations, Chronological and Non-Chronological, Intermittent Sources, Porto Santo

Resumo

Um dos parâmetros mais importantes na avaliação de um sistema elétrico é a sua fiabilidade. O aumento da penetração de energias renováveis altamente variáveis e intermitentes (solar e eólica) e, para além disso, a redução de fontes convencionais e o aumento cada vez mais acentuado da procura, melhorar ou mesmo manter os índices de fiabilidade será uma tarefa complicada. Mais exigente e desafiador será em pequenos sistemas de energia isolados, como os presentes em muitas ilhas.

Com isso em mente, foi desenvolvido uma ferramenta em ambiente MATLAB que aplica os métodos de Monte Carlo Cronológicos e Não Cronológicos e que usa os índices "Well-Being" para avaliar a fiabilidade de um qualquer sistema fornecido pelo utilizador. Esta "Well-Being Analysis" (WBA) caracteriza o sistema em 3 estados distintos, estado saudável, marginal e de risco. Este sistema é utilizado visto que as análises convencionais apenas avaliam o sucesso e o insucesso (sistema saudável ou em risco) e um estado intermédio (marginal) possibilita uma melhor análise e deve ser considerada.

Esta ferramenta (para o método Cronológico) pode trabalhar com dados de geração e/ou procura já existentes, ou pode criar usando os dados do sistema (capacidades fora de serviço e respetivas probabilidades) combinadas com dados sobre a disponibilidade do recurso, manutenção, entre outros. Para o método Não-Cronológico, a Tabela de Probabilidade de Perda de Geração do sistema é criada usando as mesmas capacidades fora de serviço e respetivas probabilidades acima referidas e depois é trabalhada com um valor N de simulações para se obter os "well-being" índices.

A ferramenta desenvolvida é testada no Roy Billinton Test System (RBTS) para ser feita a sua validação onde se testa o caso base e depois é feita uma análise onde existe um aumento da carga em 5% ao ano.

Finalmente, esta ferramenta vai ser aplicada ao sistema elétrico da ilha de Porto Santo, Madeira, Portugal onde vão ser analisados alguns casos de variação da capacidade instalada de produção convencional (neste caso térmica diesel) e aumento da penetração de solar e/ou eólica no sistema.

Com isso conclui-se que o crédito de capacidade é zero para as renováveis variáveis.

***Palavras-Chave**: Fiabilidade, Well-Being Analysis, Simulações Monte Carlo, Cronológicos e Não-Cronológicos, Fontes Intermitentes, Porto Santo*

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Acronyms

aFRR	Automatic Frequency Restoration Reserve
ARMA	Auto-Regressive and Moving Average
CC	Capacity Credit
CFS	*“Capacidade Fora de Serviço”*
CO_2	Carbon Dioxide
COPT	Capacity Outage Probability Table
E(“…”)	Duration/Expectation of …
EPS	Electrical Power Systems
EU	European Union
FCR	Frequency Containment Reserve
FOR	Forced Outage Rate
FTA	Fault Tree Analysis
GHG	Greenhouse Gases
IEEE	Institute of Electrical and Electronics Engineers
IEEE-RTS	IEEE-Reliability Test System
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MCS	Monte Carlo Simulation
mFRR	Manual Frequency Restoration Reserve
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
P(“…”)	Probability of …
PRIMES	Price-Inducted Market Equilibrium System
RBD	Reliability Block Diagram
RBTS	Roy Billinton Test System
RES	Renewable Energy Sources
RS	Secondary Reserves
RTdown	Tertiary Reserves Down
RTup	Tertiary Reserves Up
SPP	Southwest Power Pool
WBA	Well-Being Analysis
WECS	Wind-Energy Conversion System
WTG	Wind Turbine Generator

Symbols

λ	Failure Rate
μ	Repair Rate
A	Availability
H	Healthy State
M	Margin State
R	Risk State
U	Unavailability

Chapter 1. Introduction

In this section, it will be firstly explained the motivation for this work which is the dissemination of Renewable Energy Sources (RES) into the electricity grid. This has increased exponentially to combat environmental problems caused by conventional generation using fossil fuel sources, placing governments under increased pressure to reduce emissions [1]–[4] which impose challenges to the security and reliability of the electrical system [5].

Secondly, there will be a brief rundown of the goals behind this dissertation, followed by an outline of the same.

1.1 Motivation

It is undeniable that electrical energy plays a crucial role in today's society, being involved in almost every aspects of a person's routine. Thus, it takes a central position in the economic, social, technological, cultural and industrial aspects of humanity.

Despite the introduction of measures aiming at improving the efficient use of energy and, despite the good results obtained, electricity demand has been increasing in recent decades, following a growing pattern: by 2050, it's expected that energy consumption will double when compared with values from 2010 [4]. With this increased demand, new generating units need to be set up and/or older ones must be upgraded or discarded.

In recent decades, concerns have emerged worldwide regarding the use of fossil fuels in power systems, not only because of the need to reduce Greenhouse Gases (GHG), but also because of the potential shortage of these sources. With that in mind, the European Union (EU), side by side with "The Union of the Electricity Industry – EURELECTRIC", has set ambitious targets concerning Carbon Dioxide (CO_2) emissions. The goal is that the countries that belong to EU would reach a 75% reduction of CO_2 by 2050 [4], therefore reaching carbon neutrality that is defined by the following conditions [4]: reducing emissions as much as possible and minimize GHG elsewhere, e.g., via reforestation and calculating emissions unequivocally. In the energy sector, the obvious way to contribute to these goals is by further improving the efficient use of energy and the use of energy from renewable sources. However, changes happening in the power systems due to massive penetration of solar and wind generation have raised concerns about reliability and operational management of the electricity systems.

Since solar and wind power are the most popular RES (not considering Hydro), their dissemination brings new challenges to the power system operation due to their intrinsic characteristic: variability which depends on local weather conditions [6]. Variable availability means that the dissemination of wind and solar power requires adequate backup capacity (reserves) for a reliable power system operation.

Considering that the increase of RES contribution for electricity generation is now a major goal for many governments, it’s important to better understand the impacts of such policy in the different aspects of the power systems, namely the ones directly linked to reliability of an electrical system.

1.2 Goal

The goals of this dissertation was to design a software tool for reliability indexes’ calculation, namely one able to carry out a Well-Being Analysis (WBA), and also make a reliability assessment of the Porto Santo’s power system considering different scenarios for the generation system, with the intent of the increase of solar and wind power.

Two different Monte Carlo Simulations (MCS) will be implemented, Chronological and Non-Chronological, both using the Well-Being evaluation.

Porto Santo has a project - Smart Fossil Free Island - that consists in being totally independent of fossil fuel energy resources, with six independent intervention areas connected between them: Historical and Cultural Identity, Environment and Natural Resources, Innovation and Local Economy, Sustainable Tourism, Sustainable Energy and Sustainable Mobility [7], [8]. To achieve that, studies about reliability of the electrical system are important to ensure a proper supply of electricity to all habitants.

1.3 Outline

This dissertation is divided into five chapters.

First, after this introduction, chapter two will have a literature review about the reliability in power systems, and particularly about the challenges posed by the dissemination of variable renewable sources. Commonly used reliability assessment indexes will be presented and described, and the WBA approach will be analyzed in detail. Some of the most recent studies addressing the reliability and the very high penetration of RES in the electricity system will be discussed in the final of this chapter.

Chapter three presents the developed software tool giving all the specs of the program and how it works. Furthermore, the process of validating the algorithm will be disclosed.

In chapter four, the case of Porto Santo will be analyzed using the program already cited and an extensive analysis will be presented.

The main conclusions of this dissertation will then be summarized in chapter five. In view of possible future researches based on this project, some suggestions are made in this last chapter.

Chapter 2. Literature Review

The following chapter summarizes some of the theoretical aspects behind this dissertation, giving the reader a good grounding to understand the topic and presents the most commonly used reliability assessment indexes. Afterwards, some recent studies will be presented about the reliability in modern power systems, that have increase contribution from renewable sources.

2.1 Reliability

Electrical Power Systems (EPS) have been evolving to provide energy to consumers in a reliable and safe manner.

"The term reliability has a very wide range of meaning and cannot be associated with a single specific definition such as that often used in the mission-oriented sense. It is therefore necessary to recognize this fact and to use the term to indicate, in a general rather than a specific sense, the overall ability of the system to perform its function."[9]

In the EPS, that function is providing consumers with a non-stop service with the right quality.

Therefore, in order to study the reliability of a system, we need to establish models for the behavior of that system whose components may suffer damage, leading in some cases to the system not fulfilling the functions for which it was designed and built for [10]. When analyzing the reliability of any EPS the same question always arises: how reliable should the system be? It's not possible and easy to have a single response, still, is extremely important and must be defined before any network expansion or reinforcement is initiated, as it is impossible to have a single solution for each situation, because different systems businesses and consumers will have different ideas of the reliability wanted or needed. Also, planning and arranging an EPS is a complex task, as there are several factors that should be considered in the decision-making process. It is worth remembering the need for uniformity between the reliability of different parts of the system. There is no point in strengthening a strong part of the network when weak areas that need improve exist. However, there are meant to be differences in reliability between zones - production, transport and distribution -, as a failure of the transport system could lead to far more serious consequences than a distribution failure. So, before deciding, it must always be ensured that we will benefit from the improvement of the reliability of that given part of the system [11].

In addition to ensuring that it must be beneficial to the system, it must take into account utilities and consumers. With this, the aspects of reliability and economics should be evaluated, by comparing reliability cost (the cost of investment needed to achieve a certain level of reliability) to reliability worth (the benefit derived by the customer and society).

The basic concept of reliability-cost and reliability-worth evaluation is relatively simple and can be presented by the cost/reliability curves of Fig. 2.1. In these curves it’s possible to see that higher reliability implies higher costs. On the other hand, the customer costs - **associated with failures only** - decrease as the reliability increases. The total costs, therefore, are the sum of these two individual costs. This total presents a minimum, and so an "optimum" or target level of reliability where the cost its acceptable for both sides. Two difficulties arise in its assessment: firstly, the calculated indexes are obtained from approximate models that cannot correspond to the real system. Secondly, there are significant problems in the meaning of system failure costs to the consumer [12].

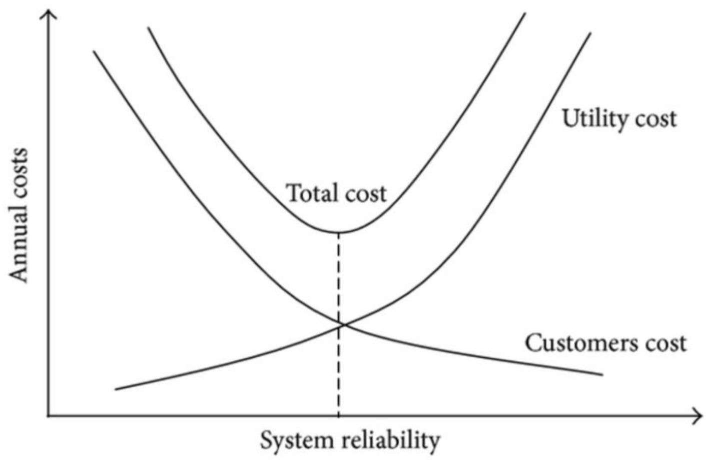

Fig. 2.1 – Total Reliability Costs [12].

In the reliability of an EPS, there are two concepts that always must be considered, adequacy and security [12].

Adequacy is connected to the existence of enough means in the system to meet the existing demand, being the focus of this work.

Generation adequacy measures the greater or lesser capacity of the system to meet demand when considering the time that the generators are out of service. Decreasing the probability of not meeting demand, that is to say, better adequacy, usually means more reserve capacity available with its consequent costs. Another alternative of reducing the probability of not satisfying demand, i.e., improving reliability, can be managing the demand peak to shortening is time of happening.

And, security is related to the system's ability to respond to disturbances, i.e., the responsiveness of a system to any internal or external disturbances must be possible in the less time available.

So, to summarize, a system reliable it's a system where you must have more generation than your demand. It's like a reserve: the higher the difference, the higher the value of the reserve.

2.1.1 Deterministic and Probabilistic Approaches

Several techniques were developed to deal with the adequacy problem in the EPS. Two main approaches can be pointed out: the deterministic approach and the probabilistic approach.

The deterministic approach is a simple method (more straightforward) to measure the adequacy of any EPS and was extensively used in the past by electrical utilities to support their decisions. In short, this approach quantifies the EPS reliability using a pre-specified rule based on the pass-experience of the utilities so, each utility selects different criteria according to the internal organization and their know-how about their EPS, not taking into account the uncertainty and variability associated with some of the parameters and components of the system. A typical example of this approach, which is common used, is the static reserve which is the difference between the expected maximum demand and the generating capacity, using as reference the capacity of the largest generating unit from the system [12].

In today's electrical power systems, these deterministic criteria is not very suitable for the reliability assessment because, from an economical point of view, if we don't take into account the randomness of the system load and of the variable generation, and the uncertainty of the components to malfunction, this type of approach take us, in most cases, to expensive solutions that use financial resources without an apparent justification, wasting them, like an over dimensioned system.

The main advantages are the straightforwardness and robustness of the results since the criteria chosen it's usually developed to be on the side of the security of supply. But, because of limitations, this approach can also lead to under-investment and probably to an unacceptable number of interruptions on load supply (under dimensioned system) [13]. That presents a problem since society does not tolerate a frequent failure of load supply and will always question unjustified investment of large amounts of money to improve power system reliability.

With all this in mind, the deterministic approach is being gradually replaced by probabilistic methods or methods that combine a bit of both, although several utilities still use this type of approach.

The probabilistic approach is the other way to assess power system reliability which incorporates the fact that here is an uncertainty associated to the events that can occur in this type of systems. The most usual types of uncertainties are components states (like malfunctions), weather, hydrological resources and load states.

Inside this approach, we have the simulation methods and the analytical methods. The analytical methods represent the system through a mathematical model but although they are generally able to provide index expectations in a short period, they often must use assumptions to simplify problems and, consequently, the results from these techniques can sometimes lose some meaning. Simulation techniques, in turn, use simulations of the actual process (including the random behavior) for the calculation of reliability indexes. This last one can follow two different approaches depending on whether the system history has or not an influence on its behavior. The Fig. 2.2 represents all the methods discussed.

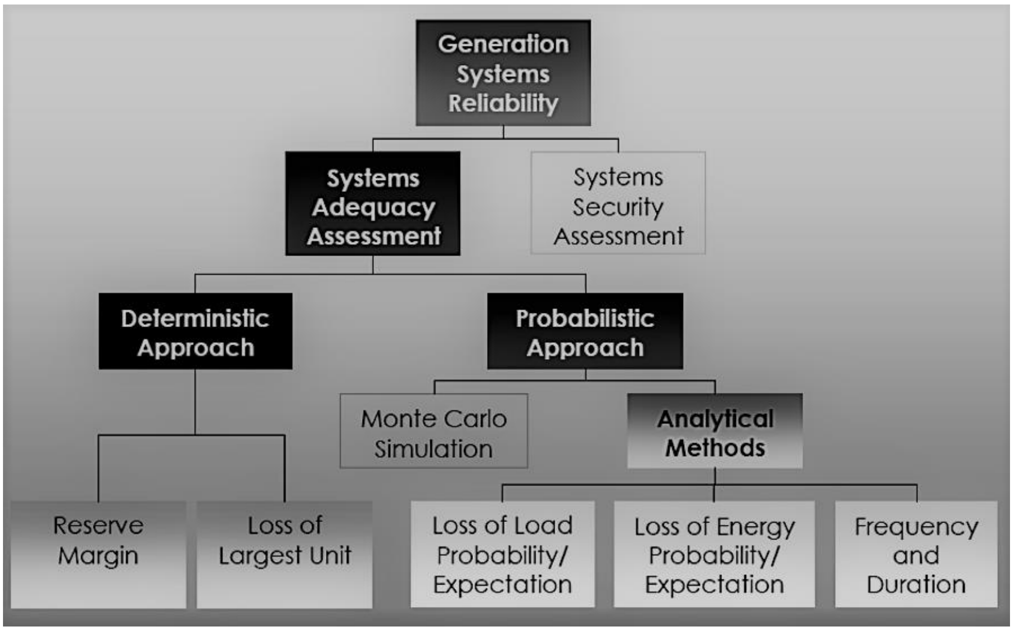

Fig. 2.2 – Different Methods in Systems Reliability [14].

2.1.2 Conventional Reliability Model for an Alternator's Representation

All the components/equipment - from an EPS or not - may malfunction at random times and the ones that can be repaired have, during its life, an operation cycle characterized by a cycle of working, malfunction, repair and back to work.

Usually, the way of representing a generation system for reliability studies it's using the capacity and the probability of failure/malfunction of each unit individually. The probability of a component damaged, i.e. not working, it's called unavailability (U) and the opposite, the availability (A).

The unavailability can have countless factors like ageing or a poor maintenance, for example. It is determined, for the units already installed, by using previous records of incidents occurred. For new units, they use similarly machines for obtaining the value of U.

The unavailability can be obtained from the following equation, where λ it's the failure rate and μ it's the repair rate.

$$U = \frac{\lambda}{\lambda + \mu} \qquad (2.1)$$

$$\mathrm{A} = \frac{\mu}{\lambda + \mu} \qquad (2.2)$$

Since $\lambda = \frac{1}{\mathrm{MTTF}}$ and $\mu = \frac{1}{\mathrm{MTTR}}$,[13] equations (2.1) and (2.2) become:

$$\mathrm{U} = \frac{\mathrm{MTTR}}{\mathrm{MTTR} + \mathrm{MTTF}} \qquad (2.3)$$

$$\mathrm{A} = \frac{\mathrm{MTTF}}{\mathrm{MTTR} + \mathrm{MTTF}} \qquad (2.4)$$

where, MTTF it's Mean Time to Failure and MTTR it's Mean Time to Repair.

The equation 2.3 it's equal to the Forced Outage Rate (FOR), a probability needed to construct the capacity outage probability tables [12], [15].

2.1.3 Loss of Load Probability/Expectation

As part of the analytical methods, Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE) are two indexes related with loss of load, as implied by its name.

LOLP is the probability that the load will exceed the available generation at a given time. This value only gives an indication of generation capacity's shortfall and, so, lacks information on the importance and duration of the outage.

LOLE is the expected time (in hours/year, days/year or days/10 years) during which the load will not be met over a defined time period [16], [17].

So, LOLP can be calculated by:

$$\mathrm{LOLP} = \sum_{j} \mathrm{P}\left[\mathrm{C_A} = \mathrm{C_j}\right] * \mathrm{P}\left[\mathrm{L} > \mathrm{C_j}\right] \qquad (2.7)$$

where:

P probability of

L expected load

$\mathrm{C_A}$ capacity of available generation

$\mathrm{C_j}$ capacity of the j state

This index is used all over the world and some aspects must not be forgotten: it doesn't give information about duration or frequency of the malfunctions and the incidents don't always happen in the peak of the demand, so when they happen at hours with lower demand, the reserve will be higher than predicted and big failures in generation are sometimes preceded by small problems that can be solved instantly with emergency mechanisms [10].

LOLE it's the LOLP multiplied for the desired time interval (T):

$$\mathrm{LOLE} = \mathrm{LOLP} * \mathrm{T} \qquad (2.8)$$

Usually, an international reference value for LOLE it's 1 days/10 years or 0.1 days/year This means that in 10 years it is expected that the load is not totally served in 1 day [10].

2.1.4 Capacity Outage Probability Table

Capacity Outage Probability Table (COPT) or Generation Loss Probability Table is the generation model required in the loss of load approach which uses the unit data (FOR, Out of Order Capacity or Capacity Outage, nominal power and number of groups) for its construction.

The unit data can be modulated in a two-state Markov model - the ON state and the OFF state -, the most basic model for a unit in power systems or it can have multiple states - multi-state model.

In the two-state model, you just need the probability of the unit being OFF (represented by the FOR). The probability of being ON its just applying the rule of probabilities, 1-less-that probability, since the sum of all probabilities must be equal to 1.

In a multi-state model, the system is represented by a set of states where the unit can reside and its respective probabilities, arranged accordingly to the unit capacity (Capacity Outage value), remembering that the sum of those probabilities must be 1 [18]. This model provides a better distribution and a better proximity to the real world since a machine can have a malfunction but still work at 50%, for example.

So, COPT is a simple table with Out-of-Order capacity levels (ascending order) and the respective probabilities of happening. The units can be combined using probability concepts and this can be extended to a simple but powerful recursive technique in which units are added sequentially to produce the final generation system model.

This table can be manipulated using cumulative probability and, also, can be rounded for reducing its size since the larger the system is, the bigger the COPT. How, you may ask? It’s possible to achieve that using equations 2.5 and 2.6 for reducing the number of states, imposing a higher interval between states that causes the shortening of the COPT.

$$P(C_j) = \frac{C_k - C_i}{C_k - C_j} * P(C_i) \qquad (2.5)$$

$$P(C_k) = \frac{C_i - C_j}{C_k - C_j} * P(C_i) \qquad (2.6)$$

All states “i” falling between the required rounding states “j” and “k” [12].

2.2 Reserves

The power systems cannot operate without reserves so to maintain reliability and quality of supply, we need both active and reactive power reserves. These reserves are needed for compensation of load deviations from expected values and for satisfying generation deficit in the case of unexpected outages of power units or other unexpected outages [12].

The control over power systems is a complex process and it’s divided into stages. For every stage, adequate reserves are needed. The operating reserves are usually divided into three parts:

1. Primary Control Reserve or Frequency Containment Reserve (FCR) (available within 10 s) – Local automatic control which delivers reserve power against any frequency change [19];
2. Secondary Control Reserve or Frequency Restoration Reserve (available within 30 s) – Centralized automatic (aFRR) and/or manual (mFRR) control which delivers reserve power in order to bring back the frequency and the interchange programs to their target values [19];
3. Tertiary Control Reserve (available within 15 min or less) – Manual change in the dispatching and unit commitment used to restore the secondary control reserve, to manage potential congestions, and to bring back the frequency and the interchange programs to their target if the secondary control reserve is not sufficient [19];

These reserves must also be present in the electrical lines and networks (stability reserve, distribution reserve, etc.) [20], [21].

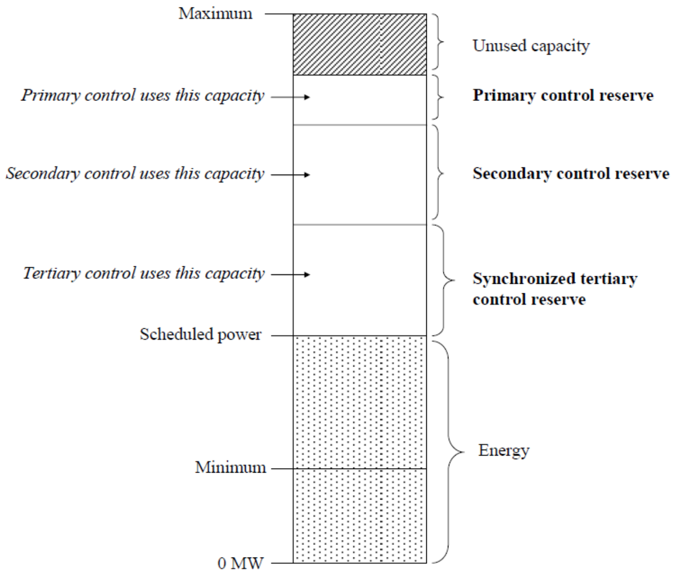

Fig. 2.3 - Possible allocation of the Capacity of a Generating Unit [21].

Theoretically, a generating unit could participate in all three levels of control presented.

Fig. 2.3 illustrates how its capacity would then be divided. In reality, a generating unit might provide only one, two or none of these reserve services [21].

2.3 Capacity Credit

Capacity Credit (CC) is a concept used to evaluate the impact of intermittent energy sources in the generating system' expansion planning, measuring its contribution to the reliability. In other words, it is the fraction of installed renewable capacity by which the conventional power generation sources can be displaced without decreasing LOLP [14].

E.g., if a system has 100 MW of wind energy, one of the possible types of intermittent renewable energy, and has a CC equal to 15%, it is possible to avoid the installation of 15 MW of conventional generation.

This capacity credit depends on a lot of factors such as the primary source availability, the location of the generation sites, among others. For example, in the UK's network, studies state that the CC is about 35% for the wind but for solar it's too low to even consider [14], since it is one of the European countries with the least amount of sunlight per day.

So, if the CC of a given intermittent source equals to zero, then the same conventional generation capacity must be installed as that intermittent source to ensure the load supply (in other words, to maintain the LOLP value).

2.4 Monte Carlo Method

Monte Carlo Simulations (MCS)

"are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty in prediction and forecasting models" [22].

MCS can be used to undertake a range of problems in virtually every field such as finance, engineering, supply chain, and science. It can be also referred to as Multiple Probability Simulation [22].

In reliability analysis, one way of using the MCS is, for example, to estimate the indexes by simulating the actual process and random behavior of the power system elements. For that having the COPT is essential.

The main advantage of this technique is the high flexibility and detail in the simulation of any complex system operation and/or configuration conditions. On the other hand, the disadvantages may or not exist: the utilities must face some cost of computing time, the rather long CPU time for high complexity and detailed systems, and the number of sample data generated which can be extensive and dependent on the system reliability level, but those cannot be disadvantages, always depends of the circumstance.

The MCS can be classified as Sequential/Chronological MCS or Non-Sequential/Non-Chronological MCS.

In Sequential MCS, a mathematical model of the system is made to generate artificial history of failures and recoveries of generators, i.e., system state is sequentially determined. It can be implemented in both independent and dependent events.

The Non-Sequential MCS consists of performing random sampling over the aggregate of all possible states the system can assume during the period of interest, i.e., the state of each component is sampled, and the system state is non-chronologically determined (using the COPT with cumulative probability, e.g.) [23].

2.5 Well-Being Framework

The evolution of the conventional generation system reliability evaluations from pure deterministic assessments, to a range of probabilistic methods, was met with some resistance from some electrical power utilities to completely abandon deterministic considerations since, the approaches from probabilistic methods, that computes reliability as indexes, are, sometimes, difficult to interpret and that creates a discomfort.

Therefore, this dilemma between the use of deterministic and probabilistic methods can be eased by including accepted deterministic criteria in a probabilistic framework using an approach known as Well-Being Analysis (WBA), which bridges the gap between these two methods.

This approach can be used in every area from finance, to health care, society, tourism, etc. and, of course, power systems.

In WBA, the reserve margin is evaluated using probabilistic techniques and compared to an accepted deterministic criteria, like for example, the loss of the largest unit of the system in order to measure the degree of system comfort [24], [25].

WBA has three indexes, namely, the probability of health P(H), the probability of margin P(M) and the probability of risk P(R). These indexes reflect the three states in which the system can reside. The E(H), E(M) e E(R) are the expected time or duration which the system can be in those states. The model for system WBA is shown in Fig. 2.4 [26], [27].

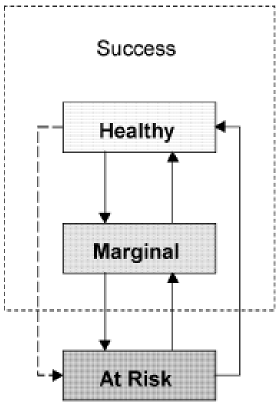

Fig. 2.4 – Model for system Well-Being Analysis [27].

The Healthy states (H) are those where the available reserve capacity is equal to or greater than the required reserve capacity, so that the generation always meets the demand. In the Margin states (M), the available reserve is less than the required capacity reserve but greater than zero, in other words, the reserve it’s not enough and the system may not survive without shedding load if any component of the system goes on outage. Risk states (R) it's when the load exceeds the available generation so, the P(R) is equal to the LOLP of the system [24], [27].

The three states are interconnected. A system can enter at the risk state or marginal state from the healthy state due to the failure of certain generating units (normally the biggest ones) or due to a sizable load growth. Again, a system can go to the healthy state from marginal or risk state due to the addition of new generating facilities or due to a certain amount of load curtailment. From the basic probability theorem [24] :

$$\mathrm{P(H)} + \mathrm{P(M)} + \mathrm{P(R)} = 1 \qquad (2.9)$$

With all this in mind, WBA can prove useful in generation capacity planning of large systems that routinely use conventional probabilistic techniques, as these indexes provide more flexibility to the system planners in the decision-making process.

2.6 Recent Studies

Research about reliability assessment has been done for a long time now still, now, the focus it's on the wind and solar integration in a bigger scale and what their impact is on the reliability, reserve capacity and operating reserves.

Why? Sun and wind are sources available all over the world and are two of the power technologies in where every country is investing in since they have low impact on the environment.

The evolution of technology is already enough for almost any country to be independent from fossil fuels, the main obstacles are the monetary cost, political reasons, regulation and reliability [28]. Problems about storage and supply can lead to long periods of unavailability, but solutions are being looked into.

One of the questions that has been extensively analyzed is how wind power generation can be modeled for reliability evaluation. One way, is grouping all generating units into an equivalent multi-state Markov model, where you only need the failure and repair rates, and combining that with the wind series, a diagram that captures the wind speed and power conversion characteristics [6].

A more recent study, *"A review of the state-of-the-art in wind-energy reliability analysis"*, reveals another way which consists of studying the Wind-Energy Conversion System (WECS) using failure and repair rates for each component of a single wind-turbine.

Instead of evaluating the machine as one big piece, it evaluates as a group of components for each machine. This evaluates the ageing, wear, strength degradation, fatigue, etc. of components like electrical system, electronic control, gearbox and nine more components, making it a total of twelve components. To sum up, this method using the WECS only focuses on the failure intensity function of wind turbines rather than focusing on other parameters such as availability, capacity factor, wind conditions and the consequences of equipment failure [29].

Other way of modeling wind power is to try and create a multi-state model that considers three factors. The first one is the random nature of the natural resource, the wind. The second one is the relationship between the power output and the site resource, and the last one is the unavailability of the Wind Turbine Generator (WTG) expressed by the FOR [30]. This analytical model is best suited for adequacy and reliability assessment using analytical or Monte Carlo techniques. In [30], the authors conclude that using a COPT created with this data is really effective and it can be applicable to large wind farms which are composed of a number of identical or non-identical WTG. With the analysis made, they also concluded that a five-state model of the unit data is enough for a reasonable assessment in practical studies using state-sampling methods like Monte Carlo [30].

In relation to the EURELECTRIC program towards a low carbon EU economy by 2050, a series of scenarios accomplishing progressively very high levels of RES are being analyzed and studied. For that, the PRIMES (Price-Induced Market Equilibrium System) model was used and it is a simulation tool that combines economics and engineering for representing the energy decisions of agents, such as demanders and suppliers [31].

In "*Very high penetration of renewable energy sources to the European electricity system in the context of model-based analysis of an energy roadmap towards a low carbon EU economy by 2050*", the authors propose using Hydrogen Energy Storage and/or new DC interconnectors between countries as moderators for the exponentially increasing of RES in the system. And, based on the cited paper, all case studies are worth the investing of the proposes above, the Hydrogen Energy Storage best for higher RES penetration and DC interconnectors better for lower RES penetration. It can be concluded that energy storage is the more suitable way for dealing with the increased back-up demand since convert stored energy into electricity provides a flexible power capacity, offsetting the inconvenient characteristics (variable and intermittent sources) of the wind and solar power [31].

With Energy Storage studies, Capacity Credit can also be studied. CC is usually used regarding wind power, and in the research *"Capacity credit assessment of wind power considering energy storage"* [32], ARMA (auto-regressive moving average) was used to create the wind power model using wind speed models. But instead of calculating the CC only with that, they used the energy storage to stabilize the fluctuations presented in this type of resource to try and have a more precise value. The authors tested their proposal in the IEEE-RTS (IEEE-Reliability Test System) and the method was verified effectively and accurately with this system data. They tested the impacts of different sizes of energy storage and, with more storage, better was the Capacity Credit as expected, however, energy storage is expensive and an optimum point in the selection of size was discovered [32]. Storage and variable resources have a strong connection since one can balance the other very well, improving Capacity Credits and improving economic investments.

In relation to methods used in Reliability Assessment, MCS is not the only method used, with Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) being the other two methods that can be applied. These three methods are part of the three probabilistic safety analysis (PSA) methods [33].

The FTA method is used to evaluate the causes and their respective combinations that lead to the system failure. This method is deductive, so it is based on the definition of the top event that represents an undesired occurrence and deducts the various interruptions connected that led to the top event [33].

In the RBD method, the base is a graphical representation of the systems components using blocks that are linked with each other depending on their effects on the system. With that, each block has its own reliability or unreliability and that can test their impacts on the system, as a sequence, and how often that can happen [33].

These three methods have some differences but produce about the same results. The FTA makes a quantitative evaluation, but its qualitative assessment is based on the calculation of MCS. In RBD and Monte Carlo methods, the quantitative reliability assessment is ensured by computing the failure probability of the system. The complexity of the FTA and RBD is increased with the size of the studied system. The MCS is better suited for complex systems but requires a larger number of samples [33].

These methods (FTA and RBD) won’t be used but nonetheless they are important to mention as they can, as well, be part of a reliability assessment.

The use of Well-Being has been growing because it gives that intermediate state that it’s very important as already referred to in this document and can be applied in almost everything. Regarding transmission network expansion or power system planning in general, for example, this method is shown to be effective and can be combined with the economic analysis [34] where the costs vs benefit can be analyzed, and that extra state (the marginal state) helps to give some handling and a more precise evaluation.

Similar to the work presented in this dissertation, in the [35], the authors use the Chronological MCS and the WBA for analyzing the impact of the replacement of a conventional generating unit by wind power generation. To study the intermittency, they used ARMA once more for modulating the wind power, simulating hourly wind speeds with the MCS. They used the IEEE-RTS and the results indicated that "*the system security level of a power system containing significant wind generation could deteriorate considerably, even though the specified system adequacy level is maintained to satisfy the long-term capacity planning reserve requirement*" [35]. Based on these conclusions, it's possible to understand the importance of analyzing both security and adequacy in the reliability assessment, since an adequate system is always safe and when considering intermittent sources, security risks are more at stake.

In *"Future generation adequacy of the Hungarian power system with increasing share of renewable energy sources"* [36], an adequacy assessment model was used to calculate the capacity credit of hydro and wind. Solar was also considered but as a very simplified approach since the solar installed capacity was too low and with no available data. The authors conclude, based on the values for the capacity credit, that wind energy sources were the most ideal to develop. That was based on the COPT constructed, considering a histogram of the wind power output. They also consider this method an approximate approach, since the information on wind/load correlation and the seasonal and diurnal patterns of wind were not considered. Still, despite these concerns, in an initial phase of RES development with limited amount of data, this approach can be justified [36].

All of these studies, besides further ones still being investigated as we speak, reflect that the focus is in high penetration of renewable resources, especially solar and wind. This presents some inconveniences but still are the best sources to archive the decarbonization (100% green energy sources), since are available all over the world and are infinite but present some impacts on the reliability and safety of the electric system.

Chapter 3. Developed Software Tool

To assess the reliability of power systems using WBA, a tool has been developed that implements two methods, the Chronological MCS and the Non-Chronological MCS, methods already explained in this dissertation.

The tool was developed in a MATLAB® environment, a mathematical computing software from MathWorks® that combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly [37].

Additionally, Microsoft Excel® spreadsheets were used to import all system data and export all results to create the possibility for even more detailed and accessible analysis on almost any computer with software capable of reading spreadsheets. That Excel page works like the interface of the program and is where the user fills it with all the data regarding the system.

With regards to the flowcharts, they were done using Lucidchart®, a visual workspace that combines diagramming, data visualization, and collaboration to increase understanding and drive innovation [38].

The following subchapters will, then, describe the implementation and the validation of the software tool.

3.1 Structure/Features

All the features are delineated and explained throughout this subchapter.

The Appendix A and B have some images and flowcharts to support the information as well a user guide for the program itself. Some images/flowcharts are repeated on the main body of this dissertation and in the appendices for user-friendly principles, since the text supports some of the pictures.

3.1.1 Input/Analysis File – Parameters

All input parameters for the algorithm are entered in an Excel book (Fig. 3.1/Fig. A.1), which has been designed intuitively, so that it can be filled quickly and easily by a user. Throughout the work book the user will find help messages and tips for guidance.

The file contains seventeen pages, where one is the Parameterization, thirteen are for the generating unit data (FOR, Capacity Outage, nominal power and number of groups) of each technology, one for the availability indexes, one for the demand vectors and the last one is for the generation vectors. In this dissertation, it is possible to work with generating unit data with infinite states (the user chooses how many states he wants).

Further explanation will be given in the following section.

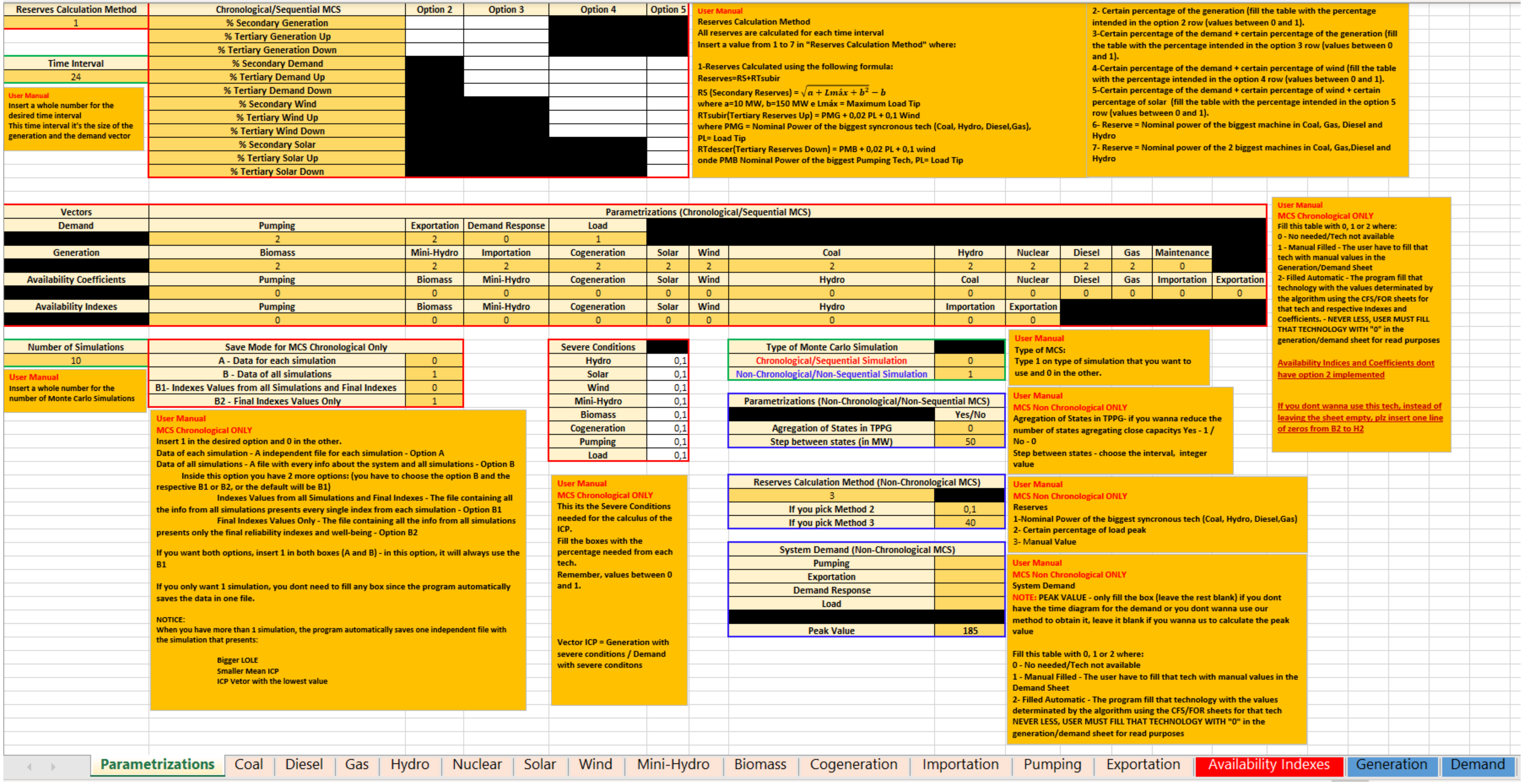

Fig. 3.1 - Parametrizations Page – Import Excel File.

3.1.2 Algorithm Implementation/Functionalities

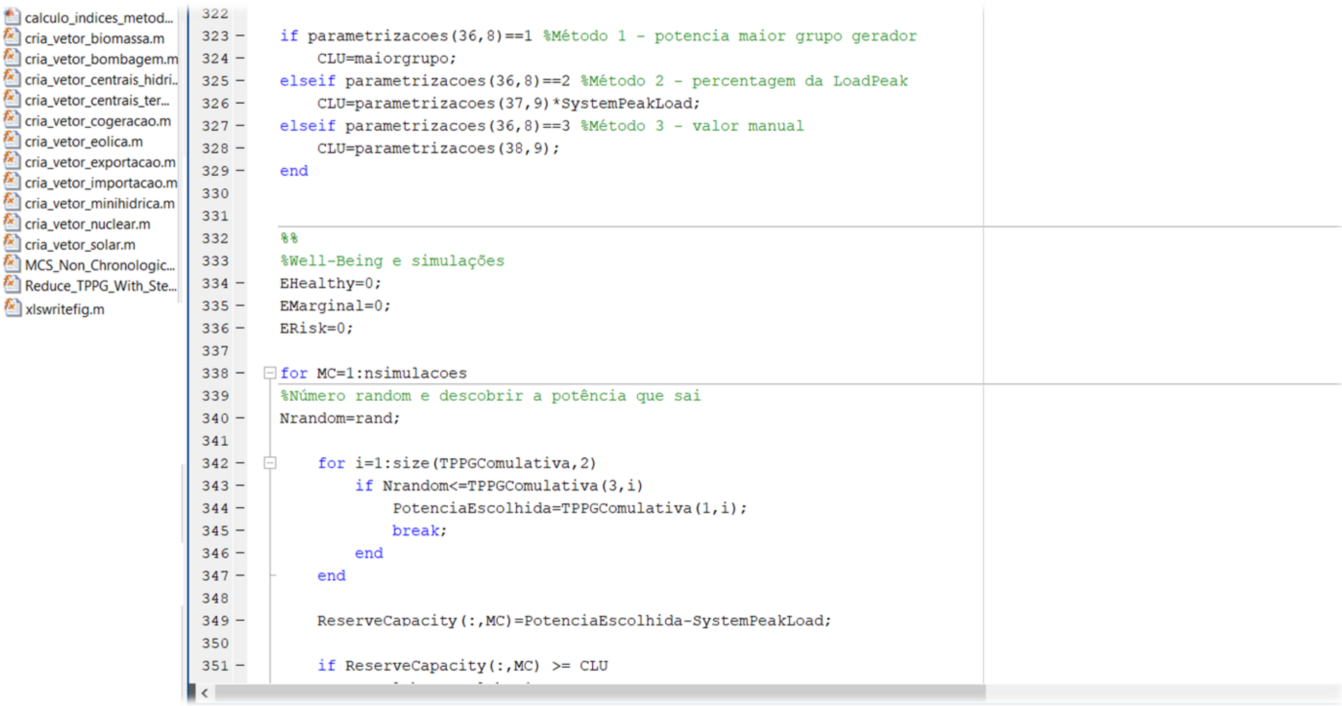

Fig. 3.2 - Example of part of the code.

The algorithm consists of the main code and thirteen functions (Fig. 3.2) that are responsible for the manipulation of data and calculations and are called throughout the main code.

To better explain all the features and how the process is done, the algorithm will be explained by detailing the two methods that have been implemented.

In both methods, the user must choose, in the respective fields of the parameterization page (Fig. 3.1/Fig. A1), the Time Interval (number that defines the length of the vectors) and the number of simulations. Beyond that, the pages of each desired technology must be filled with the generation unit data, remembering that all technologies can be modulated by an infinite number of states, so the user has complete control regarding the number of states [6].

The remaining fields to be filled in will be explained throughout this document with the help of flowcharts created (Appendix A and B).

When using the program, the import '.xlsx' file has some notes for the user which are recommended reading.

a. Chronological MCS Method

In this method, we have time vectors for generation and demand where the length can be a diagram for a day, month and/or year (the Time Interval variable shows the length). The final vector of the generation is formed by the sum of vectors of each of the technologies (that can assume positive or negative values) as in (3.1) and the final vector of the demand is calculated using (3.2).

$$\begin{gathered} Generation(t) = Biomass(t) + Mini\ Hydro(t) + Importation(t) + Cogeneration(t) + Solar(t) \\ + Wind(t) + Coal(t) + Hydro(t) + Nuclear(t) + Diesel(t) + Gas(t) - Maintenance\ All\ Tech(t) \end{gathered} \quad (3.1)$$

$$Demand(t) = Load(t) + Pumping(t) + Exportation(t) + Demand\ Response(t) \quad (3.2)$$

Regarding the Demand Response, remember that if you want to increase the demand, it must be positive and negative if the response is decreasing the demand.

All technologies, availability coefficients and availability indexes must be indicated in the parameterizations file (Fig. 3.1/Fig. A1) using the respective boxes in the Excel file.

a.1. Availability Coefficients

These coefficients are defined in all technologies, for each power plant, can be inserted by the user on each Excel page or can be made by the MATLAB (Fig. A3) (the code its ready for it, but a function has not yet been implemented, but it will be discussed in future work what can be done). One example for this function is estimating the availability of a given resource and that can be done based by a statistical analysis of existing data or using forecasting tools.

These can represent maintenance aspects and/or breakdowns.

a.2. Availability Indexes Vector

Availability Indexes are available for the following technologies: Pumping, Biomass, Mini Hydro, Cogeneration, Solar, Wind, Hydro, Importation and Exportation.

Like Availability Coefficients, they can be manually entered by the user (in the Availability Coefficients page) or can be created by MATLAB (Fig. A4). The code is also ready for it, but a function has not yet been implemented. These indexes are vectors with the length defined by the variable Time Interval. They can represent unusual unavailability's/variations/shortages in the primary source not considered in the availability coefficients, or extreme situations that may be interesting to simulate, like a drought, or even to simulate the variability of a given resource due to market or other issues (like variable availability of interconnections, e.g.).

As availability coefficients and availability indexes may be built with different sources of data/information, and may also be the target of different kinds of studies, it was decided to have two different data sets instead of a single one representing the availability for the different resources.

a.3. Vector of each Technology

Time vectors representing the contribution of each technology can be manually entered by the user or created automatically by a MATLAB function developed in the framework of this work and using the unit data entered in the corresponding worksheet. This function uses the Unit data of each tech (Fig. A2) and generates a random number ($r \in [0,1]$) for each group and each power plant (e.g. 2 centrals, one with 3 groups and another with 1 group, r will be generated 4 random numbers) and then it compares r with the FOR. The algorithm for determining the contribution of each group (PG_{gc}) with three-states is as follows:

g – Represents the group;

c – Represents the central;

r_{gc} – Random number for group g of the central c;

CFS_{gc} – Capacity outage for the group g of the central c;

FOR_{gc} – FOR of the group g of central c;

PN_{gc} – Nominal power of group g of central c;

Unit Data:

Capacity Outage [MW]	P_{gc-1}	P_{gc-2}	P_{gc-3}
FOR	FOR_{gc-1}	FOR_{gc-2}	FOR_{gc-3}

Table 3.1 - Unit Data Explication.

with:

$$FOR_{gc-1} + FOR_{gc-2} + FOR_{gc-3} = 1 \qquad (3.3)$$

$$P_{gc-1} > P_{gc-2} > P_{gc-3} \qquad (3.4)$$

and usually:

$$P_{gc-1} = PN_{gc} \text{ and } P_{gc-3} = 0 \qquad (3.5)$$

Generate r_{gc};

Case r_{gc}:

$$\leq FOR_1 \;\Rightarrow\; PG_{gc} = PN_{gc} - P_1 \qquad (3.6)$$

$$> FOR_1 \wedge \leq (FOR_1 + FOR_2) \;\Rightarrow\; CFS_{gc} = P_2\,;\; PG_{gc} = PN_{gc} - P_2 \qquad (3.7)$$

$$> (FOR_1 + FOR_2) \wedge \leq (FOR_1 + FOR_2 + FOR_3) \;\Rightarrow\; CFS_{gc} = P_3\,;\; PG_{gc} = PN_{gc} - P_3 \qquad (3.8)$$

The following Fig. 3.3 shows how the comparison works:

Nominal Power = 200 MW

Capacity Outage [MW]	200	100	0
FOR	0.1	0.1	0.8

$$r_{gc} \leq 0.1 \Rightarrow CFS = 200$$
$$0.1 < r_{gc} \leq 0.2 \Rightarrow CFS = 100$$
$$0.2 < r_{gc} \leq 1 \Rightarrow CFS = 0$$

Fig. 3.3 – Example of the Algorithm.

$$\text{Power} = \text{NominalPower} - \text{CFS} \qquad (3.9)$$

The Out of Order capacities are manipulated using equation 3.9 for obtaining the Power contribution of that group/Power Plant. After that, the value obtained is multiplied by the Availability Coefficient corresponding to that Power Plant.

This process is repeated for all groups and power plants of the respective tech and the sum of all obtained Power is the first value of the respective tech (3.10).

$$\text{PowerTotal} = \Sigma\, \text{Power} \qquad (3.10)$$

This entire process is repeated for each time interval until the vector of a particular tech is complete [39].

Once the vector of each tech is completed, they are multiplied by the vectors of the Availability Indexes, thus obtaining the final vector for each technology.

Then, the equations 3.1 and 3.2 are applied and it results in the final vector of the Generation and Demand, respectively (Fig. 3.4/Fig. A7).

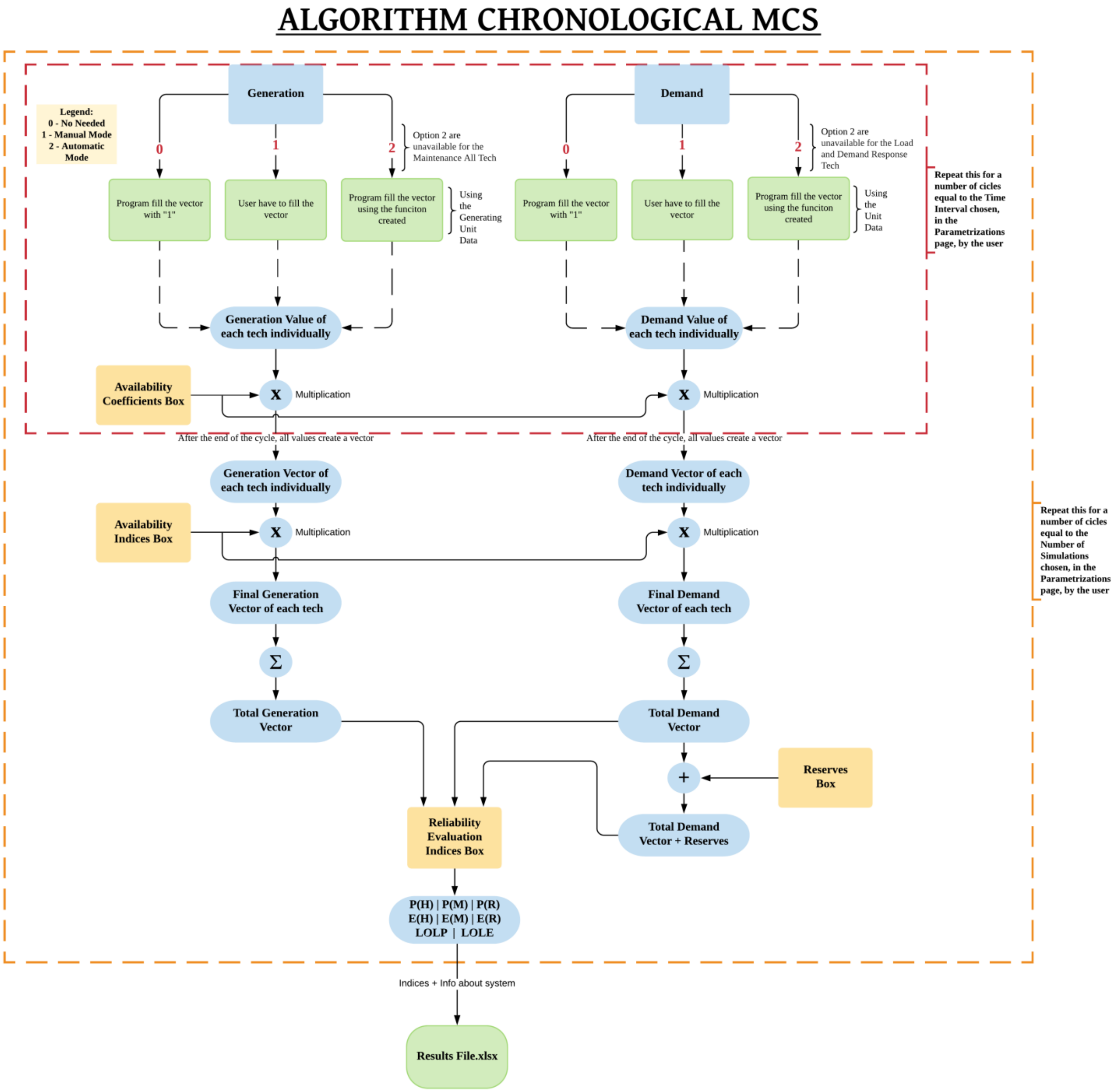

Fig. 3.4 – Chronological MCS Flowchart.

a.4. Reserves

As regards to the reserves, as already described in this document, we have three types of reserves, but in the algorithm implementation, two types are implemented, the Secondary Reserves (RS) and Tertiary Reserves which are then divided into two subcategories: Tertiary Reserves Up (RTup) and Tertiary Reserves Down (RTdown). The final reserves are calculated using 3.11.

$$\mathrm{Reserves} = \mathrm{R}S + \mathrm{RTup} \qquad (3.11)$$

To allow the user more freedom, seven methods for calculating the reserves were implemented (Fig. A5):

Method 1 > RS, RTup and RTdown are calculated using the following equations [40]:

$$\mathrm{RS} = \sqrt{\mathrm{a} + \mathrm{Lmax} + \mathrm{b}^2} - \mathrm{b} \quad (3.12)$$

$$\mathrm{RTup} = \mathrm{PMG} + (0.02 * \mathrm{PL}) + (0.1 * \mathrm{Wind}) \quad (3.13)$$

$$\mathrm{RTdown} = \mathrm{PMB} + (0.02 * \mathrm{PL}) + (0.1 * \mathrm{Wind}) \qquad (3.14)$$

Where:

a and b are constants of 10 MW and 150 MW, respectively

$Lmax$ – Maximum Load

PL – Load Tip

PMG – Nominal Power of the biggest Synchronous Tech (Coal, Hydro, Diesel and Gas)

PMB – Nominal Power of the biggest Pumping Tech

Wind – Wind Generation

Method 2 > RS, RTup and RTdown are an independent percentage for each, chosen by the user, of the total generation.

Method 3 > RS, RTup and RTdown are an independent percentage for each, chosen by the user, of the total generation and the total demand.

Method 4 > RS, RTup and RTdown are an independent percentage for each, chosen by the user, of the total demand and the Wind generation.

Method 5 > RS, RTup and RTdown are an independent percentage for each, chosen by the user, of the total demand, the Wind generation and the solar generation.

Method 6 > Reserves are the nominal power of the biggest Synchronous tech in Coal, Gas, Diesel and Hydro.

Method 7 > Reserves are the nominal power of the two biggest Synchronous techs in Coal, Gas, Diesel and Hydro.

a.5. Reliability Indexes Calculation

Finally, the last part of this method is the reliability indexes calculation and assessment (Fig. 3.5/Fig. A6). To calculate the indexes, we need three vectors: Final Generation Vector, Final Demand Vector and the Vector containing the sum of the Reserves Vector with the Final Demand Vector.

For the Well-Being Analysis, each element of the above vectors goes through the following analysis [24], [39]:

$$\text{TotalDemand} + \text{Reserves} < \text{TotalGeneration} \quad (3.15)$$

$$\text{TotalDemand} + \text{Reserves} > \text{TotalGeneration} \;\&\&\; \text{TotalDemand} < \text{TotalGeneration} \quad (3.16)$$

$$\text{TotalDemand} > \text{TotalGeneration} \quad (3.17)$$

If the 3.15 is true, the system is on a Healthy state, 3.16 is associated to the Marginal state and finally, the 3.17 defines the Risk state, (see Fig. 3.5).

```
if 3.15 is true then
    E(H)=E(H)+1;
else
if 3.16 is true
    E(M)=E(M)+1;
else
    E(R)=E(R)+1;
end.
```

After all the elements pass the analysis, the E(H), E(M) and E(R) are obtained.

$$\mathrm{P(H)} = \frac{\mathrm{E(H)}}{\mathrm{Time\ Interval}} \qquad (3.18)$$

$$\mathrm{P(M)} = \frac{\mathrm{E(M)}}{\mathrm{Time\ Interval}} \qquad (3.19)$$

$$\mathrm{P(R)} = \frac{\mathrm{E(R)}}{\mathrm{Time\ Interval}} \qquad (3.20)$$

where:
E(H) is expected/duration of being in Healthy State
E(M) is expected/duration of being in Marginal State
E(R) is expected/duration of being in Risk State
P(H) is probability of being in Healthy State
P(M) is probability of being in Marginal State
P(R) is probability of being in Risk State

With them, and using 3.18, 3.19 and 3.20, the probability of the system be in a determinate state is obtained. Having the WBA indexes, the Loss of Load indexes are easy to attain, LOLP is equal to the probability of the system be in the Risk state, as already said in this document. With LOLP, using the equation 2.8, LOLE is obtained.

This is the process of a single simulation of the Chronological MCS. This can be repeated as many times as necessary to obtain an adequate error margin, and with all the data collected, it is possible to study the evolution of the indexes and capture some information about each run, for example, which one had the worse/best values. Furthermore, the results obtained are stored into two files, one with all the information about all simulations and one with the simulation with the best LOLE value.

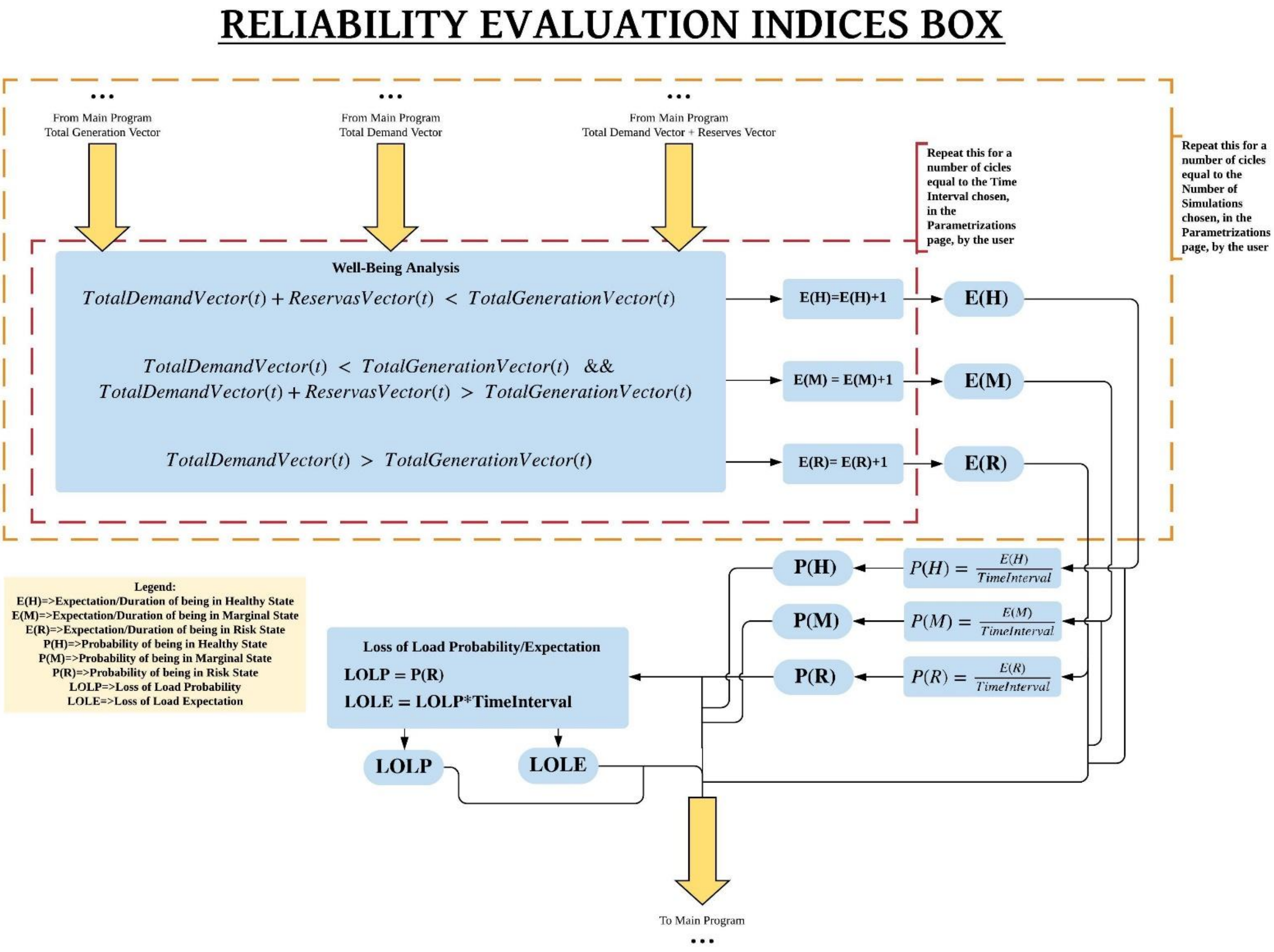

Fig. 3.5 – Reliability Indexes Flowchart.

b. Non-Chronological MCS Method

To start this method, the first step is to get the system generation model (COPT). For this, the program gathers all the Generating Unit Data of each tech in a big matrix (the user just fills the pages of the technologies he wants, leaving the others empty). Afterwards, the tool combines all possible states forming the COPT of the system (Fig. 3.6/Fig. B3).

With the COPT done, the user has the control of whether to aggregate or not the COPT states, to reduce its size, by entering the desired step between states (Fig. B1).

Then, the COPT will be manipulated to have the cumulative probabilities, and all states with probabilities under or equal to 10^{-6} will be removed, this way obtaining the Final COPT (Fig. 3.6/Fig. B3).

Still, one needs to analyze the demand and reserves before advancing to the reliability evaluation.

b.1. Demand

For this method, the Peak Load value is required, which can be given directly by the user or calculated within the program. In this calculation, the different vectors that create the final demand vector are given or calculated by the same process as in Chronological MCS, and the maximum value of that vector is the Peak Load value (Fig. 3.6/Fig. B3).

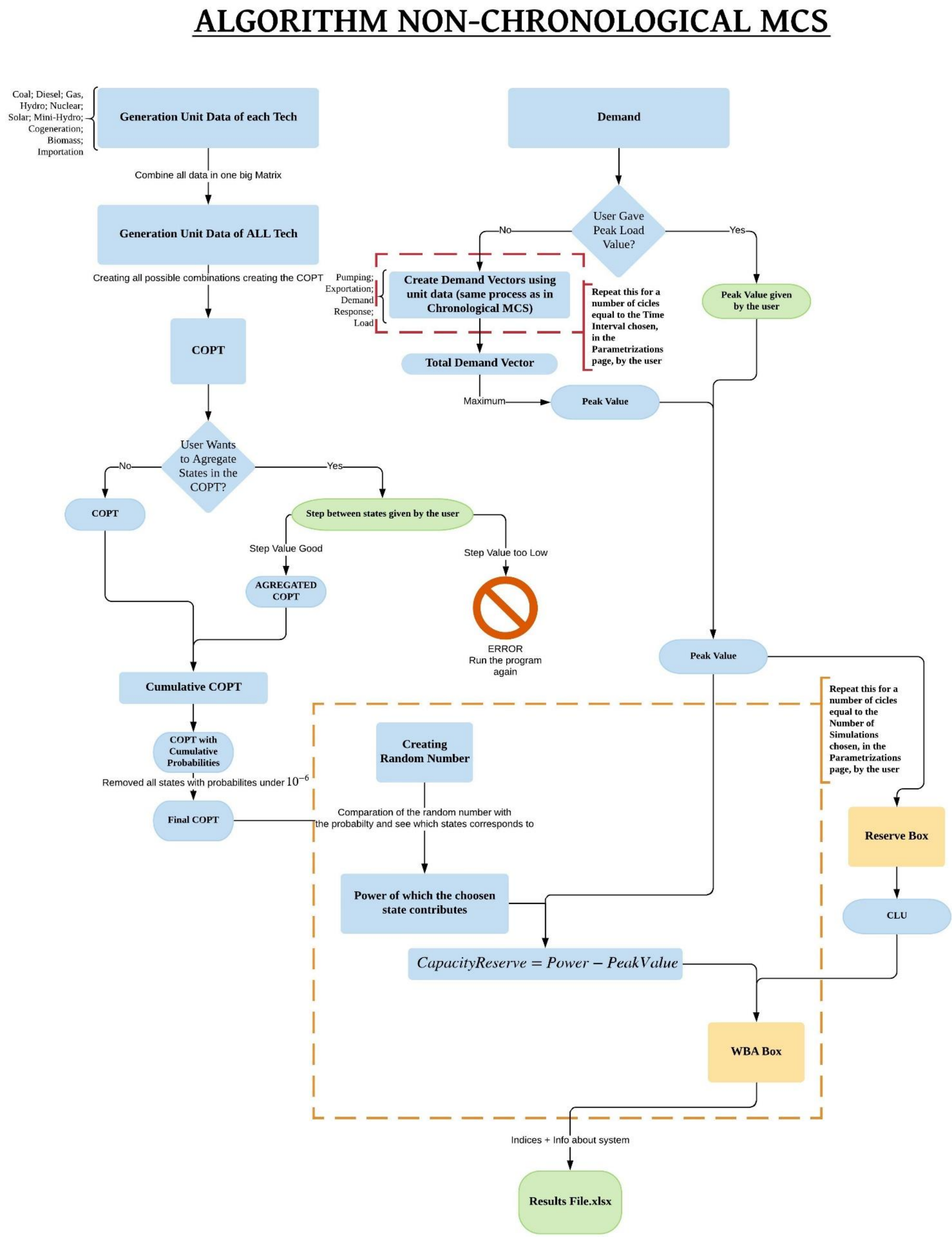

Fig. 3.6 – Non-Chronological MCS Flowchart.

b.2. Reserves

Regarding the reserves, there are three calculation methods which are as follows (Fig. B2):

Method 1 > Reserves are the nominal power of the biggest Synchronous tech in Coal, Gas, Diesel and Hydro.

Method 2 > Reserves are an independent percentage for the Load Peak.

Method 3 > Reserves are a Manual Value chosen by the user.

At this point, a random number (r) between 0 and 1 is generated, it is compared with the COPT probabilities and the state sampled, and the corresponding value of the Power are found (the later as in the Chronological MCS).

With that, the reserve capacity can be calculated. (3.21)

$$\text{Reserve Capacity} = \text{Power} - \text{Peak Load} \qquad (3.21)$$

b.3. Well-Being Analysis

Now, with all the aforementioned variables up and running, the program is ready to start the WBA, considering the following steps:

$$\text{Reserve Capacity} \geq \text{Reserves} \quad (3.22)$$
$$\text{Reserve Capacity} < \text{Reserves} \ \&\& \ \text{Reserve Capacity} > 0 \quad (3.23)$$
$$\text{Reserve Capacity} < 0 \qquad (3.24)$$

If the 3.22 occurs, the system is on Healthy state, 3.23 is on the Marginal state and finally, the 3.24 is on the Risk state [24].

Inbetween the generation of the random number and this last step, this process repeats itself several times equal to the number of simulations decided by the user. (Fig. 3.7/ Fig. B4)

After that, the final count of the number of simulations that were in Healthy State (E(H)), Marginal State (E(M)) and Risk State (E(R)) are settled. Then, we can calculate the probabilities of being in those respective states (3.25, 3.26 and 3.27).

$$\mathrm{P(H)} = \frac{\mathrm{E(H)}}{\text{Number of Simulations}} \qquad (3.25)$$

$$\mathrm{P(M)} = \frac{\mathrm{E(M)}}{\text{Number of Simulation}} \qquad (3.26)$$

$$\mathrm{P(R)} = \frac{\mathrm{E(R)}}{\text{Number of Simulation}} \qquad (3.27)$$

Here is the end of the Non-Chronological MCS (Fig. 3.6/Fig. B3) that is a bit different to the Chronological one, as already expected.

In this type of studies, with this tool and with the methods in themselves, it is possible to compare different simulations with different types of techs, and that can enable investigations like the consequences of the increased penetration of RES in the system, the consequences of the loss of the biggest power plants in the system, among others.

As regards to the Availability Indexes and Coefficients, it will be discussed later in a future work section, but for good values, a good history of the respective technology is necessary.

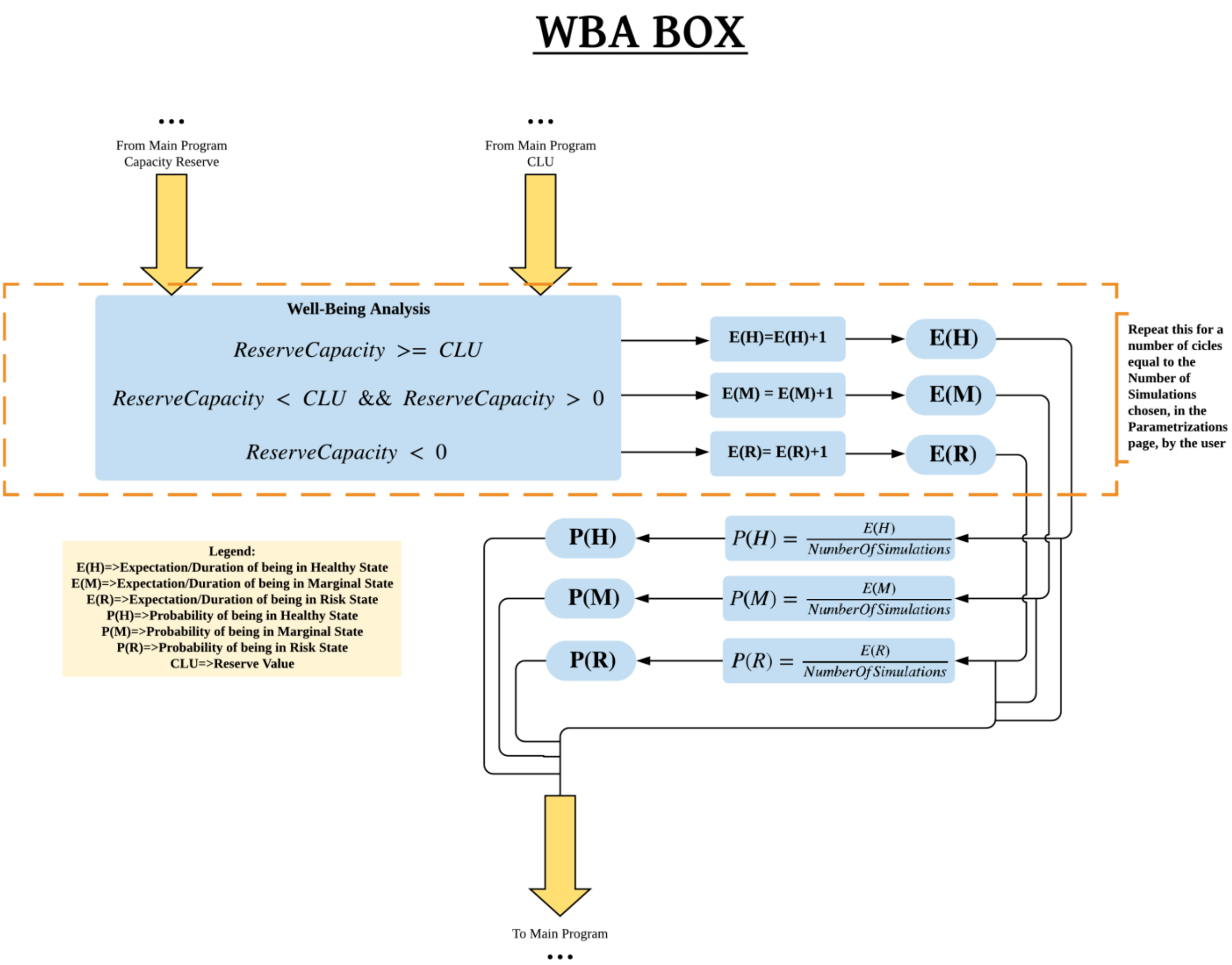

Fig. 3.7 – WBA Flowchart.

Remember, in the Appendix A and B, some helpful instructions (as a User Guide) are provided for each method, along with some figures and flowcharts for better comprehension.

3.2 WBA Validation

For a correct use of the tool in future case studies, the implementation must be validated first. With this in mind, was used an article "*Well-being Analysis for Generating System Expansion Planning*" [24] which uses an algorithm with some similarities to the one created in this work, as a test base where some simulations done in the referred paper were replicated.

This paper uses the Roy Billinton Test System (RBTS) which is a small but powerful education-based reliability test system which was developed by Roy Billinton for use in the power system reliability research program [24].

The RBTS has six buses, nine transmission lines and eleven generating units. The total generating capacity is 240 MW and the annual peak load of the system is 185 MW. The generation data for RBTS is given in Table 3.2 [24], considering a two state model as the paper states.

Table 3.2 – Generating Unit Data of the RBTS.

Type	No. of units/ groups	Nominal Power [MW]	Out of Order Values [MW]	FOR	Out of Order Values [MW]	FOR
Thermal	2	40	40	0.0299	0	0.9701
Thermal	1	10	10	0.0250	0	0.9750
Thermal	1	20	20	0.0102	0	0.9898
Hydro	4	20	20	0.0148	0	0.9852
Hydro	2	5	5	0.0102	0	0.9898
Hydro	1	40	40	0.0201	0	0.9799

The paper doesn't say how many runs they've done, so a substantial number will be chosen to test the created algorithm. Regarding the reserves, the paper considers the reserves equal to the capacity of the largest unit, so it will be used the method 1 in the Non-Chronological MCS and the method 6 in the Chronological MCS.

We don't have load diagrams, so we will consider the load vector equal to the Load Peak for each time interval, in the Chronological MCS.

The WBA will be presented in the following table (Table 3.3). The remaining results are shown in Appendix C (Fig. C1 and Fig. C2).

Table 3.3 – Calculated Well-Being Indexes.

Paper Values with unknown simulations	Our Values with 20 000 simulations Chronological MCS	Our Values with 20 000 simulations Non-Chronological MCS
$\mathbf{P(H) = 0.859761}$	$\mathrm{P(H)} = 0.860096$	$\mathrm{P(H)} = 0.8581$
$\mathbf{P(M) = 0.133025}$	$\mathrm{P(M)} = 0.13285$	$\mathrm{P(M)} = 0.1341$
$\mathbf{P(R) = 0.007213}$	$\mathrm{P(R)} = 0.007054$	$\mathrm{P(R)} = 0.0078$

It is possible to see the similarities between the values and have a good idea that the algorithm works. In the Healthy State, the differences are -0.04% and 0.19% for Chronological MCS and Non-Chronological respectively, in the Marginal State the differences are 0.13% and -0.81. But, for a final test, the paper tests an increase by 5% per year of the Peak Load [24]. Results presented in the Table 3.4.

Table 3.4 – WBA indexes considering 5% load growth per year – results.

Year	Peak Load [MW]	P(H)	P(M)	P(R)
1	194.25	0.838146	0.152820	0.009032
2	203.96	0.000000	0.920418	0.079581
3	214.16	0.000000	0.918893	0.081106
4	224.87	0.000000	0.859761	0.140238
5	236.11	0.000000	0.821272	0.178727

As expected, and with no additional capacity, the load evolving like this degrades the electrical system reliability indexes. In the fourth and fifth year, the probability to be in the Risk State is so high, that almost in 1/5 of the year, there is the risk of non-supplying some demand.

The following results are from the created program (Table 3.5 and Table 3.6):

Table 3.5 – Calculated WBA indexes considering 5% load growth per year – Chronological MCS.

Year	Peak Load [MW]	P(H)	P(M)	P(R)
1	194.25	0.838178	0.152893	0.008929
2	203.96	0.000000	0.920575	0.079425
3	214.16	0.000000	0.919222	0.080778
4	224.87	0.000000	0.86006	0.13994
5	236.11	0.000000	0.821362	0.178638

Table 3.6 – Calculated WBA indexes considering 5% load growth per year – Non-Chronological MCS.

Year	Peak Load [MW]	P(H)	P(M)	P(R)
1	194.25	0.83965	0.1515	0.00885
2	203.96	0.000000	0.9187	0.0813
3	214.16	0.000000	0.9163	0.0837
4	224.87	0.000000	0.85955	0.14045
5	236.11	0.000000	0.8197	0.1803

Part of the above results are in Appendix C (Fig. C3 and Fig. C4).

The results obtained are pretty much the same and, as a result, we can conclude that the algorithm is validated and is ready to be implemented in other case studies.

Chapter 4. Porto Santo Case Study

Porto Santo is a small island of the Madeira Archipelago and is part of the Portuguese territory. It lies in the Atlantic Ocean, around 1000 km away from mainland Portugal and about 70 km from the archipelago ‘s main island, Madeira, and its capital is the city of Vila Baleira.

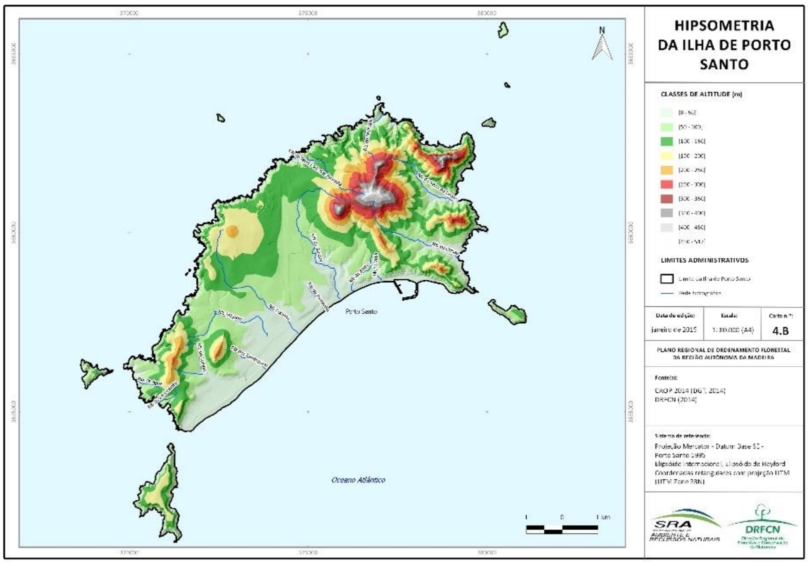

Fig. 4.1 – Hypsometric Map of Porto Santo [41].

As regards to the climate, it is dry and stable with a temperature that doesn’t vary much inbetween seasons. Porto Santo has 5,483 habitants (2011) spread over 42.48 km^2. The main source of income is tourism [42]. With tourism, the summer can bring to the island around 15,000 people and around 500 in the winter months [43].

Being isolated and relatively small, it’s like an open-air research laboratory [44] and already has ambitions for being an island free of fossil fuels. With that in mind, the project “Smart Fossil Free Island” is being implemented, as previously mentioned.

One of the methods being already funded with four million euros already invested, is energy storage using batteries, giving the possibility to be used in peak loads or when the primary source of sun and wind power is not available in the amount needed [44].

Regarding the production of electricity, Porto Santo’s power plant went into operation in 1992 and has six groups (Table 4.1) of diesel and biodiesel [45].

Table 4.1 – Thermal units.

Groups	Nominal Power
1 and 2	3.5 MW each
3, 4, 5 and 6	4 MW each

The groups 1 and 2 are deactivated and are only used in extreme emergency [45].

In relation to renewable sources, wind and solar are the only ones explored with two wind sites and 20 sun sites, including micro production (Table 4.2) [46].

Table 4.2 – Wind and Solar units.

Technology	Nominal Power
Wind	1.1 MW total
Solar	2.62 MW total

Also, the generation/demand diagram is available for the year 2015[1] (Fig. D1) and it's going to be used in this work.

4.1 Simulations and Results Analysis

To do the analysis, the Chronological MCS was used with 500 runs of each simulation and the reserves were calculated using method 1. Along with that, this analysis is based in the fact that the transmission and distribution network are considered 100% reliable.

As regards to the modulation of these resources, thermal will be modulated in a Two-State Markov Model as their availability is almost always guaranteed, except for any malfunction or scheduled maintenance. The FOR value is unknown, so the value will be obtained from one of the thermal groups of the RBTS (FOR = 0.02).

For modeling wind and solar, several approaches were analyzed.

[1] Provided by the supervisor

4.1.1 1st Approach

In this first approach, an eleven-states model for solar and wind was created and, considering the generating data from the year 2015, the residence time in each state is calculated. The resulted unit data is presented in the following table (Table 4.3):

So, in conclusion, the main focus is not to evaluate only the failure rate of the machine but the source since, as it is common sense, the sun and wind aren't available at all times.

Table 4.3 – Eleven-State Markov Model Generating Unit Data of Solar and Wind.

Solar		Wind	
Capacity Outage [MW]	**FOR**	**Capacity Outage [MW]**	**FOR**
0	0	0	0
0.262	0	0.11	0
0.524	0	0.22	0
0.786	0.017237	0.33	0.000114
1.048	0.031735	0.44	0.011187
1.31	0.044292	0.55	0.018607
1.572	0.076256	0.66	0.043151
1.834	0.093379	0.77	0.130251
2.096	0.086644	0.88	0.190297
2.358	0.146233	0.99	0.375913
2.62	0.504224	1.10	0.230479

Solar will have a manual availability index vector (Table D1) where it was considered the value 0 for the night time hours and 1 for the daytime hours, considering the average daylight time between 8 A.M to 7 P.M. In other words, during the night, the generation is always 0 and during the day, it can assume one of the values presented in the state model.

The following table (Table 4.4) presents the results with this approach for various tests, where the capacity installed was manipulated to see its impact on the WBA indexes and on the Loss of Load indexes. In the Table 4.4, the number before "Wind Group" and "Solar Group" means the test number.

Table 4.4 – Results of the 1st Approach.

Nº	Tests	P(H)	P(M)	P(R)	LOLP	LOLE [h/year]
1	4 Diesel Groups 1 Solar Group 1 Wind Group	0.999241324	0.000752511	6.16438E-06	6.16438E-06	0.054

2	3 Diesel Groups 1 Solar Group 1 Wind Group	0.980500228	0.01919863	0.000301142	0.000301142	2.638
3	2 Diesel Groups 1 Solar Group 1 Wind Group	0.65291484	0.336728311	0.010356849	0.010356849	90.726
4	3 Diesel Groups 2 Solar Group 1 Wind Group	0.982175799	0.01755	0.000274201	0.000274201	2.402
5	3 Diesel Groups 1 Solar Group 2 Wind Group	0.982719406	0.017023288	0.000257306	0.000257306	2.254
6	3 Diesel Groups 2 Solar Group 2 Wind Group	0.984323744	0.015450228	0.000226027	0.000226027	1.98
7	3 Diesel Groups 3 Solar Group 3 Wind Group	0.98763516	0.012192237	0.000172603	0.000172603	1.512
8	3 Diesel Groups 4 Solar Group 4 Wind Group	0.990294977	0.009580137	0.000124886	0.000124886	1.094
9	3 Diesel Groups 1 Solar Group 11 Wind Group	0.995164612	0.004790639	4.47489E-05	4.47489E-05	0.392
10	3 Diesel Groups 11 Solar Group 1 Wind Group	0.988480365	0.011348858	0.000170776	0.000170776	1.496
11	3 Diesel Groups 1 Solar Group 21 Wind Group	0.99878105	0.001214612	4.3379E-06	4.3379E-06	0.038
12	3 Diesel Groups 31 Solar Group 1 Wind Group	0.988919635	0.010911416	0.00016895	0.00016895	1.48
13	3 Diesel Groups 41 Solar Group 1 Wind Group	0.988884247	0.010960046	0.000155708	0.000155708	1.364
14	3 Diesel Groups 51 Solar Group 1 Wind Group	0.988972603	0.01085274	0.000174658	0.000174658	1.53
15	0 Diesel Groups 31 Solar Group 61 Wind Group	0.886661187	0.113327854	1.09589E-05	1.09589E-05	0.096

In the third simulation, the number of thermal production sources were cut in half and that reflected in a LOLE very highly (90.726 h/year). This value means that in one year, we had almost four days where we cannot fully supply the demand and that created high costs and risks. In the WBA, you see a decrease of the probability of being in the Healthy State by almost 35%, which implies that the Marginal State went a lot higher and, in this situation, if an accident or any forced maintenance would happen to any component, the system would not have the ability to totally satisfy the demand, decreasing even more the reliability of this system.

One of the things that is also possible to notice, is that in the 4th and 5th simulation the wind power has slightly more impact on improving the reliability indexes. This happens despite the higher contribution of solar for the generation diagram (Fig. D1) and also with a higher nominal power of solar groups. This approach reflects that wind has a better impact in reliability indexes. This shows that the higher demand zones occur at night where the solar power is always zero, and that the wind power can be zero or not and be the reason why less installed capacity can have more impact.

The 9th and 10th simulations are worth mentioning, as these reinforce the idea discussed above.

With the addition of 20 wind groups (11th simulation), the LOLE is even better (so it's lower) to the base case as well the rest of the indexes. So, this approach, gives us an equivalent of 20 wind groups (22 MW) for 1 group of thermal (4MW), which means that the CC of wind power generation is 18.18% (4.1) and that

$$\begin{aligned} 100\% &=> 22\ \text{MW}\ (20 * 1{,}1) \\ \text{x} &=> 4\ \text{MW} \\ \text{x} &= 18.18\ \% \end{aligned} \tag{4.1}$$

means that for a wind capacity installed of 22 MW, we can avoid the installation of 4 MW of conventional power.

Now, for the solar power, with this approach, it is impossible to have a value for the CC because when you reduce by 4 MW the diesel capacity, the indexes already go up. With only solar power, they are capped because most of load-peaks occurs in summer nights where the solar power can't help, so only increasing the quantity of solar capacity, the indexes (LOLE) will float between 1.30 and 1.55, as is possible to see in the 12th, 13th and 14th simulation.

$$31 * 2.62 \text{ MW} = 81.22 \text{ MW}$$
$$61 * 1.1 \text{ MW} = 67.1 \text{ MW} \qquad (4.2)$$

So theoretically, to replace all diesel units (16 MW) and leave them only as emergency purposes, 67.1 MW of wind and 81.22 MW of solar (4.2) seems to be enough, as it is possible to see in the 15th test where the value of LOLE is almost as low as the LOLE in the real case. Of course, these are enormous values of capacity installed since the load peak registered its 7.27 MW (in year 2015).

Furthermore, even with low value of LOLE, it's possible to notice a difference of 11% in the P(H) and that proves how fragile the system can be only with variable resources available because in the case of an emergency this system will breakdown more often that the actual case where the P(H) is almost 100%. This means that it is not possible to go 100% green without other technologies supporting solar and wind generation-based units.

Must be said that this approach loses the sequence of the unavailability of the resource, so an availability vector based on real data it's a must for real and trustworthy values.

4.1.2 2nd Approach

The wind and solar generation data available is taken into account, but as a negative demand. This approach is well suited to retrospective analysis since enough data is available.

The results are in the following table (Table 4.5).

Table 4.5 – Results of the 2nd Approach.

Nº	Tests	P(H)	P(M)	P(R)	LOLP	LOLE [h/year]
1	4 Diesel Groups	0.999290411	0.000700685	8.90411E-06	8.90411E-06	0.078
2	3 Diesel Groups	0.981823744	0.0179	0.000276256	0.000276256	2.42
3	2 Diesel Groups	0.677679452	0.312918721	0.009401826	0.009401826	82.36

Even working with a negative demand, the system presents higher values of LOLE when you retire one of the diesel groups and present a degradation in the P(H) of the system. The improvement is not too high when compared with the approach before, since the capacity installed and respective production are too low and occur in moments where the demand is already low, the impact of removing diesel groups stays almost the same. In this retrospective approach, the generation that occurs is always taken into account in the calculations, hence the best results.

4.1.3 3rd Approach

A different approach was considered. In this one, the Capacity Credit of the intermittent sources in the Porto Santo was obtained using the following evaluation by the Southwest Power Pool (SPP): the top 10% of the load values are taken from the data available and its respective wind and solar generating values and then, the 85th percentile is calculated, and that is considered the capacity value for the respective resource [47].

Using this method, the CC for both sources is 0, which reinforces the idea that in the case of Porto Santo is not possible to have a 100% green power system. This happens mainly because the availability of variable resources does not match the demand profile, the capacity installed and the generation of both these resources are both too low in comparison to the thermal generation. As the load-peaks happen during summer nights, as this island depends on tourism and its beaches, and in the summer nights, the tourists are in hotels, bars, etc., leading to more demand. This causes a null CC since the load-peaks happen at night when the sun power is null and the wind is too low, since Porto Santo is not very windy.

In addition, it’s important to note that an adequate use of this method requires enough data, at least three years instead of just one[47].

Computing the CC of solar generation, taking into consideration the availability of the resource, the computed value will be low (0,0876532 = 8%) but higher than 0.

By analyzing these facts, this approach can support that solar power has a better contribution on reliability indexes and is best suited for replacing some thermal units, but methods regarding energy storage must be implemented.

4.2 Discussion

One of the conclusions of these simulations, is that it is possible to see in the generating diagram both solar and load are higher in the summer days, as expected. Considering the third approach presented above, that the solar contribution when you need it the most is appreciable, and considering that the unavailability during the summer nights can be solved with storage implementation (as already mentioned), solar generation (with storage) may be a solution to Porto Santo.

By comparing the approaches in the section above, one can see some different values and perspectives, since some of them consider the difference between the availability of wind and solar power using existent generating diagrams, while Porto Santo has a lot more production from the sun than from the wind, even though wind power can be available both day and night.

Chapter 5. Conclusion

The main goal of this work, as suggested by its title, was to do a reliability assessment regarding the increase of renewable energy in a specific electrical power system, in this case, the one in Porto Santo island, Madeira Archipelago, Portugal.

But to achieve that, a tool had to be created. So after some investigation about how to implement these methods, a program was created in a MATLAB environment. This tool is a means to an end, so to speak. As my dissertation supervisor always reminded me, *"to build a good boat, you must first build the best shipyard possible"*.

As so, during this work, the algorithm is of paramount importance and has become the star of this dissertation, where much of the time devoted to the dissertation was spent in its development. It's important to have that in mind since the program was created with the intent of analyzing any system, not only the Porto Santo's one. And some characteristics can be highlighted:

- Versatility/flexibility to handle different generation and demand profiles;
- Various methods to calculate the reserves;
- The method chosen, the MCS is the most common and the most used in reliability assessment;
- Possibility to upgrade the program since some features can be customized and/or implemented;
- Well-Being Analysis that gives a better assessment since it incorporates a deterministic and a probabilistic consideration;
- Import and Export data through the Excel, which gives easy access to that data and can be used in other platforms for statistical analysis, for example.

Once the program was created, it was tested to see how it performed and, as it is possible to see in the section three of this document, the validation was a success.

After that, the program was ready to be implemented in the Porto Santo's case, giving us the results presented in the chapter four.

The project "*Smart Fossil Free Island"* can be a success since, with the analysis of these approaches, one can see that it is possible to have enough capacity installed of renewable energy to be total independent from fossil fuels. Using the Chronological MCS, we could produce enough power to supply all the demand, without any diesel units, while maintaining the WBA indexes and the Loss of Load indexes equal or even better than actual reality. The data used was based only on one year (2015), which is not perfect, and the results can have a slight error, because 1 year its not enough.

With the approaches applied, we noticed that the system today is not yet ready for giving up fossil fuel sources since the CC of each intermittent source is a key to have success on accomplishing an island free of fossil fuels.

Of course, the analysis only had the reliability as main focus, not thinking on how much it will cost, but with the data that we have, we can add that a good study about energy storage and demand response can help reduce that cost by a lot and increase its effectiveness.

Ultimately, the two main ideas that can be retained from this project, is that without storage, it is not possible to go 100% green, since the capacity credit of those sources its 0, and reliability, only with renewable energy, requires high investments.

The work developed in this dissertation contributed to my extensive knowledge on this topic and to the awareness that it is possible to have a reliable system only with renewable energy, even with the unpredictability of the main source.

5.1 Future Work

Since this work started with the implementation of a software tool, which took a lot of the time invested in this work, that allowed the reliability assessment of any power system, this dissertation can serve as a basis for the development of other studies on reliability and on the increase of renewable energy sources in any electric system.

However, there are some aspects viable for improvement in this work, such as:

- Building maintenance schemes to give the algorithm scheduled maintenance regime's values beyond equipment failures;
- Having more data (at least 5 years) will improve effectiveness, accuracy and reliability of the methods applied;
- Applying methods regarding energy storage to have better insight about the future of being free of fossil fuels;
- Consider wind and solar data info, like wind speed and profile, solar radiation, etc., in form of models, like the ARMA model, to allow the proposed algorithm to be more realistic, using prediction methods/software;
- Creating functions that can create availability indexes and coefficients for any source of power, improving even more the realism and the studies about the

prediction of indexes. Remembering that the code is already optimized and ready for the functions, only needing their implementation;

- Implementing different ways of assessing the contribution of renewable generation and its impacts on reliability indexes, e.g., considering a vector of states for variable generation, computed from available data;
- Making risk assessments is also important and this tool can be the base of those type of studies.

Besides all of that, as my dissertation supervisor always pointed out, to have “the juice” (the best) of this work, and from the tool created, it should be applied in other real and important cases, like the decommissioning of the Sines and Pego’s thermal power plants, in mainland Portugal.

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Appendix A – Chronological MCS

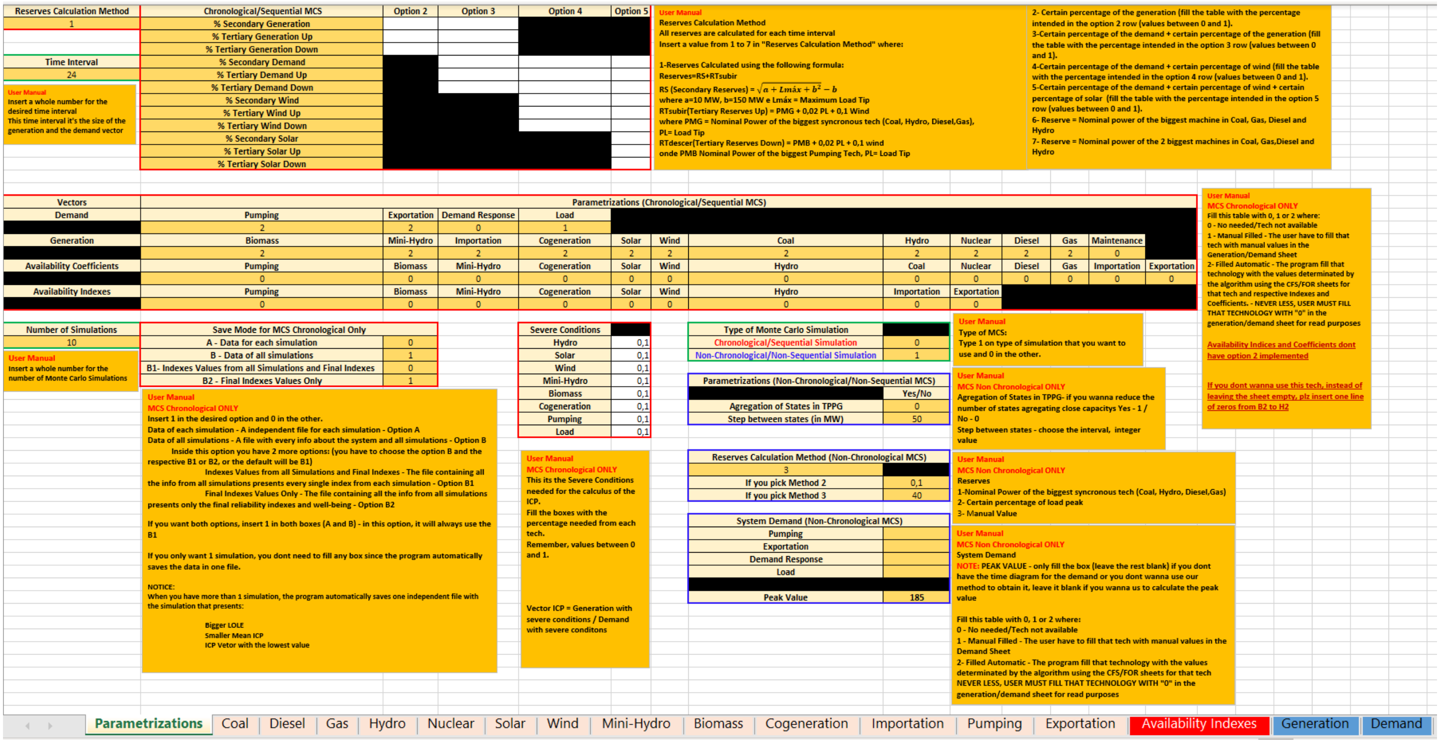


Fig. A1 – Parametrizations Page – Import Excel File.

User Guide Chronological MCS

As it is possible to notice, all the boxes with a **red outline** is for the Chronological MCS, a **blue outline** is for Non-Chronological MCS and a **green outline** is common in both methods. The *"Type of Monte Carlo Simulation"* box must be filled with 0 and 1 for the desired option, where 0 is NO and 1 is YES. For reading purposes, if the value 1 is on the Chronological MCS the user must put a 0 on the Non-Chronological MCS.

In this page (Fig. A1), the user must fill it with all the data intended for the algorithm to work properly. In the box *"Reserves Calculation Method"*, the user must fill it with a number between 1 and 7, representing which method intended for the reserve's calculation. For the options 2, 3, 4 and 5, the user must also fill the box on the right with the percentage wanted (so, values between 0 and 1), according to the option chosen (Fig. A5).

The *"Time Interval"* box is for the value of the time interval for your demand/generation diagram. In other words, it's the size of the vectors of each technology.

The “Vectors” box must be filled with 0, 1 or 2 where:

0 – *Tech not available*

1 – *Manual Values*

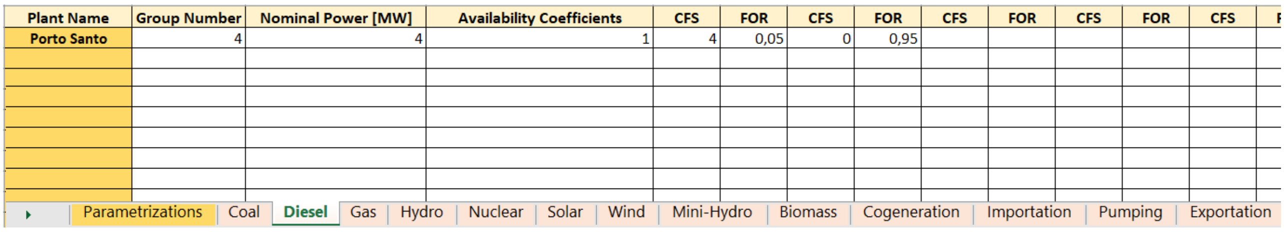
2 – *Automatic Values*,

as already explained in chapter three and in other flowcharts in this appendix (Fig. A7).

The *“Number of Simulations”* box must be filled with a value above 0 and represents the number of runs.

Under the *“Save Mode”* box, 0 represents NO and 1 represents YES. You can just choose one option (A or B), where in A, the program saves an excel file for each simulation run, and B, the program saves a unique file with all data where all the vectors of demand, generation, availability indexes and coefficients are mean vectors. Under option B, you have B1 or B2, after the user picks option B, B1 prints in the excel all indexes calculated for each run and the final indexes. The B2, only prints the final indexes of the simulation.

In this method, the last box *“Severe Conditions”* must be filled with values between 0 and 1 (its percentages) of the respective percentage needed for obtaining the Severe Conditions vector.



Plant Name	Group Number	Nominal Power [MW]	Availability Coefficients	CFS	FOR	CFS	FOR	CFS	FOR	CFS	FOR	CFS	F
Porto Santo	4	4	1	4	0,05	0	0,95						

Fig. A2 – Part of one Unit Page – Import Excel File.

This is an example of one page where the unit data must be organized by the FOR in ascending order.

The values of the CFS (“Capacidade Fora de Serviço”, Out of Service or Capacity Outage values in English), can’t be higher that the nominal power of that group, since you can’t have 5 MW out of service in a 4 MW unit, for example. If the user doesn’t respect that rule, an error will occur and a message will appear in the console. The FOR must have values between 0 and 1, since it is a percentage and the sum of all FOR for one group must be 1, respecting the theory of probability. If that doesn’t happen, the program will also give a warning and a message for the user stating the problem and, once it is fixed, the user can run the program again.

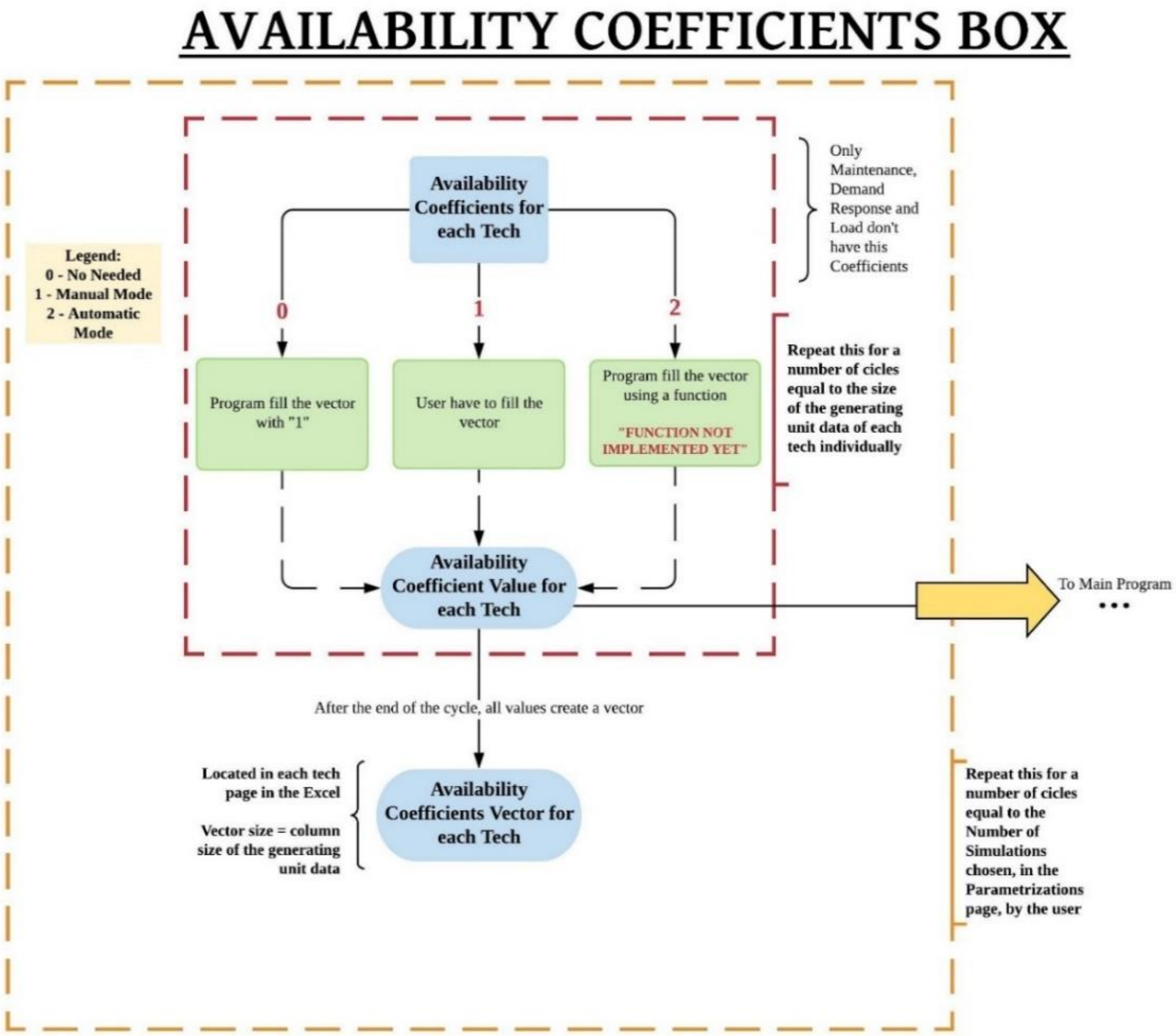


Fig. A3 – Availability Coefficients Flowchart.

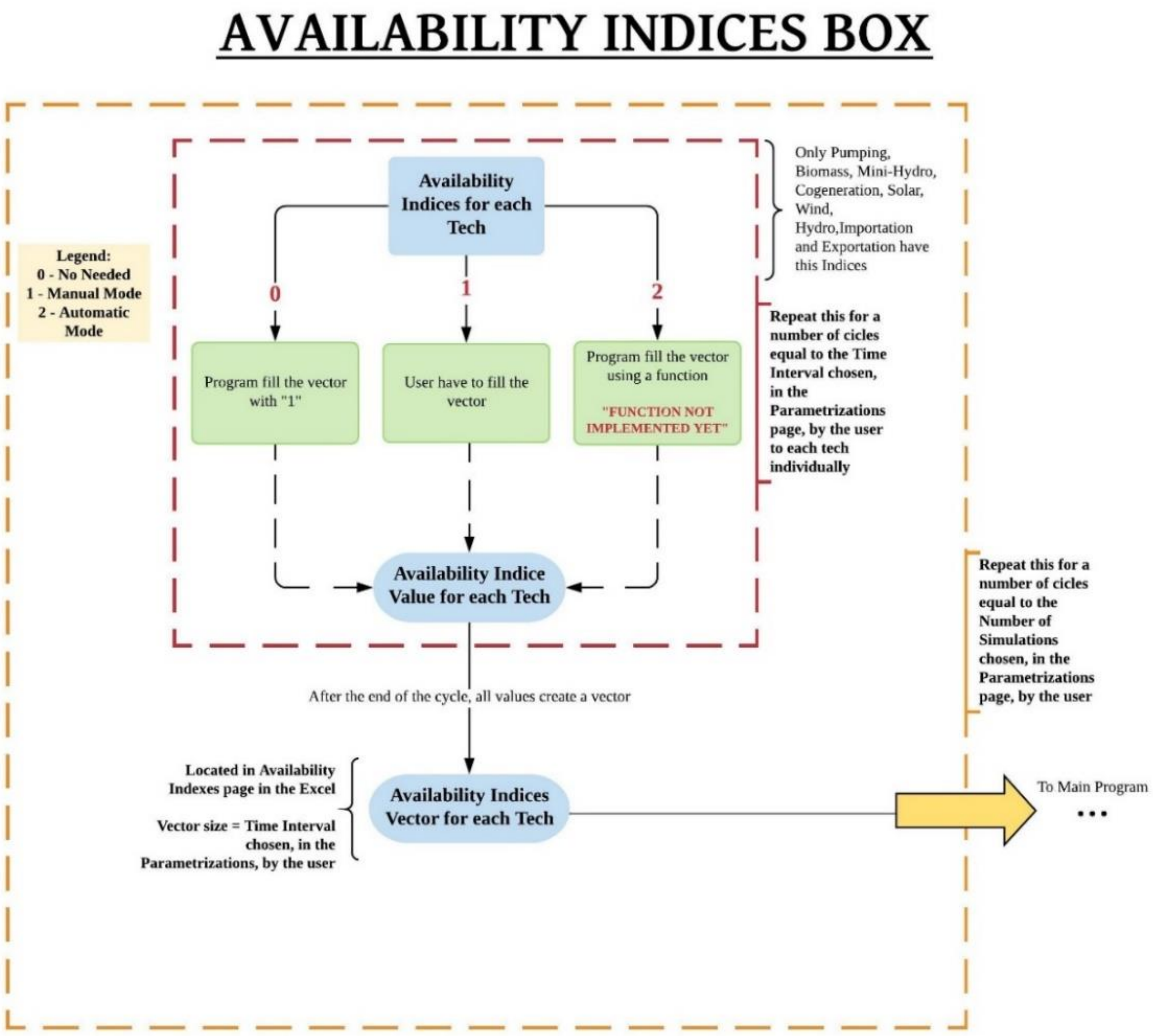


Fig. A4 – Availability Indexes Flowchart.

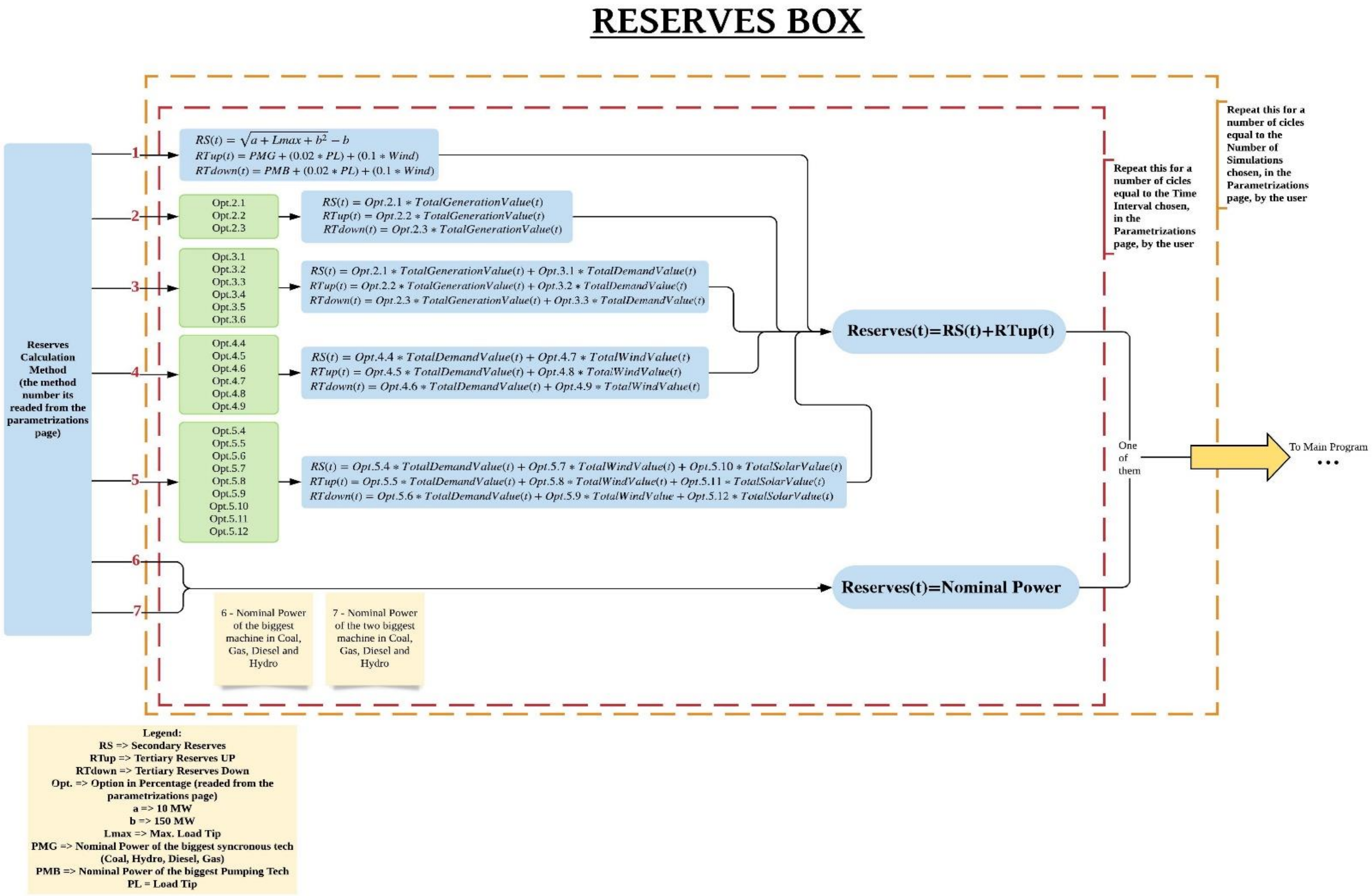


Fig. A5 – Reserves Flowchart.

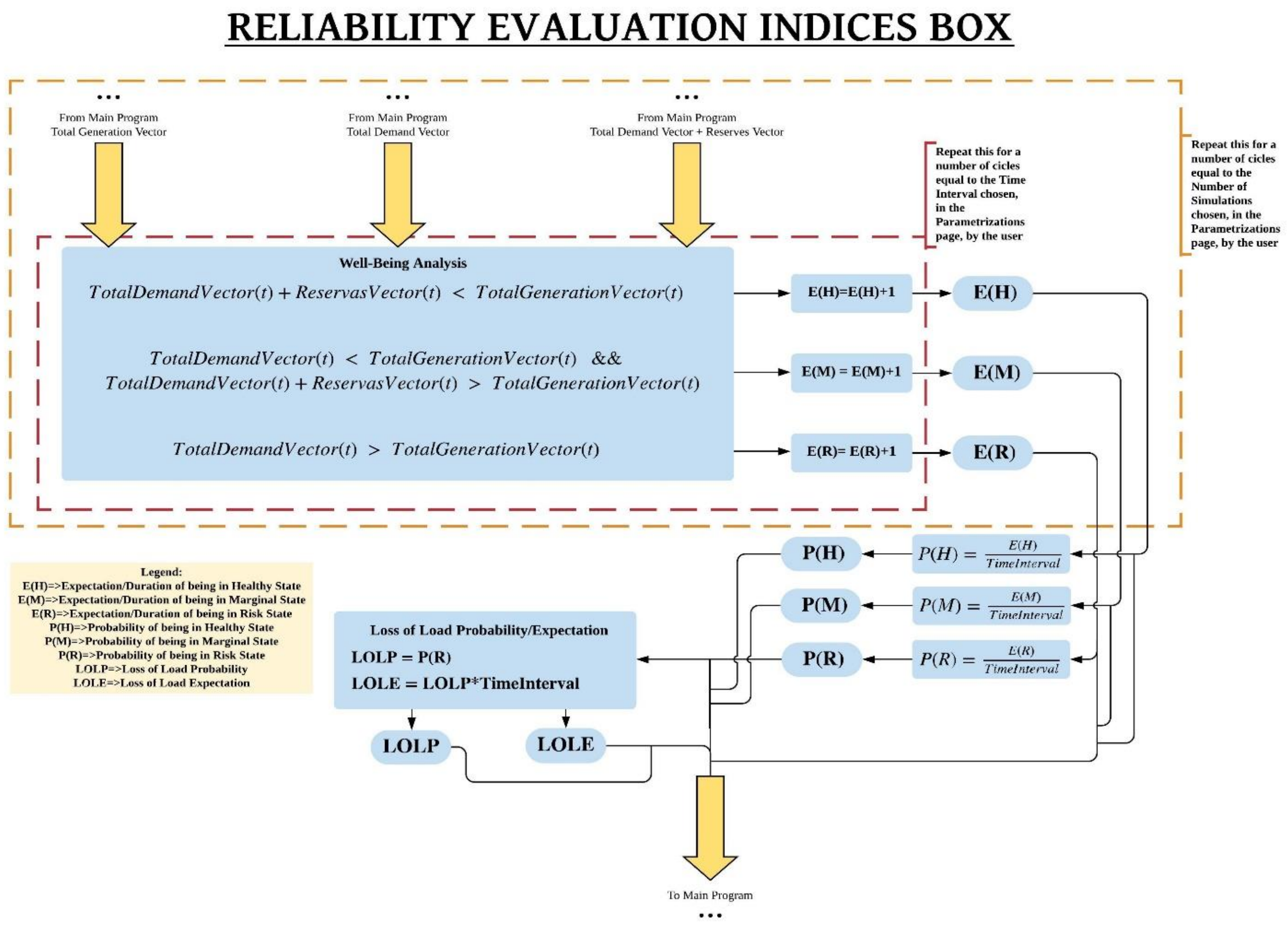


Fig. A6 – Reliability Indexes Flowchart.

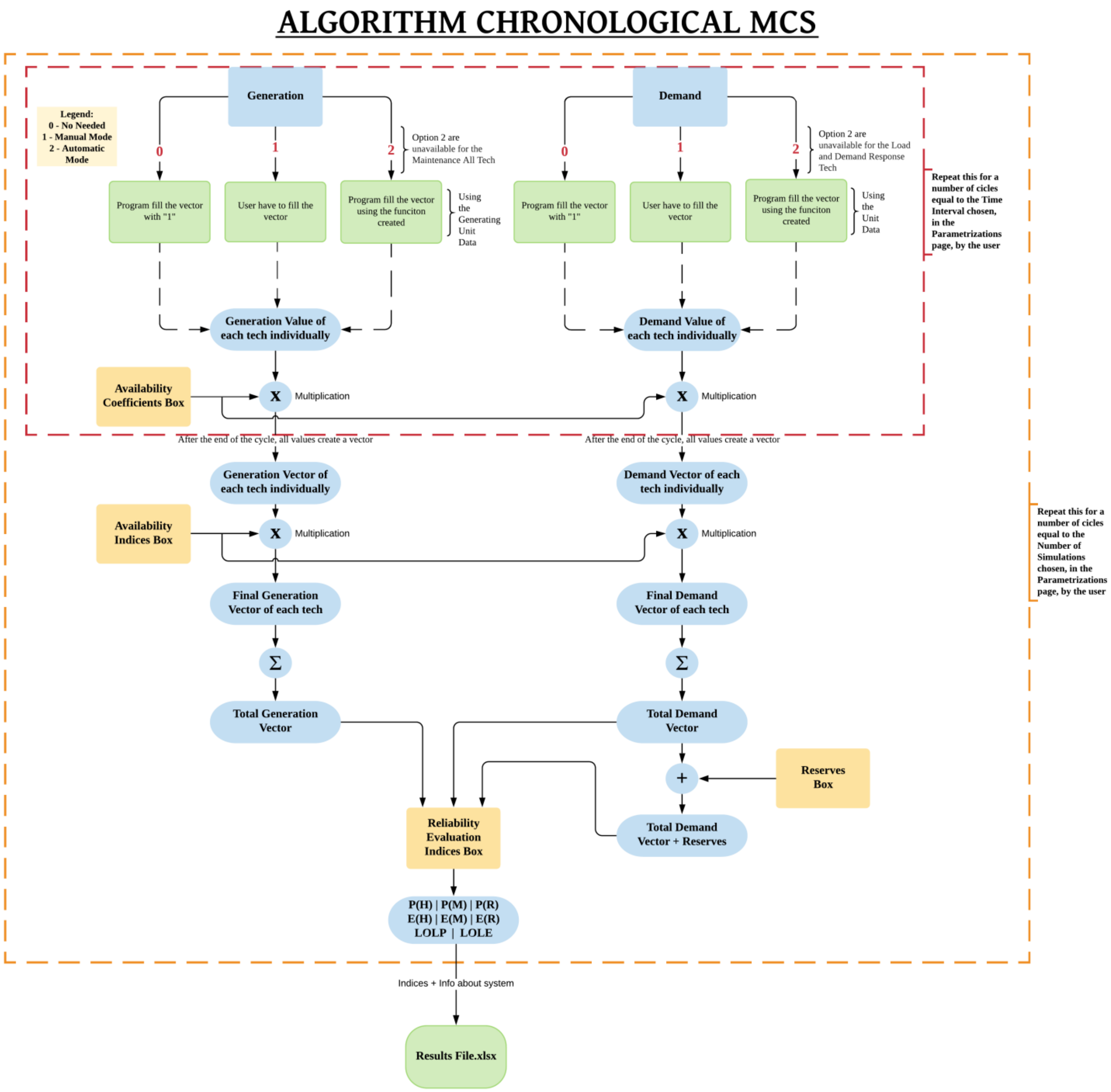


Fig. A7 – Chronological MCS Flowchart.

This is the main code Flowchart where it is possible to see one run of the program. The yellow boxes are functions called by the main routine, already presented in this document.

Appendix B – Non-Chronological MCS

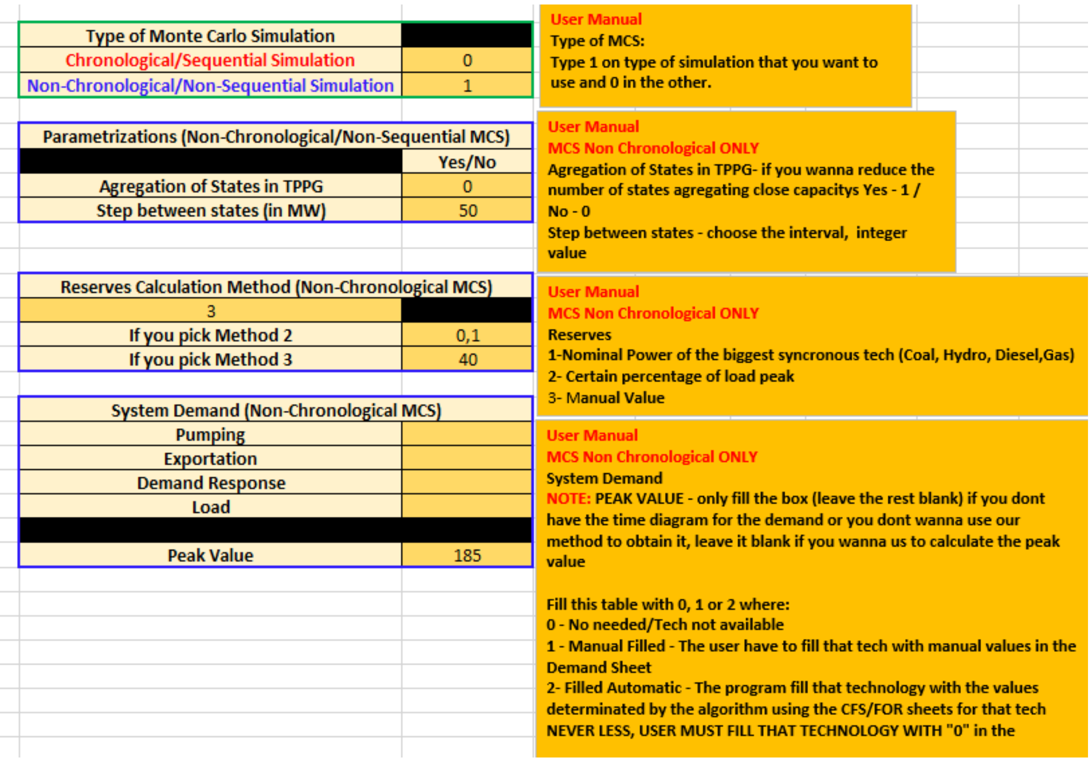


Fig. B1 – Part of the Parametrizations Page – Import Excel File.

User Guide Non-Chronological MCS

As it is possible to notice, all the boxes with a **red outline** is for the Chronological MCS, a **blue outline** is for Non-Chronological MCS and a **green outline** is common in both methods. The *"Type of Monte Carlo Simulation"* box must be filled with 0 and 1 for the desired option, where 0 is NO and 1 is YES. For reading purposes, if the value is 1 it's on the Non-Chronological MCS, the user must put a 0 on the Chronological MCS.

The *"Parametrizations"* box refers to the aggregation of states in the TPPG (same meaning as COPT in Portuguese). If the user wants it, he must fill in the 1st space with a 1 and afterwards, give the desired interval (step) in the 2nd space. If the step chosen is a value too small or not adequate to the COPT, the program will indicate an error to the user, and he must replace the chosen value for another one.

The *"Reserves Calculation Method"* box is for the reserve's calculation, where the user must fill the space with a number between 1 and 3, inclusive. The methods are already explained in chapter three. If the method 2 is chosen, the user must give a value between 0 and 1 (it's a percentage) and for the method 3, the user must give a fix value for the reserve above 0 (Fig. B2).

And finally, for the *"System Demand"* box, if the user has the peak value, he must insert it on the respective space but, if you want the program to obtain it, you give the values of the demand vectors manually or the program creates the vectors using the unit data (FOR and respective Out of Order capacities) (Fig. B3).

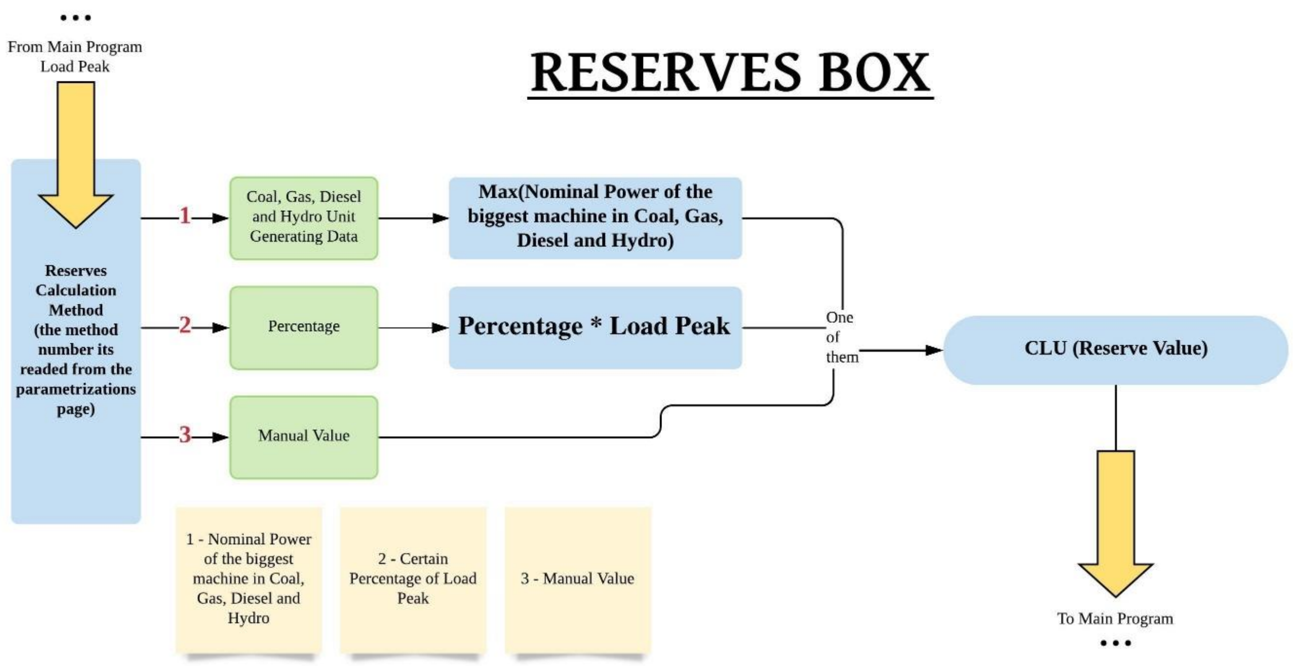


Fig. B2 – Reserves Flowchart.

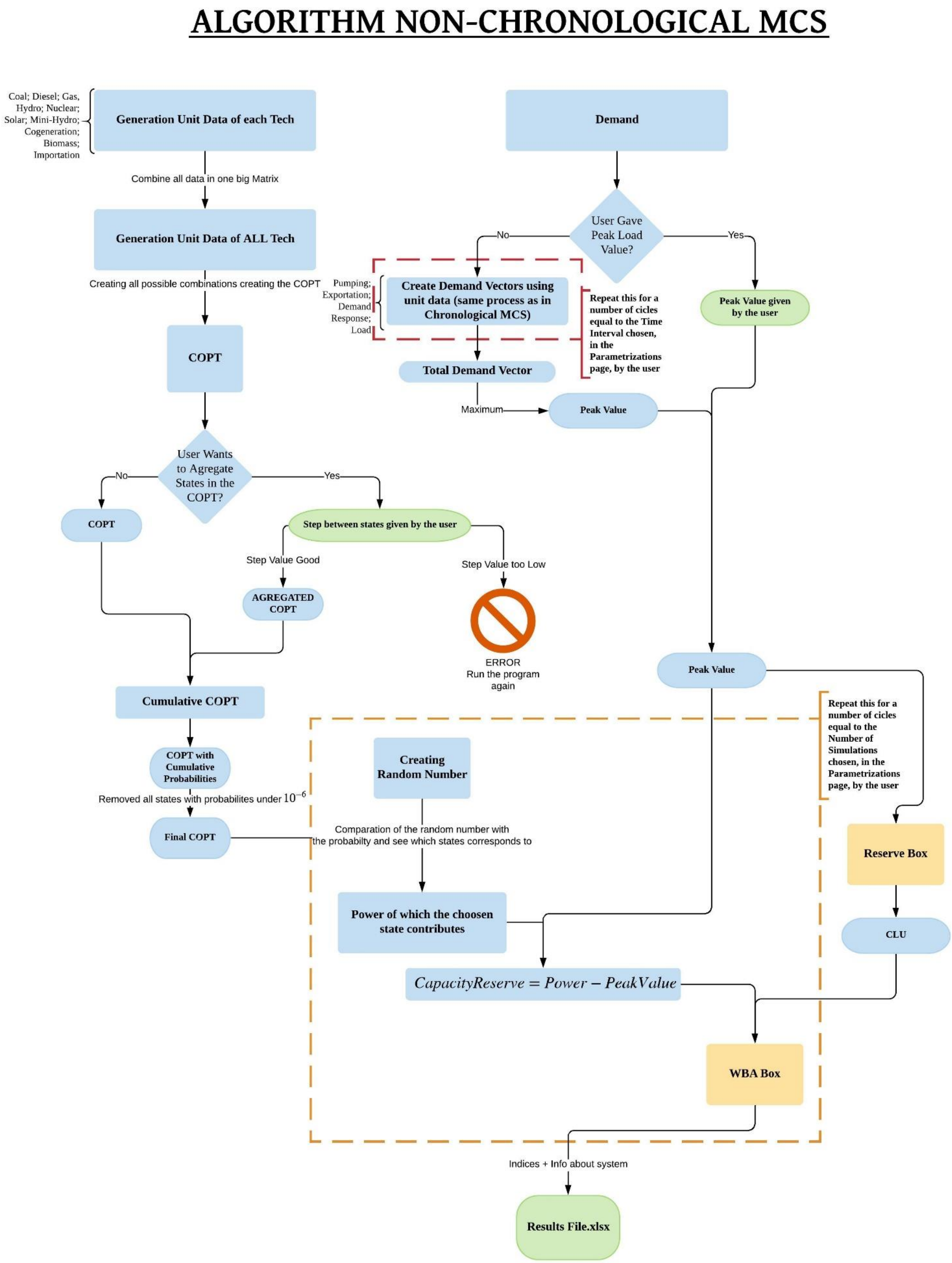


Fig. B3 – Non-Chronological MCS Flowchart.

WBA BOX

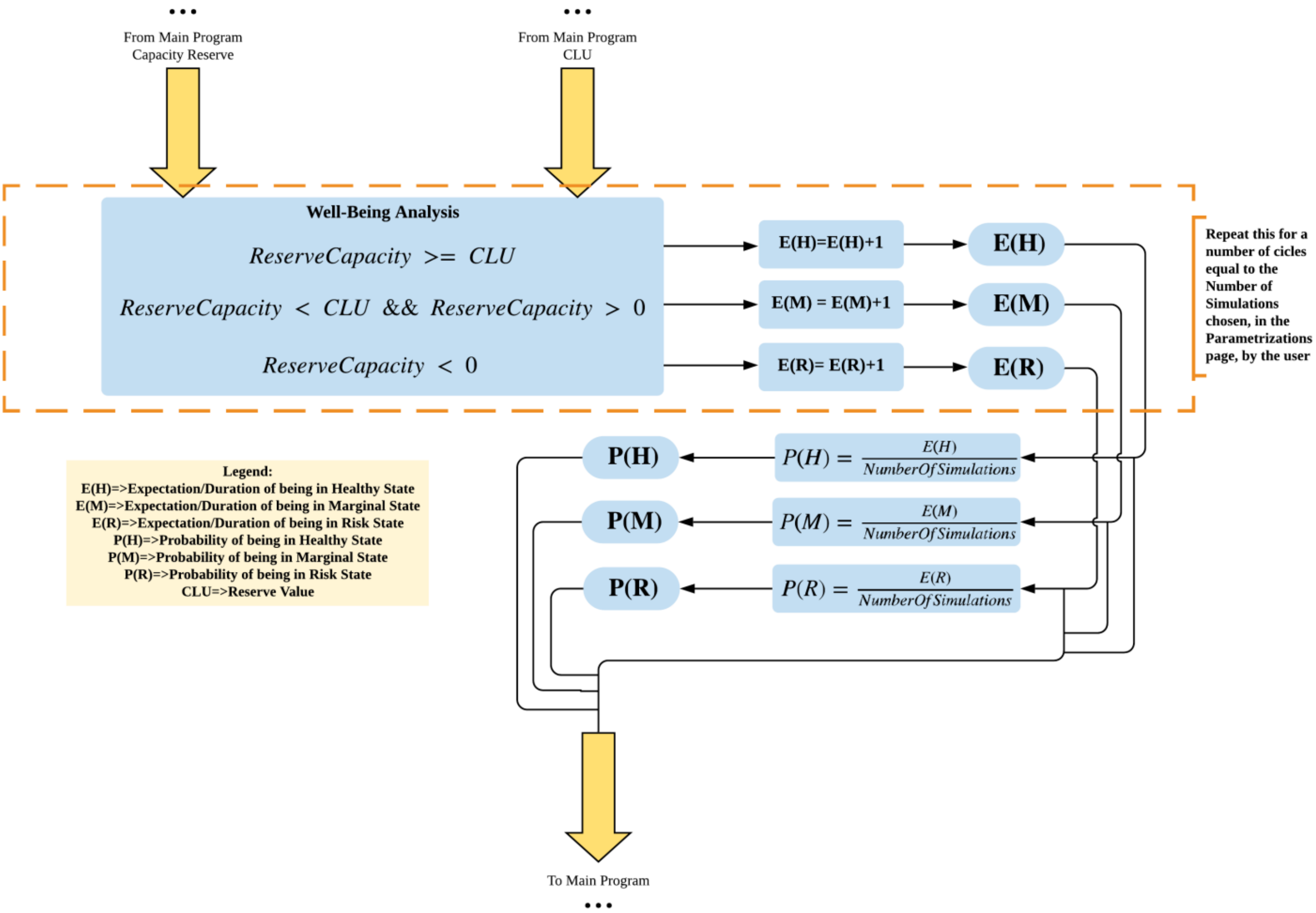


Fig. B4 – WBA Flowchart.

Appendix C – WBA Validation

Info:	
Number of Simulations:	20000
Reserves Calculation Method:	1
Reserve:	40
Peak Load:	185

Group Nu	Nominal F	Availabilit	CFS	FOR	CFS	FOR
2	40	-	40	0,0299	0	0,9701
1	10	-	10	0,025	0	0,975
1	20	-	20	0,0102	0	0,9898
4	20	-	20	0,0148	0	0,9852
2	5	-	5	0,0102	0	0,9898
1	40	-	40	0,0201	0	0,9799

Well-Being Indexes:	
H -> Healthy | M -> Marginal | R -> Risk	
P(..)= Probability | E(..)=Time in that state	
E(H)	17162
E(M)	2682
E(R)	156
P(H)	0,8581
P(M)	0,1341
P(R)	0,0078

Fig. C1 – Part of the Results file – Non-Chronological MCS – 1st Test.

Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
Indexes:	0,007054	0,1693		0,860096	0,13285	0,007054	20,6423	3,1884	0,1693

Fig. C2 – Part of the Results file – Chronological MCS – 1st Test.

LOLE its in days/year.

	Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
1 year	Indexes:	0,008929	3,259		0,838178	0,152893	0,008929	305,935	55,806	3,259
	Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
2 year	Indexes:	0,079425	28,99		0	0,920575	0,079425	0	336,01	28,99
	Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
3 year	Indexes:	0,080778	29,484		0	0,919222	0,080778	0	335,516	29,484
	Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
4 year	Indexes:	0,13994	51,078		0	0,86006	0,13994	0	313,922	51,078
	Simulation	LOLP	LOLE		P(H)	P(M)	P(R)	E(H)	E(M)	E(R)
5 year	Indexes:	0,178638	65,203		0	0,821362	0,178638	0	299,797	65,203

Fig. C3 – Part of the Results file – Chronological MCS – 2nd Test.

LOLE its in days/year.

Info:			
Number of Simulations:	20000	E(H)	16793
Reserves Calculation Method:	1	E(M)	3030
Reserve:	40	E(R)	177
Peak Load:	194,25	P(H)	0,83965
		P(M)	0,1515
		P(R)	0,00885

Info:			
Number of Simulations:	20000	E(H)	0
Reserves Calculation Method:	1	E(M)	18374
Reserve:	40	E(R)	1626
Peak Load:	203,96	P(H)	0
		P(M)	0,9187
		P(R)	0,0813

Info:			
Number of Simulations:	20000	E(H)	0
Reserves Calculation Method:	1	E(M)	18326
Reserve:	40	E(R)	1674
Peak Load:	214,16	P(H)	0
		P(M)	0,9163
		P(R)	0,0837

Info:			
Number of Simulations:	20000	E(H)	0
Reserves Calculation Method:	1	E(M)	17191
Reserve:	40	E(R)	2809
Peak Load:	224,87	P(H)	0
		P(M)	0,85955
		P(R)	0,14045

Info:			
Number of Simulations:	20000	E(H)	0
Reserves Calculation Method:	1	E(M)	16394
Reserve:	40	E(R)	3606
Peak Load:	236,11	P(H)	0
		P(M)	0,8197
		P(R)	0,1803

Fig. C4 – Part of the Results file – Non-Chronological MCS – 2nd Test.

Appendix D – Porto Santo Case

Table D1 – Availability Indexes Solar Power.

T	Solar
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	1
9	1
10	1
11	1
12	1
13	1
14	1
15	1
16	1
17	1
18	1
19	1
20	0
21	0
22	0
23	0
24	0
.	.
.	.
.	.
8752	1
8753	1
8754	1
8755	1
8756	0
8757	0
8758	0
8759	0
8760	0

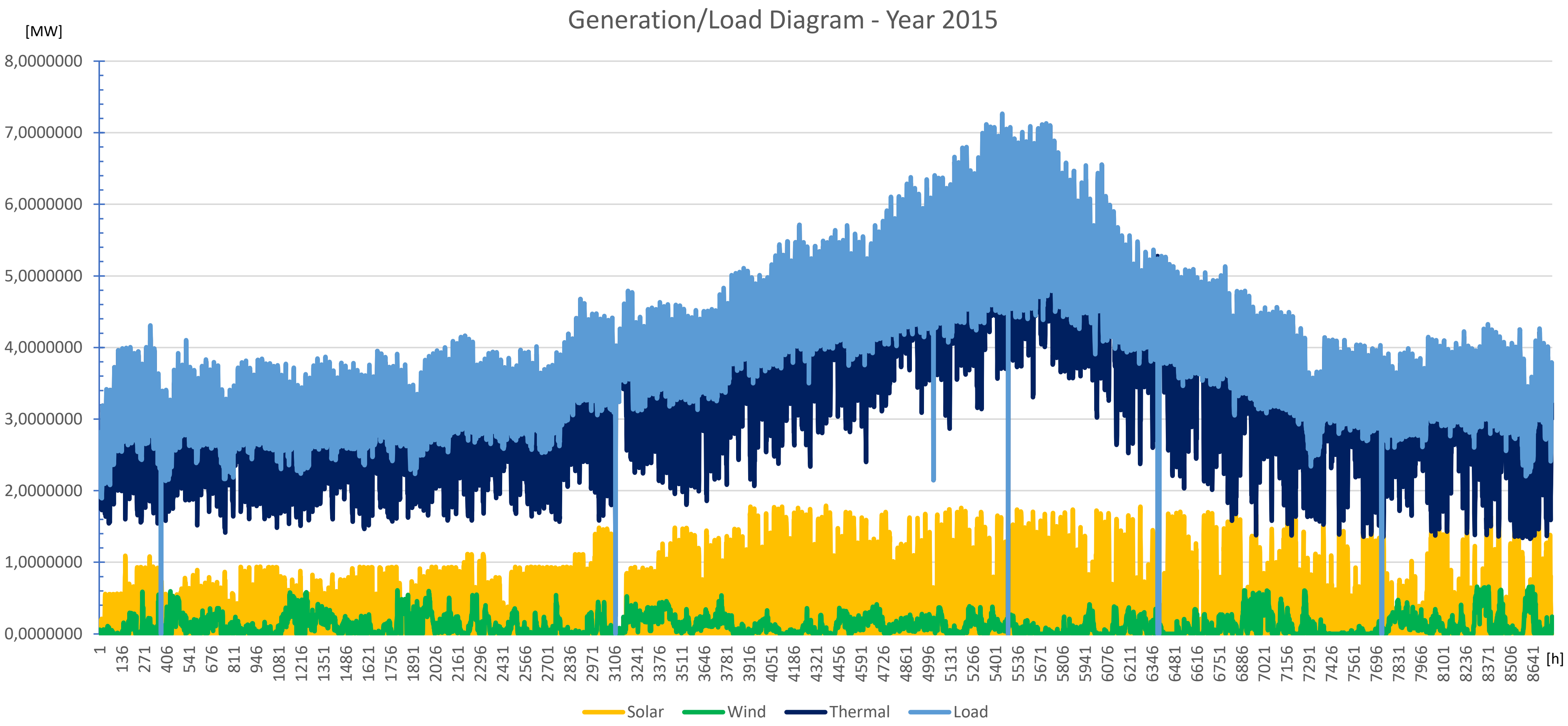


Fig. D1 – Generation/Load Diagram Porto Santo – Year 2015.