ATTEST

Ref. Ares(2021)4392085 - 06/07/2021

WP5

Development of a smart environment for asset management in power grids

Specification of the asset management tools

D5.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864298.

DOCUMENT CONTROL PAGE

DOCUMENT	D5.1 – Specification of the asset management tools
TYPE	Report
DISTRIBUTION LEVEL	Restricted
DUE DELIVERY DATE	30 / 06 / 2021
DATE OF DELIVERY	06 / 07 / 2021
VERSION	V2.1
DELIVERABLE RESPONSIBLE	Comillas
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DOCUMENT HISTORY

VERSION	AUTHORS	DATE	CHANGES
0.1	Gopal Lal Rajora COMILLAS	10 / 06 / 2021	First complete version
0.2	GOPAL LAL RAJORA COMILLAS	16 / 06 / 2021	Comments from internal review
1.0	GOPAL LAL RAJORA COMILLAS	24/06/2021	Included comments from HOPS as official reviewer
2.0	GOPAL LAL RAJORA COMILLAS	30/06/2021	Included comments from KONCAR-KET as official reviewer
2.1	GOPAL LAL RAJORA COMILLAS	06/07/2021	Included comments from INESCTEC Project Coordinator

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Abbreviations and Acronyms

ACCRONYM / ABBREVIATION	Extensive form
ACSR	Aluminum Conductor Steel Reinforced
AMS	Asset Management System
CDF	Cumulative Distribution Function
DGA	Dissolved Gas Analysis
DGAF	Dissolved Gas Analysis Factor
DSO	Distribution System Operator
EI	Economic Impact
HAZOP	Hazards and Operability
HI	Health Index
LA	Life Assessment
LTC	Load Tap Changer
MCCB	Molded Case Circuit Breaker
MS	Maintenance Strategy
MTTF	Mean Time To Failure
PHM	Proportional Hazard Models
TDCG	Total Dissolved Combustible Gas
TSO	Transport System Operator
TTF	Time to Failure

1. Executive summary

Power systems are immersed in continuous evolution for reaching the best service to the customers and, in general, to society at the same time with the best technical effort and less environmental impact. In this direction, significant measures are being developed towards low carbon energy systems that are requiring new challenges both in technical and economic aspects of the power systems asset management. The ATTEST project aims to solve some of those challenges by developing an open-source toolbox comprising a suite of innovative tools to support TSOs / DSOs synergic operation, optimal maintenance of assets, and coordinated planning of both transmission and distribution systems for 2030 and beyond. In this context, the assets of the power systems, as their core elements, require special attention to their life and condition in order to take the more convenient actions about their operation, maintenance, and replacement. Work package 5 of the ATTEST project has as main objective to give support to this process.

This document presents deliverable 5.1 “Specification of the asset management tools” which provides a general description of the different tools to be developed within WP5, namely:

- Task 5.1: Tool for the characterization of the condition of assets.
- Task 5.2: Tool for the definition of condition indicators based on heterogeneous information sources.
- Task 3.3: Tool for the definition of smart asset management strategies.

The document includes a short review of the most relevant points of the current state-of-the-art of asset management in power systems. After that, for each tool to be developed in WP5 of the ATTEST project, a description of objectives, functional characteristics, data requirements, and expected results will be provided. The tools are complementary and, the results obtained in the tool of a level are the main inputs required for the tool in the next one. The design principles of the tools will be inspired by the use of open source codes and an easy adaptation to any data context of power companies.

2. Introduction

Work package 5 has the primary goal of developing instruments that can help the process of making decisions by the electrical companies about managing the assets involved in the typical operation of TSO/DSO power systems. This goal will be reached by the evaluation of a set of indicators obtained from different perspectives of the life and maintenance of the assets. The strategy for bringing these indicators and the interpretation of them will be implemented in three different tools that will support the whole process of asset management in the context of the ATTEST project.

This deliverable describes the strategy followed in the ATTEST project for the characterization of the assets according to their life and maintenance observed and/or expected. This knowledge is essential for detecting potential weak points in the power systems that could affect the operation and for rescheduling maintenance and replacement strategies of assets, all this keeping the balance between quality of service and availability of resources.

2.1. Description of the tools

The asset management work package of the ATTEST projects is conceived as a sequence of three different levels of information that are the following:

- The first level consists of the identification of the critical information/data to quantify the health condition of the asset. Typically, there is a multiplicity of data collected during the observed life of the assets with different granularity and formats. This information needs to be properly handled, converted, and ranked according to its contribution to the condition indicators to be developed in the next level;
- The second level of the smart asset management environment entails the definition and development of methods for estimating condition indicators for the assets. These methods will be based on the heterogeneous information/data sources selected in the first level. The idea is to obtain comparable condition indicators for different assets including a factor of certainty (or confidence) of the indicators created.
- The third and final level of this smart environment will create a tool to simulate and quantify the evolution of the condition indicator previously defined for the asset under different management strategies.

The asset management tool is based on three tools that cover the three levels previously mentioned. The tools are the following:

- **Tool for the characterization of the health condition of assets:** The goal of this tool is the characterization of the assets using indicators based on different aspects of their lives.
- **Tool for the definition of condition indicators based on heterogeneous information sources:** This tool defines an innovative approach to translate the results obtained from the previous tool into a set of harmonized, easily measurable, and comparable indicators for different types of assets, which will allow identifying which assets require special attention from an asset management point of view.
- **Tool for the definition of smart asset management strategies:** This tool permits the comparison of assets under different perspectives (operation, maintenance, cost, impact) resulting in priority

lists. Smart strategies for asset management based on the previous asset evaluation and common life indicators will be also developed.

2.2. Structure of the report

The rest of the document is structured as follows:

- Section 3 presents a short review of the basic essential points of the current state-of-the-art in asset management of power systems.
- Section 4 describes the main variables that inspire the foundations of the asset management tools.
- Section 5 is the core section of this report where the specification of the three tools for asset management is developed.
- Section 6 presents the definition of interactions with other work packages in the ATTEST project.
- Section 7 describes the requirements for the implementation and use of the tools.
- Section 8 concludes the deliverable.

3. State-of-the-art of asset management in power systems

3.1. General overview of the state-of-the-art

Asset Management System (AMS) is a hardware-cum-software application used to manage and maintain assets in a power network for improving their efficiency and optimal utilization. The term asset management can mean many things, ranging from paper lists of assets the company is responsible for, to sophisticated interconnected distributed systems collecting data from different assets and extrapolating and creating work orders to be performed on yet another asset. The installation of asset management system in practice is much more challenging than just implementing an additional piece of software that helps in running established processes. In an asset heavy industry as the power grid is, this is precisely the reason asset management causes confusion. The asset management does not merely accompany existing processes, in many cases it turns them on their heads. Also, many departments of a large scale grid operator have surely devised tools to help them in their day to day business. Installing an asset management system there means reconciling these partial asset management "subsystems" and accepting the processes that rely on these.

It enables power networks to achieve excellence in operation and maintenance. There are many AMSs deployed for different applications, which facilitate continuous monitoring, prediction, analysis, and error reporting of an asset's functioning at the plant level. The sub-segments of this growing development are primary (priority) load, secondary (deferrable) load, grid supply, and local energy. All these segments are integrated into a central monitoring and control station for their continuous tracking. Automation of the system using AMS provides remote monitoring, control, and regulation of all the associated assets to optimize the power grid's operations. This ensures an effective supply of reliable power to the respective consumers. In general, an AMS manages workflow, maintenance schedules, purchase, analysis, and inventory activities of assets, which includes corrosion monitoring of fixed assets, management of host and field devices, and network of automation assets. Overall, the asset management activities are provided for handling sustainable risk over the life cycle, which lengthens the effective life of typical assets (Jung, Ray, & Salkuti, 2019).

3.2. Key drivers for the deployment of AMS

A typical power system may have thousands of assets to manage. Tracking and managing these assets manually is no longer possible. Software diagnostic tools are the basic requirements to identify and diagnose problems. Nowadays, various power networks have gradually deploying AMS to improve their operational proficiency. The use of AMS for the optimal use of resources in a transmission and distribution network is highly encouraged by smart grid initiatives. The fundamental drivers for AMS deployment are shown in Figure 1. The importance of these key drivers for AMS deployment is given as follows:

- Reliability is a competitive business parameter, which affects the overall success of the power system. Any unintended shutdowns will have a considerable impact on productivity.
- Quality is an endurance point in the commercial market for better services.
- Extended use on aged assets delays new capital investment while sustaining the existing operation.
- Reduction of manpower resources.

- Cost reductions in operations and maintenance.
- Environmental safety concerns and tracking of footprints of various kinds have become an overall interest in any industry, hence the importance of making suitable management decisions (Farhangi, 2009).

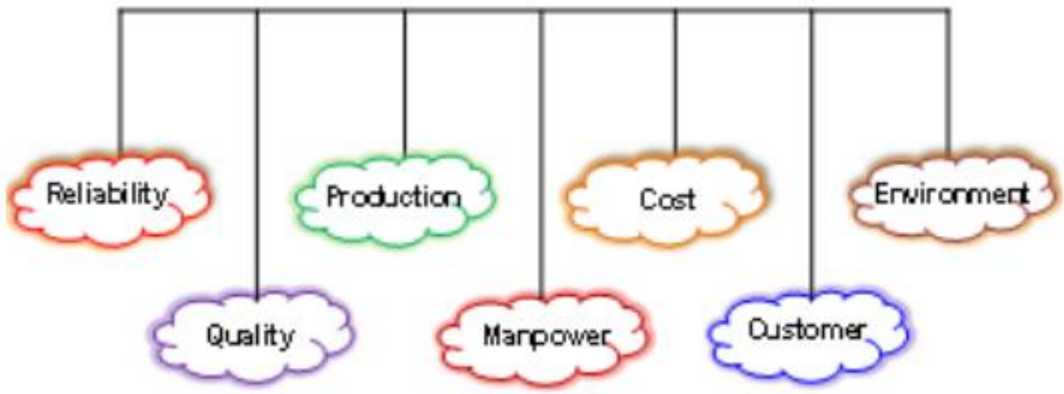

FIGURE 1 KEY DRIVERS OF AMS DEPLOYMENT

3.3. Asset Management System Architecture

The typical AMS architecture in a smart distribution system describes the integration of various assets through individual networks or communication technologies to be managed by a single centralized system. It is monitored by various clients for analysis and control actions, to maintain and protect the assets.

3.3.1. AMS Server

The AMS server is implemented by supervisory control and data acquisition system (SCADA) to communicate with various AMS clients for monitoring and for taking control actions. The detailed objectives of the AMS server are as follows:

- It has to maintain the database of information regarding all devices. Information such as history, manufacturer, asset type, audit trail reports, offline tasks, service and calibration status of assets, etc.
- It can generate maintenance alarms for necessary actions.
- It follows diversified networks, viz., FDT, safety systems, modem, DCS, hardware multiplexers, etc.

More modern SCADA applications actually do not merely do “Acquisition” but perform “Analysis”, so the second A is actually Supervisory Control and Data Analytics. The line between “old-fashioned” SCADA and newer intelligent analytics systems is much less pronounced in recent years, particularly with the increase in data volume. (Gungor, Sahin, Kocak, & Ergut, 2012).

3.3.2. AMS Clients

Software packages called clients provide a user interface and enable remote server connectivity. The objectives of clients are for example as follows:

- It has to identify a device and perform device-to-device connections to check their health status and detect communication errors. This helps to trigger maintenance alarms, diagnostics alerts (unit diagnosis and process interface diagnosis), etc.
- Provide a graphical user-friendly interface working platform with a navigation tool to select any specific device. This also helps the user to configure and calibrate any of the devices, that are generally operating on protocols such as HART (highway addressable remote transducers), FF (foundation fieldbus), or PB (Profibus). The user interfaces of an asset management system should work as transparently as possible, regardless of the field-level communication protocol the actual devices use
- Identification tags are assigned to the devices so each device can be uniquely identified. It shares the device information (such as operation and maintenance status) across various engineering and operational personnel.
- Indicating device health status in a simpler way (e.g. using a status display icon on the user interface to indicate device communication status, etc.).
- Along with the abovementioned standard diagnostic tasks, modern AMS possess tools such as FDT (field device tool), DD (device description), DTM (device type manager), EDD (electronic device description), etc. These tools provide innovative diagnostics as well as smooth user experience (Wen , Yangdong, Weixing, & Hongwei, 2014).

3.3.3. System Networks

System network layer provides the required technologies and standards for the smart devices to communicate with the server. However, the fruitful deployment of an AMS network depends on accurate information rendering. To make these deployments more effective and mature, various technology standards are being continuously developed by reputed consortiums. Some common technologies or standard communication languages such as DD, FDT, EDD, and DTM have been developed by these consortiums. These help to increase the compatibility of the devices made by multiple/different manufacturers to common systems. Besides, these guidelines help to homogenize the functional parameters of all such devices. In the perspective of these new initiatives, the typical user scenario is that the devices should be delivered with any of the standard DD/FDT/EDD/DTM technology." It provides the functionality to import/dump all these files into the local AMS of the respective device to make it compatible with the other devices of the system, thereby operating as intended. So, these files will be subjected to only periodical versioning updates. These updates help to develop rich user device interfaces and provide better diagnostics capabilities. The key objective of these technologies is to enable device self-diagnostics, device integration to central server or control room, and troubleshooting the device during failures (Wen , Yangdong, Weixing, & Hongwei, 2014).

3.3.4. On-field Smart Devices

On-field smart devices provide essential information such as, preciseness of its own operations and the health of nearby assets. These diagnostic features are facilitated by modern digital communications (e.g. HART, FF, etc.). Recently, the IEC 61850 protocol has become the de facto industrial automation standard, within the substations and in the grid in a wider sense. Devices featuring such diagnostics are treated as data servers which are the basis for managing abnormal/faulty situations, process control and optimization, etc. (Gungor, Sahin, Kocak, & Ergut, 2012).

3.4. Risk Assessment

In the cycle of AMS operation, the identification and mitigation of risks are the key issues. Another concern for electricity distribution companies is the identification of relevant risks and their assessment to reduce the effects of failures on the business. Along with the business, these risks can also affect the network safety and ecological footprint. There are many types of risks identified for electricity distribution companies such as those associated with safety, economy, environment, company reputation, supply quality, regulatory policies and maintenance, etc. Not all these risks are relevant for each decision-making process in the business, but; they are related and the consequence of mitigating one risk may cause the increase of another risk. This needs to be assessed at each and every decision that is being implemented in the system. Fundamentally, there are three risk analysis categories: standard risk analysis, simplified risk analysis, and model-based risk analysis. They are described as follows:

- Simplified Risk Analysis: This is a qualitative approach method. It includes informal and/or non-technical procedures applied to risk analysis such as group discussions, brain storming sessions, one-to-one discussions, coarse risk analysis, etc.
- Standard Risk Analysis: This is a qualitative and/or quantitative approach method. This includes more formalized procedures. Here, recognized risk analysis procedures along with risk metrics are used for the analysis. This analysis is assisted by HAZOP (hazards and operability) metrics.
- Model Risk Analysis: This is a quantitative approach method. This includes formal methods such as fault tree analysis or, event tree analysis, to calculate the risk (Dwarkadas & Vijayapriya, 2011).

3.5. Asset Management Techniques

In 2014, ISO, the International Organization for Standardization, published the series of standards ISO 55000, ISO 55001 and ISO 55002, (Sanford, 2015) these standards were conceived to help organizations and companies to obtain the maximum value from their assets, aligned with their objectives, mission, policies and interests of their environment. These international standards can be applied to optimally manage any type of asset, from physical assets such as machinery, through human assets represented in the workforce, to intangible assets such as reputation or trust. The standard is applicable to all types of public or private, large or small, business or non-profit organizations. In general terms, the ISO 55000 series of standards provides general information.

The publication of the set of ISO 55000 standards is the result of more than three years of work by the Technical Committee 251 for Asset Management (ISO / TC 251: Asset Management) made up of 28 countries. The development of this standard has its origin and is also based on BSI PAS 55 (Sanford, 2015), which is the British Publicly Available Standard Specification for Management of Physical Assets, PAS 55 defines the requirements to establish and audit an integrated management system optimized to throughout the life cycle of an asset. ISO 55000 takes these aspects and generalizes them to other types of assets important to an organization. ISO 55000 focuses on the strategic objectives of the organization and their influence on the environment.

This standard is made up of three standards, which, although separate, complement each other:

1. ISO 55000, General information, principles and terminology.

2. ISO 55001, Requirements.

3. ISO 55002, Application Guide for ISO 55001

An organization depends on diverse and interrelated assets for optimal operation, including-physical, human, financial, informational and intangible assets. All these assets are subject to aging, and their value decreases over time. Therefore, they all require maintenance, care plans and improvements. But also, each asset has a role in the production chain and they are interrelated. Consequently, only with the optimal performance of each of them it will be possible to achieve the strategic goals of the organization, complying with all regulations and responsibilities.

The performance of a physical asset throughout its life cycle inexorably depends on the performance of other assets, the optimal operation of a machine (physical asset) depends fundamentally on knowledge and information management, which in turn are attributes of a resource suitable human. A failure in the chain will undoubtedly affect the performance of a physical asset which could potentially impact the safety of the environment with effects on the finances and the reputation of the organization. All these interdependence and complex relationships between the various assets and asset systems require a coordinated, sustainable and systematic management strategy that guarantees obtaining the maximum value from each asset efficiently, safely and reliably.

An asset is any item, entity, element or object that has real or potential value for an organization. Not only are tangible or physical assets represented in infrastructures, machines and equipment, but also an organization integrates human assets with their knowledge, work and skills; financial assets made up of investments and capital; information assets and finally intangible assets that represent a value beyond the business but that can certainly impact it, such as security, reputation, morale, status.

According to the definition established in PAS 55, Asset Management refers to "the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, its performance, risks associated and costs throughout its life cycle in order to achieve the goals of the strategic plan".

To efficiently manage an asset, it is necessary to know what is the objective for the asset, and then establish the strategy and activities to this objective, considering the risks and costs. In short, it is a long-term strategy supported by predefined and concrete actions. Asset management is designed to guarantee performance specified by design, in a safe, socially beneficial and environmentally friendly manner.

3.5.1. Principles of Asset Management: ISO 55000

Asset management is a management methodology with a holistic vision that allows unifying the different parts of an organization to achieve common strategic objectives; it is about observing the entire panorama, interdependence, relationships and contributions of assets within each system. It is methodological and systematic; it promotes consistency, repeatability and auditable decision making. Combat isolation and individualism with a systemic orientation that considers the asset part of a system and with a circle of influence. Resources and priorities are addressed based on risks, identifying them and determining the cost/benefit ratio. Establishes the tradeoffs between performance, costs and risks to define the optimization point of the life cycle. It considers the long-term consequences of short-term actions to ensure future requirements and obligations, giving it a character of sustainability and social responsibility. It recognizes that interdependence and the combination of effects are fundamental for success; it is based on the integration of teams in favor of common goals.

Many organizations and their managers do not have clear information about the condition of their assets, much less have a defined portfolio of assets, this places them in a defensive position in the face of the challenges of achieving their objectives, making decisions on the fly according to unexpected events. A consequence of this reactive form of management translates into losses, non-compliance, fines and a series of factors that prevent growth, not only not improving, but also not finding the way to solve the problems and weaknesses of the organization. In this sense, the main and quickest solution is to obtain real knowledge about the assets and asset systems that make up your organization; another important thing is to know in detail the so-called stakeholders, which are all those entities, communities, clients.

Asset Management does not always create economic value from all its resources, the so-called intangibles often represent a strategic value, moral, collective benefit, all this translates into trust and reputation that will ultimately have a positive impact for the organization and its circle of influence.

Asset Management is aimed at improving:

- Customer satisfaction by optimizing the controls of products and services.
- Environmental and personal health.
- Coordination between quality, environment, security and finances.
- Understanding of assets, their roles and risks.
- Long-term planning and sustainability mechanisms.
- Compliance with government regulations and the reduction of unexpected events and fines.
- The risk management system and audit systems.
- Relationships between partners, allies, suppliers, clients, employees and the community.
- Corporate reputation and knowledge of its impact on the value chain.
- The ability to demonstrate that sustainable development and social responsibility is an active, real and effective policy.
- The relationship between assets and asset systems throughout their life cycle.

4. Foundations of the asset management tools

The asset management tools consider the power network as the main skeleton that will support all the assets of the company. The network itself is the primary asset the distribution or transmission network operator manages.

The power network will be described for these tools in terms of the same format used by other WPs of the ATTEST project. WP5 tool creates an object per asset or component included in the power network description.

The object associated to each asset has a unique identifier based on the labeling method used in the file describing the power network and its components.

The objects belong to different specific types according to the asset involved.

Each asset is considered under four main dimensions: Life Assessment (LA), Health Index (HI), Maintenance Strategy (MS) and Economic Impact (EI). All these dimensions are supported by several indicators that described in the following sections.

4.1. Life Assessment *(LA)*

This dimension will be focus on indicators related to the expected reliability of the asset and its risk of failure. Two main indicators are considered: life models for the assets, and evaluation of their workload.

4.1.1. Life models

Lifetime analysis has as a main objective the characterization of the most relevant features of the life observed in a component or industrial system. This characterization allows for knowing better the behavior observed in the components and also, to predict the future life. This is important for any process related with maintenance, replacement, inventory, and, in general, asset management.

The characterization of the component life tries to minimize the number of features parameters. Typically, in order to reach this objective several methodologies have been developed. They can be classified in parametric and non-parametric techniques. The first ones reduce the information observed to a minimum number of characteristic parameters. The last ones use mathematical algorithms to reproduce synthesize the life observed.

In these tasks, two main parametric methods were tested to model the history of faults when it was available: exponential and Weibull fitting. They are very common and well known techniques. The exponential model characterizes the life based on one parameter and the Weibull method uses two. The main equations of Exponential and Weibull methods are explained in Annex I.

The method used for modelling, when failure records are available, is as follows:

- Description of the Cumulative Distribution Function (CDF). Once a reference date was determined, the Time to Failure (TTF) from this reference until the date of the registered fault is calculated. Once the set of TTFs is obtained for all the population of faults, it is ordered from low to high values and each case is represented as a point on the X-Y plane determined by the TTF (on the X axis) and the proportion of failures (on the Y axis). Obviously, the CDF representation on the Y axis is in the range 0 to 1.

- Once the CDF is obtained, it is possible to observe the slope or slopes of failure proportions and an exponential and or Weibull models can try to reproduce the life observed. The models obtained can be used for reliability prediction. Typical life models based of failure probability (to be developed):

- Exponential
- Weibull
- Non-parametric models: Proportional Hazard Models (PHM)

The main equations of Exponential and Weibull models are the following:

<u>Assets life described by an exponential Model</u>

The characteristic of this model is that the failure rate is considered ***constant***. The formulation of the ***failure density function (1)*** for the exponential model is the following:

$$f(t) = \lambda e^{(-\lambda t)} \qquad \lambda > 0, t \geq 0 \tag{1}$$

Where t is time.

The expressions for the ***Reliability (2)*** function for a lifetime exponential model is:

$$R(t) = e^{(-\lambda t)} = 1 - F(t) \tag{2}$$

where F(t) is the failure cumulative distribution function (CDF).

A reformulation of the ***failure density function (3)*** is

$$f(t) = F'(t) = (1 - R(t))' = -R'(t) = \lambda e^{(-\lambda t)} \tag{3}$$

The expression for Mean Time to Failure (**MTTF**) (4) for an exponential model is:

$$MTTF = \frac{1}{\lambda} \tag{4}$$

Finally, the **median life (5)** is given by the expression:

$$(ln(2)) * \frac{1}{\lambda} = 0.693147 * MTTF \tag{5}$$

<u>Weibull Model</u>

The formulation of the ***failure density function (6)*** for the Weibull model is the following

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad \beta > 0, \eta > 0, t \geq 0 \tag{6}$$

Where the parameter η is the lifetime characteristic (scale parameter) and **β** is the shape parameter. **t** is the time

The expressions for the ***Reliability (7)*** and ***Hazard (8)*** functions for a lifetime Weibull model are respectively:

$$R(t) = exp\left[\left(\frac{t}{\eta}\right)^{\beta}\right] = 1 - F(t) \quad (7)$$

$$\lambda(t) = f(t)/R(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \quad (8)$$

The expression for Mean Time To Failure (**MTTF**) (9) for a Weibull model is:

$$MTTF = \eta\int_0^{\infty} t^{1/\beta}e^{-t}\,dt \ = \eta\Gamma(1+\frac{1}{\beta}) \quad (9)$$

Finally, the **median life (10)** is given by the expression:

$$\eta * (ln(2))^{1/\beta} \quad (10)$$

A β value lower than 1 means infant mortality in a Weibull lifetime analysis.

4.1.2. Load history

This corresponds to the typical profiles of a load of the assets, for example, the power profile in a transformer. This will define how the asset was working during its life and how much is stressed due to this has accumulated.

4.2. Health Indexes (HI). Assets condition monitoring procedures

4.2.1. Health index for power transformers

A Health Index (HI) represents a practical tool that combines the results of operating observations, field inspections, and site and laboratory testing into an objective and quantitative index, providing the overall health of the asset. Asset HI is a powerful tool indicator for managing assets and identifying investment needs as well as prioritizing investments in capital and maintenance programs.

The aim of a health index is the condition representation of the health condition of an individual asset. The health index reduces the amount of information to be processed, while keeping its relevance. The health index must be a metric that will correctly reflect the state of health of an asset, at the same conflating the conflicting objectives of "condensing" a lot of data into a single index, while trying to maximize the information content in the same index.

This enables a more effective comparison between individuals in a population to gain a better overview of a utility's assets. Consequently, maintenance and replacement decisions can be based on a common indicator. The health index processes the gathered condition monitoring data into an easily understandable value, especially if the health score is transformed into linguistic expressions such as very good, good, moderate, bad, and very bad. This also allows for automatic monitoring of assets and alarms to be created if certain predefined thresholds are crossed. The health index can also illustrate long-term degradation, or short-term changes can become visible if it is recorded over time (Jürgensen, Godin, & Hilber, 2017).

Using the health index as an effective decision-making tool does come with several challenges that every user has to be aware of when developing or using health indices. These challenges can be divided into data acquisition, definition and calculation, interpretation, and implementation. (Piercy, Cress, Service, & Wang, 2009)

According to the latest CIGRE WG 12 report, the main subsystems of a transformer that are exposed to degradation are:

- Dielectric (major/minor insulation, leads, windings)
- Magnetic circuit (core, clamping)
- Tap changers (LTC)
- Mechanical parts (bushing, tank, cooling, etc.)

The most applicable methods currently used as a routine test, diagnostic method, or monitoring technique are dissolved gas analysis (DGA), oil quality, furfural, power factor, tap changer monitoring, load history, and maintenance data. Condition monitoring tests and measurements can differ widely from one utility to another; however, the common methods used in the case of large/medium size power transformers are those mentioned.

4.2.1.1. Dissolved gas analysis (DGA)

DGA permits to distinguish internal faults in power transformers such as arcing, partial discharge, low-energy sparking, severe overloading, and overheating in the insulation system. IEC 60599 provides a coded list of faults detectable by dissolved gas analysis, and (C57.104, 2019) introduces a four-level criterion to classify risks to transformers for continued operation at various combustible gas levels. Practically, DGA data by itself does not always provide sufficient information from which to evaluate the integrity of a transformer. Normal operation will also result in the formation of some gases. Information about the history of a transformer (maintenance, loading practice, previous faults, manufacturer data, and so on) is an integral part of the information required to make an evaluation. Some transformers can operate throughout their useful life with substantial quantities of combustible gases present. (Piercy, Cress, Service, & Wang, 2009)

DGA Factor (DGAF):

$$DGAF = \frac{\sum_{i=1}^{7} S_i \times W_i}{\sum_{i=1}^{7} W_i} \qquad 11$$

where S_i = 1, 2, 3, 4, 5, or 6, and Wi is the assigned weighting factor. An initial value for W_i is allocated to be equal to 1 for both CO and CO_2; 3 for CH_4, C_2H_6, and C_2H_4; 5 for C_2H_2; and 2 for H_2.

S_i is the score of each gas based on Table 1. For example, if CH4 is more than 600 ppm, its score is 6. The weighting factors can be adjusted according to the current practice of a utility.

TABLE 1 SCORING AND WEIGHT FACTORS GAS LEVELS [PPM]

	Score (S_i)						
Gas	1	2	3	4	5	6	W_i
H_2	≤ 100	100-200	200-300	300-500	500-700	>700	2
CH_4	≤ 75	75-125	125-200	200-400	400-600	>600	3
C_2H_6	≤ 65	65-80	80-100	100-120	120-150	>150	3
C_2H_4	≤ 50	50-80	80-100	100-150	150-200	>200	3
C_2H_2	≤ 3	3-7	7-35	35-50	50-80	>80	5
CO	≤ 350	350-700	700-900	900-1100	1100-1400	>1400	1
CO_2	≤ 2500	≤ 3000	≤ 4000	≤ 5000	≤ 7000	>7000	1

According to the DGAF value the condition of the power transformer should be:

TABLE 2 TRANSFORMER RATING BASED ON DGA FACTOR

Rating Code	Condition	Description
A	Good	DAF < 1.2 **[AU8: I would left align the last column on DGAF]**
B	Acceptable	1.2 ≤ DGAF < 1.5
C	Need Caution	1.5 ≤ DGAF < 2
D	Poor	2 ≤ DGAF < 3
E	Very poor	DGAF ≥ 3

The rating code starts with A as the best condition to E, which represents the worst situation. This type of coding is employed for the remaining factors. This scoring system is not recommended for use as a diagnostics tool. It tries to give provide an overall figure of DGA results in a long-term time frame. (Bing , et al., 2020) (Duval, 2002).

In addition, the daily or monthly rate of gas production is important. IEEE recommended more frequent oil sampling based on the growing rate of total dissolved combustible gas (TDCG) When sudden increases in the dissolved gas content of the oil occur, an internal fault is suspected. A reduction of the HI is recommended if the rate of gas increment is more than 30% for three consecutive gas samples or 20% for five consecutive oil samples.

TABLE 3 DISTRIBUTION OF TRANSFORMER SAMPLE DATA

Date	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
2012/1/9	97	30.23	4.02	5.39	17.22	160	610	56.86	23.7	332.4	−9
2012/1/13	96.7	30.28	3.81	5.36	16.59	152.38	615.93	56.04	22.9	332.03	−14
2012/1/17	102	34.62	5.7	5.43	20.6	182	647	66.35	22.8	332.05	−12
2012/1/21	110	43.07	6.72	5.5	28.06	153	553	83.35	23.8	330.91	−14
2012/1/25	101	33	5.77	5.53	23	157	524	67.3	29.7	330.17	−12
2012/1/29	112	42.71	6.63	5.59	25.5	162	490	80.43	28	331.29	−11
2012/2/2	96	44.34	7.38	5.63	31.2	154	466	88.55	25.2	330.54	−11
2012/2/6	102	42.71	6.63	5.7	30.25	198	456	85.29	26.1	332.4	−9
2012/2/10	104	48.91	6.7	5.76	28.7	169	437	90.07	24.7	328.3	−9
2012/2/14	89	42.88	4.88	5.78	25.3	165	455	78.84	33	332.03	−6
2012/2/18	102	42.71	6.63	5.8	25.5	200	409	80.64	31.8	327.19	−6
2012/2/22	104	54.09	7.23	5.82	31.8	161	453	98.94	36	326.07	−5
2012/2/26	102	56.23	8.53	5.89	35.8	167	405	106.45	33.8	330.54	−2
2012/3/1	112	43.6	6.63	6.03	39.5	200	414	95.76	36	158	1
2012/3/5	125	53.67	5.64	6.07	36	200	456	101.38	40.1	329.79	1
2012/3/9	144	53.88	5.66	6.1	36.55	201	449	102.19	24.1	329.79	3
2012/3/13	122	52.71	6.63	6.13	35.01	200	439	100.48	40.8	329.42	3
2012/3/17	122	49.63	6.63	6.16	29.5	200	459	91.92	39.3	334.27	5
2012/3/21	122	42.71	6.63	6.23	25.5	200	409	81.07	39.9	332.78	5
2012/3/25	140	52.68	8.63	6.26	35.8	207	582	103.37	39.7	330.54	7
2012/3/29	147	55.76	9.1	6.31	34.9	197	630	106.07	38.5	332.03	8
2012/4/2	125	45.17	7.4	6.33	28.9	166	596	87.8	39.3	329.42	8
2012/4/6	131	47.12	8.21	6.34	29.65	171	609	91.32	39.5	329.33	12
2012/4/10	132	47.21	8.2	6.34	29.73	171	607	91.48	39.3	326.07	12
2012/4/14	145	42.61	5.74	6.3	24.35	171	591	79	42.1	330.54	12
2012/4/18	137	44.6	7.11	6.37	30.44	160	510	88.52	42.1	334.64	14
2012/4/22	122	42.71	6.63	6.36	25.5	196	496	81.2	49.3	332.78	14
2012/4/26	128	50.73	8.05	6.4	32.07	167	487	97.25	56	329.79	14
2012/4/30	135	63.94	10.78	6.46	39.8	121	392	110.98	48.8	335.01	14
2012/5/4	123	47.8	6.4	6.42	24.68	124	399	85.3	51.6	324.95	14
2012/5/8	122	42.7	6.63	6.43	25.5	160	406	81.26	43.1	324.5	15
2012/5/12	135	54.22	8.3	6.48	30.38	122	456	99.38	44	327	15
2012/5/16	145	65.41	10.03	6.54	35.7	138	496	117.68	48.1	256.2	15
2012/5/20	147	65.36	10.16	6.75	42.2	152	616	124.47	48	336	20
2012/5/24	148	70.87	11.67	6.81	45.2	167	606	134.55	49	335	20
2012/5/28	146	68.97	11.07	6.88	48.8	172	617	135.72	51.9	333.89	23
2012/6/1	147	72.31	11.86	6.94	48	192	650	139.11	52	336	23
2012/6/5	145	69.41	12.06	7	45.7	183	686	134.17	53	334	26
2012/6/9	148	70.6	12.3	7.06	49.8	200	698	139.76	58.3	329.05	27
2012/6/13	148	74.94	12.37	7.15	49.4	208	651	143.86	50.7	332.27	24
2012/6/17	146	70	12.35	7.21	45.7	198	666	135.26	58.2	331.66	27
2012/6/21	144	77.89	12.71	7.26	47.2	202	669	145.06	56.5	333.15	25
2012/6/25	147	77.63	19.72	7.32	53.87	206	680	158.54	55	333.89	25
2012/6/29	146	78.43	17.53	7.33	45.1	201	602	148.39	22.8	330.2	25
2012/7/3	148.05	78.27	11.14	7.39	45.8	206.3	603.58	142.6	52.4	329.05	26

4.2.1.2. Oil quality

Most of the limit recommendations for oil parameters are categorized based on the rated voltage in both IEEE and IEC standards. Table 4 shows the developed rating method for oil quality evaluation considering all parameters. It is important to note that these values are recommended for continued use of service-aged insulating oil and not for new oil. Rating codes A, B, C, D, E are determined using table 4. The estimation of the index is carried out as in the case of the DGA (Bing , et al., 2020).

TABLE 4 GRADING METHOD FOR OIL TEST PARAMETERS BASED ON IEEE C57.106-2006

	U ≤ 69 kV	69 kV < U < 230 kV	230 kV ≤ U	Score (Si)	Wi
Dielectric Strength kV (2 mm gap)	≥45	≥52	≥60	1	3
	35–45	47–52	50–60	2	
	30–35	35–47	40–50	3	
	≤30	≤35	≤40	4	
IFT dyne/cm	≥25	≥30	≥32	1	2
	20–25	23–30	25–32	2	
	15–20	18–23	20–25	3	
	≤15	≤18	≤20	4	
Acid Number	≤0.05	≤0.04	≤0.03	1	1
	.05–0.1	0.04–1.0	0.03–.07	2	
	0.1–0.2	1.0–0.15	0.07–.10	3	
	≥0.2	≥0.15	≥0.10	4	
Water content (ppm)	≤30	≤20	≤15	1	4
	30–35	20–25	15–20	2	
	35–40	25–30	20–25	3	
	≥40	≥30	≥25	4	
Color	≤1.5			1	2
	1.5–2.0			2	
	2.0–2.5			3	
	≥2.5			4	
Dissipation factor (%) 25 °C	≤0.1			1	3
	0.1–0.5			2	
	0.5–1.0			3	
	≥1.0			4	

4.2.1.3. *Power factor*

Power factor measurements are an important source of data to monitor the transformer and bushing conditions. Measurements of a transformer insulation's capacitance and power factor at voltages up to 10 kV (at 50 or 60 Hz) have long been used as both a routine test and for diagnostic purposes. The Table below recommends a ranking method for the power factor of the transformer. The tests can be done in the following configurations: high-voltage winding to ground, high- to low-voltage winding, low-voltage winding to ground, high- to tertiary-voltage winding, low- to tertiary-voltage winding, and tertiary-voltage winding to ground insulation. PF_{max} is the greatest of all the measured power factors.

TABLE 5 GREATEST POWER FACTOR RATING

Rating Code	Maximum Power Factor [%]
A	$PF_{max}<0.5$
B	$0.5 \leq PF_{max} <1$
C	$1 \leq PF_{max} <1.5$
D	$1.5 \leq PF_{max} <2$
E	$PF_{max} \geq 2$

4.2.1.4. Load History

The recommendations of IEC 354 and IEEE C57.91-1995-cor. 1-2002 with respect to conductor and oil temperature inside the transformer, proposes a set of similar values, but IEC has a more conservative recommendation for conductor temperature. Moreover, IEC suggests a 1.3 per unit (p.u.) load factor for long-term emergency period and a 1.5 p.u. load factor for a short-term emergency period. The recorded monthly load peaks can be employed to calculate the load history contribution to HI calculations. The load history is categorized according to the five groups listed below:

N0 = Number of Si/SB that are lower than 0.6, i = 0,

N1 = Number of Si/SB that are between 0.6 and 1, i = 1,

N2 = Number of Si/SB that are between 1 and 1.3, i = 2,

N3 = Number of Si/SB that are between 1.3 and 1.5, i = 3

N4 = Number of Si/SB that are greater than 1.5, i = 4,

where Si is the monthly peak load, and SB is the rated loading of the transformer.

The equation below proposes a linear method of load score calculation:

$$LF = \frac{\sum_{i=0}^{4}(4-i) \times W_i}{\sum_{i=0}^{4} N_i} \quad 12$$

Table 6describes a ranking method of transformer condition using the load history data.

TABLE 6 LOAD FACTOR RATING CODES

Rating Code	Description
A	$LF \geq 3.5$
B	$2.5 \leq LF < 3.5$
C	$1.5 \leq LF < 2.5$
D	$0.5 \leq LF < 1.5$
E	$LF \leq 0.5$

4.2.1.5. Tap changer

The insulation system of a Load Tap Changer (LTC) usually consists of oil, cardboard, fiberglass, or epoxy resin depending on the construction. The insulation quality of the oil is of primary concern. The rate of degradation significantly increases at temperatures above 80 ºC.

There are two main sources of gas in LTCs (Naderian, Piercy, Cress, Wang, & Service, 2008):

- Arcing gasses (main acetylene) are affected by the speed of operation, recovery voltage, and arcing tip wear.
- Heating gasses (methane, ethane, and ethylene) are created through coking, generated by I2R losses from lead and contact impedances.

The concentration of DGA in a LTC depends on several variables, including breathing type, manufacturer, LTC model, oil brand, operating current, step-voltage of the LTC, and the number of operations. Therefore, it is not easy to recommend gas limits for DGA of LTCs, nor is there a standard recommendation. Table 7 proposes a scoring method for the DGA analysis of three different types of LTCs. It is based on Kinectrics Inc.'s common practice and other references. A similar DGA factor to (1) is employed to rank the LTC based on the DGA analysis. This Table is used to rate the LTC using the calculated DGAF.

TABLE 7 RATING OF THE LTC BASED ON DGA

		Score (S_i)				
	Gas	**1**	**2**	**3**	**4**	W_i
Vacuum LTC	CH_4	<30	30- 50	50-100	≥ 100	3
	C_2H_6	<20	20- 30	40-50	≥ 50	3
	C_2H_4	<50	50-100	100-200	≥ 200	4
	C_2H_2	<3	3- 4	4-5	≥ 5	5
Resistive LTC	CH_4	<100	100- 200	200-300	≥ 300	3
	C_2H_6	<50	50-100	100-200	≥ 200	3
	C_2H_4	<200	200- 400	400-600	≥ 600	5
	C_2H_2	<500	500- 1000	1000-5000	≥ 5000	3
Reactive LTC (Diverter comp.)	CH_4	<200	200- 300	300-700	≥ 700	3
	C_2H_6	<100	100- 150	150-500	≥ 500	3
	C_2H_4	<300	300-500	500-1400	≥ 1400	5
	C_2H_2	<1000	1000- 3000	3000-7500	≥ 7500	3
Reactive LTC (Selector comp.)	CH_4	<50	50- 150	150-250	≥ 250	3
	C_2H_6	<30	30- 50	50-100	≥ 100	3
	C_2H_4	<100	100- 200	200-500	≥ 500	5
	C_2H_2	<10	10- 20	20-25	≥ 25	3

4.2.1.6. Furfural

Measurement of the furfural content of the oil can be used for bulk measurement of the degree of polymerization of the paper insulation. If the data is available, the first 2 columns of Table 8 are employed to add those test results to the HI calculation. If the transformer's oil has been reclaimed or changed, then this test cannot give real information on the paper degradation. In such cases, the age of the transformer may be used in the HI calculation as per the third column of Table 8. Note that this table does not imply a relationship between the furan test and the transformer age.

TABLE 8 FURFURAL TEST RATING OR AGE RATING WHERE TEST NOT AVAILABLE

Rating Code	Furaldehyde [ppm]	Age Years
A	0-0.1	Less than 20
B	0.1-0.5	20-40
C	0.5-1	40-60
D	1-5	More than 60
E	>5	-

2.2.1.7 Others electrical measurements

TABLE 9 RANKING OF THE TURN RATIO TEST, LEAKAGE REACTANCE TEST, CORE-TO-GROUND TEST, AND WINDING RESISTANCE TEST.

Rating Code	Turn ratio (TR) deviation of actual to declared [%]	Leakage reactance deviation [%]	Core-to-ground resistance [MΩ]	Winding resistance deviation [%]
A	$\Delta TR \leq 0.1\%$	$\Delta X < 0.5\%$	$R > 1000$	$\Delta R < 1\%$
B	$0.1\% < \Delta TR \leq 0.5\%$	$0.5\% \leq \Delta X < 1\%$	$100 \leq R < 1000$	$1\% \leq \Delta R < 2\%$
C	$0.5\% < \Delta TR \leq 1\%$	$1\% \leq \Delta X < 2\%$	$10 \leq R < 100$	$2\% \leq \Delta R < 3\%$
D	$1\% < \Delta TR < 2\%$	$2\% \leq \Delta X < 3\%$	$1 \leq R < 10$	$3\% \leq \Delta R < 5\%$
E	$\Delta TR \geq 2\%$	$\Delta X \geq 5\%$	$R < 1$	$\Delta R \geq 5\%$

4.2.1.7. Estimation of the HI for the power transformer

TABLE 10 HEALTH INDEX SCORING

Health Index Scoring.				
#	Transformer Condition Criteria	K	Condition Rating	HIF
1	DGA	10	A,B,C,D, E	4,3,2,1,0
2	Load History	10	A,B,C,D, E	4,3,2,1,0
3	Power Factor	10	A,B,C,D, E	4,3,2,1,0
4	Infra-red	10	A,B,C,D, E	4,3,2,1,0
5	Oil Quality	6	A,B,C,D, E	4,3,2,1,0
6	Overall Condition	8	A,B,C,D, E	4,3,2,1,0
7	Furan or Age	5	A,B,C,D, E	4,3,2,1,0
8	Turns ratio	5	A,B,C,D, E	4,3,2,1,0
9	Leakage reactance	8	A,B,C,D, E	4,3,2,1,0
10	Winding resistance	6	A,B,C,D, E	4,3,2,1,0
11	Core-to-ground	2	A,B,C,D, E	4,3,2,1,0
12	Bushing Condition	5	A,B,C,D, E	4,3,2,1,0
13	Main Tank Corrosion	2	A,B,C,D, E	4,3,2,1,0
14	Cooling Equipment	2	A,B,C,D, E	4,3,2,1,0
15	Oil Tank Corrosion	1	A,B,C,D, E	4,3,2,1,0
16	Foundation	1	A,B,C,D, E	4,3,2,1,0
17	Grounding	1	A,B,C,D, E	4,3,2,1,0
18	Gaskets, seals	1	A,B,C,D, E	4,3,2,1,0
19	Connectors	1	A,B,C,D, E	4,3,2,1,0
20	Oil Leaks	1	A,B,C,D, E	4,3,2,1,0
21	Oil Level	1	A,B,C,D, E	4,3,2,1,0
22	DGA of LTC	6	A,B,C,D, E	4,3,2,1,0
23	LTC Oil Quality	3	A,B,C,D, E	4,3,2,1,0
24	Overall LTC Condition	5	A,B,C,D, E	4,3,2,1,0

$$\mathrm{HI} = 60\% \times \frac{\sum_{j=1}^{21} K_j \mathrm{HIF}_j}{\sum_{j=1}^{21} 4K_j} + 40\% \frac{\sum_{j=22}^{24} K_j \mathrm{HIF}_j}{\sum_{j=22}^{24} 4K_j} \quad (13)$$

If some data is not available for evaluation of the HIF value will be zero.

This subsection was based on the following references (Duval, A review of faults detectable by gas-in-oil analysis in transformers, 2002), (IEC 60599, 2015), (C57.104, 2019), (C57.106, 2015), (IEC_60505, 2017)

4.2.2. Health index for power lines

Energy utility companies depend upon the mechanism for ascertaining the energy framework through controlling and regulating the health condition. The procedure of the mechanism is monitored through the implementation of strategy without failure. The mechanism aims to ensure that the work is being done in a continuous conventional procedure. The virtue administration is ascertained by the effective mechanism which is possible to delineate a neutral policy for perpetuation, renovating, or renewal of

the benefit or the forte. The statistical data of the module in the communication circulating could be helpful in the evolution of the health index. Through the conventional execution of the health index, the groundwork of the conservation could be diagnosed according to which the required performance can be enforced looking upon the need of the boon (Ruqayyah , Fathoni, & Intan Nor , 2019).
It has been approached to pin down the health catalog depending upon the inuring the judgment of the overhead transmission lines. The procedure of identifying the health index is brought forth in the figure given below. The constituent is diversified in four practices namely foundation, structure, conductor, and insulator where the customization of these four constituents was surveyed in the analysis. Henceforth the assessments which were conducted by the patrolmen and the circumstances of the components were being classified. The computations of the health index which were assessed by the patrolmen were positioned on the checking list document to investigate the overhead transmission line (Aktan, Catbas, & Grimmelsman, 2000).

Figure 2 Concoct of actuate health index

As stated the modification of the conductor can be inflated to analyze the resting life. The technique by which the condition of the conductors can be emphasized is based on the figure 2. The condition of the conductor can be bifurcated into two modes, a basic health index, and a comprehensive health index. The basic health index is examined as a physical condition, service record guidelines, and the de-rating aspects. The de-rating aspects crop up once the statistics show any existence of any reconstruction or any rehabilitation, while the comprehensive health index formula comprises habitual assets, palpable assets, service records, reformations, and remaining ductile strength (Serra, Carmona, Marquez, & Sola, 2019).

4.2.2.1. Health Index of Overhead Transmission lines

Overhead Transmission Lines have been aiding in the exchange of electrical energy to the consumers since the beginning of power systems. The state of transmission lines consists of four main constituents namely foundation, structure, insulator, and conductor.

Six trivial health components assess the health index of the overhead transmission lines. The construction of the pole that supports the transmission wires which comprises the body along with four sides with a cross arm that can be made up of any materials. The construction of the pole embodies the whole transmission tower. The whole structure is thus divided into the following parts namely the tower leg, tower frame, bracing, and cross arms. The various tower constructions include a self-sufficient trelliswork, bolster or poles, or the mounted construction. Care is taken to ensure that the layout of the poles has always been constructed keeping into focus the communal agitation, the construction methodology, and lastly the conventional investigation practice. In most cases the structured poles are made of galvanized steel as of the benefits for manufacturing, rousting, and conveying purpose (Thongchai, Pao-La-Or, & Kulworawanichpong, 2013). Past researchers have come to a conclusion that the steel poles have been inconvenient as it resulted in the rusting as the wooden poles too that caused crack resulting in the fall of the tower accidentally. Along with these failures, many more processes have also been at a huge fault due to connotation, agreement, and immoderate diversion. Nevertheless, only one research stated that ravaging and ruining may have an influence be effective in influencing the state or the shape of the transmission lines. It has been clear through the above study that vandalism or ruining is the main cause of the dereliction (J. & P., 2019).

Taking into account the maximum power flow limits, the conductors act in a dedicated way. The aluminum conductor steel reinforced (ACSR) is the customarily used material for transmission lines, considering its potential, the extensive mass-producing capability, and the cost. Studies reveal that the usage of copper has become infrequent in current transmission lines, as it has more weight and is more costly compared to aluminum wires that provide the same efficiency at a much lesser cost. Due to the pollutants present in the air, it has been noted that the conductors are more prone to degradation mainly in places where there are many industries present, which release the heavy pollutants to the atmosphere (Liu et al., 2018). The pollutants thus get inside the conductor wires through the juncture and thus bring in an adverse effect on the proper functioning of the overhead transmission lines as the corrosive pollutant contaminate the joints. The level of the contamination could be detected by assessing the joints and measuring the temperature and the current power. Moreover, studies reveal that there are only three researchers that brought forth the topic of the decomposition in the conductor element. On the other hand, many other researchers believed that the overhead transmission lines are the main reason for the failure in power transmission. Several other reasons include were the unsteady, rickety wire strands and the incompatible jumpers and the sags (Velásquez and Lara, 2018).

The insulator is considered one of the most critical elements of the overhead transmission lines according to researchers. The research also states that if the transmission lines are not correctly encased the flow of the electricity would not be performed in a proper conventional way resulting in a potential threat to human lives. The proper blockage of the current through the insulators would not let the current flow down the pole. The primary materials used in the insulators are namely glass, porcelain, and polymers. The degree of pollutants effect, crack in the insulator and the life of service provided by the insulator is the basis for checking the insulation (Naranpanawe et al., 2020).

A Few researchers stressed the fact that the construction of transmission poles need to be considered when the work provided by the overhead transmission lines. The organization of the tower to the ground is a vital process that would determine the proper functioning of the tower. As seen most foundations of the tower are made up of the galvanized steel poles attached to concrete poles. Steel towers get exposed to the air and would become rusty resulting in the degradation of the walls of the poles along with the poles. The poles are also affected by their placement in the surroundings where soil erosion, floods, and many other factors contribute to the decadence of the structure. The previous reasons are responsible for the improper distribution of the electricity to the consumers because the proper flow of the supply is hindered (Liu et al., 2018).

Studies have shown the statistical data from the energy commissioner indicates being 31% of power interruption is caused by environmental factors. Based on this study the quality of each component of the electric power transmission tower is mainly affected by atmospheric corrosion. Other factors include the building components of the tower and the way they get installed (Thongchai et al., 2013). In table 11 is showing some criteria for evaluation of HI for overhead line.

TABLE 11 OVERHEAD LINES – HEALTH INDEX CALCULATION

	Criteria	Ranking	Highest score	Weight assigned	Maximum weighted score
1	Lifespan of the pole	1-5	5	3	15
2	Maintenance of the pole	1-5	5	1	5
3	Inspection of poles	1-5	5	1	5
4	Visual analysis of the poles	1-5	5	4	20
5	Visual analysis of the insulators	1-5	5	1	5
6	Visual analysis of the hardware	1-5	5	1	5
7	Life of conductors	1-5	5	1	5
8	Small risks of conductors	1-5	5	5	25
9	Conductors energy loss	1-5	5	3	15
	Total				100

4.2.2.2. HI of Underground Transmission cables

It is a crucial undergoing by which the investigation of the circuit wires is done on time. The proper maintenance of transmission lines helps to keep them in working condition for a longer period. The cable health index provides a crystal-clear analysis of the method of the assessment, based on the maintenance of the pole and the health of the overhead transmission lines (Navrud et al., 2008).

Health index quantifies equipment conditions relative to long-term degradation factors that cumulatively lead to an asset’s end-of-life. Therefore, it could be said that the proper monitoring of the live wires and the supply of energy on a time to time basis could be helpful in the conventional maintenance while ensuring the longevity of the overhead transmission poles (Somsak et al., 2019).

TABLE 12 CABLES, SPLICES AND TERMINATORS HEALTH INDEX

	Criteria	Ranking	Highest score	Weight assigned	Maximum weighted score
1	Life of circuit	1-5	5	3	15
2	Design of circuit	1-5	5	3	15
3	Capability of the cable wire	1-5	5	5	25
4	Past failures	1-5	5	8	40
5	Investigation of terminators	1-5	5	1	5
	Total				100

TABLE 13 MANHOLES AND VAULTS HEALTH INDEX

	Criteria	Ranking	Highest score	Weight assigned	Maximum weighted score
1	Constructional probity	1-5	5	8	40
2	Flooding and ways to overcome	1-5	5	4	20
3	Accessibility	1-5	5	8	40
	Total				100

4.3. Maintenance Strategy *(MS).*

This section includes some typical strategies to take into account in the maintenance of assets in power lines

4.3.1. Maintenance of power transformers. Contribution to HI

A ranking system was developed based on the maintenance work orders issued in the last five years for a transformer and its equipment. Infrared thermography and bushing conditions are two important factors in this evaluation. Oil leak, oil level, cooling system, gaskets, main tank condition, and grounding are also taken into account. Table 14 shows the condition criteria based on corrective maintenance work orders in the last five years. If there aren't any work orders in the last five years for any of these factors, the condition rating will be "A." It is suggested that the rate of increase of work orders be monitored as well. An overall condition factor is introduced to include the rate of maintenance work orders as shown in Table 14. Aside from bushing visual inspection such as oil leak and porcelain or silicon rubber condition, there are recommended tests such as oil tests (DGA, moisture, and so on), power factor tests, and hot collar tests that can be separately quantified like the transformer oil and power factor test.

TABLE 14 OVERALL CONDITION BASED ON TREND IN TOTAL CORRECTIVE MAINTENANCE WORK ORDERS

Condition Rating	Condition Criteria Description
A	[Max(last 2 yrs) < 3] OR [increased < 10% over 5 yrs]
B	[Max(last 2 yrs) > 3 AND increased > 10% over 5 yrs] OR [Max(last 2 yrs) > 5]
C	[Max(last 2 yrs) > 5 AND increased > 30% over 5 yrs] OR [Max(last 2 yrs) > 10]
D	[Max(last 2 yrs) > 10 AND increased > 50% over 5 yrs] OR [Max(last 2 yrs) > 15]
E	[Max(last 2 yrs) > 15 AND increased > 80% over 5 yrs] OR [Max(last 2 yrs) > 20]

4.3.2. Surge Arresters

TABLE 15: MAINTENANCE SCHEDULE FOR ARRESTERS

Maintenance Task	Frequency
Perform infrared inspections of energized arrestors	Outdoors: semiannually; Indoors: annually
Check tightness of line and ground connections.	Annually
Clean the porcelain surfaces, repair any damaged porcelain.	6 years
Check the apparent condition of the grounding conductors and their connections.	6 years
Check the condition of weather heads and weather hoods to determine that they remain in good condition.	6 years
Conduct insulation resistance tests and power factor tests.	6 years

4.3.3. High Voltage Cables

TABLE 16 MAINTENANCE TASKS OF HIGH VOLTAGE CABLES

Maintenance Task	Frequency
Infrared Scan, Cables.	Annually
DC, high-potential test. DO NOT test Cross-linked polyethylene cables with DC in “wet” Location.	5 years

4.3.4. Circuit Breakers

TABLE 17 MAINTENANCE TASKS OF CIRCUIT BREAKERS

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Visual inspection of Critical MCCBs	Indoors: 6 years Outdoors: 3 years
Manual operation of Critical MCCBs	Indoors: 6 years Outdoors: 3 years
Inverse-time over current and/or instantaneous trip test of critical MCCBs	Indoors: 6 years Outdoors: 3 years
Infrared scan and thermal analysis	Annually
Visual inspection of non-critical MCCBs	Indoors: 6 years Outdoors: 3 years
Manual operation of non-critical MCCBs	Indoors: 6 years Outdoors: 3 years
Inverse-time over current and/or instantaneous trip test of non-critical MCCBs	Indoors: 6 years Outdoors: 3 years
Insulation resistance test	Indoors: 6 years Outdoors: 3 years
Contact resistance test	Indoors: 6 years Outdoors: 3 years

4.3.5. Low-Voltage (600 V and Less) Draw-Out Air Circuit Breakers

TABLE 18 CAPTION MAINTENANCE TASKS OF LOW_VOLTAGE

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Visual inspection	Annually
Preventive maintenance	Indoors: 6 years Outdoors: 3 years
Manual operation	Indoors: 6 years Outdoors: 3 years
Timing tests	Indoors: 6 years Outdoors: 3 years
Insulation resistance test	Indoors: 6 years Outdoors: 3 years
Infrared scan and thermal Analysis	Annually

4.3.6. Medium Voltage (601 V – 15kV) Air and Air Blast Circuit Breakers

TABLE 19 MAINTENANCE TASKS OF MEDIUM AIR AND AIR BLAST CIRCUIT BREAKERS

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Visual inspection	Annually
Preventive maintenance	Indoors: 6 years Outdoors: 3 years
Manual operation	Indoors: 6 years Outdoors: 3 years
Insulation resistance test	Indoors: 6 years Outdoors: 3 years
Contact resistance test	Indoors: 6 years Outdoors: 3 years
Timing tests	Indoors: 6 years Outdoors: 3 years
Motion analysis	Indoors: 6 years Outdoors: 3 years
Breaker control functional testing	Indoors: 6 years Outdoors: 3 years
Infrared scan and thermal analysis	Annually

4.3.7. Medium Voltage (601 V-15kV) Vacuum Circuit Breakers

TABLE 20 MAINTENANCE TASKS OF MEDIUM VOLTAGE (601 V-15KV) VACUUM CIRCUIT BREAKERS

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Visual inspection	Annually
Preventive maintenance	Indoors: 6 years Outdoors: 3 years
Manual operation	Indoors: 6 years Outdoors: 3 years
Insulation and vacuum-integrity test	Indoors: 6 years Outdoors: 3 years
Contact resistance test	Indoors: 6 years Outdoors: 3 years
Timing tests	Indoors: 6 years Outdoors: 3 years
Motion analysis	Indoors: 6 years Outdoors: 3 years
Breaker control functional testing	Indoors: 6 years Outdoors: 3 years
Infrared scan and thermal analysis	Annually
Contact-erosion indicator check	Per Manufacturer O&M manual

4.3.8. Medium and High Voltage Oil Circuit Breakers

TABLE 21 MAINTENANCE TASKS OF MEDIUM AND HIGH VOLTAGE OIL CIRCUIT BREAKERS

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Inspect and test insulation oil	Annually
Visual inspection	Annually
Infrared Scan and thermal analysis	Annually
Preventive maintenance	6 years
Manual operation	6 years
Insulation test	6 years
Contact resistance test	6 years
Breaker timing test	6 years

Breaker motion analysis test	6 years
Breaker control functional testing	6 years

4.3.9. Medium and High Voltage SF_6 Circuit Breakers

TABLE 22 MAINTENANCE TASKS OF MEDIUM AND HIGH VOLTAGE SF_6 CIRCUIT BREAKERS

Maintenance Task	Frequency
Review equipment ratings and coordination study	5 years
Visual inspection	Annually
Preventive maintenance	6 years
SF6 gas analysis	Annually
Manual operation	6 years
Contact resistance test	6 years
Timing tests	6 years
Motion analysis	6 years
Breaker control functional testing	6 years
Internal circuit breaker inspection or overhaul	12 years, 5,000 operations, or high current interruptions
Dynamic resistance measurement	6 years
Radiography Inspection	12 years or if problems are identified by other tests

4.3.10. Overhead Distribution Lines

TABLE 23 MAINTENANCE TASKS OF OVERHEAD DISTRIBUTION LINES

Maintenance Task	Frequency
Ground line inspection – Examine entire structure from ground for the following defects: (1) Excessive checking, cracking, or splitting; particularly deep cracks along the entire length of the poles showing white wood (2) Woodpecker holes and evidence of insect colonies. (3) Excessive shell decay above the noted degree. (4) Lightning damage. (5) Damaged or corroded guying. (6) Damaged bracing. (7) If in through-drilled poles the backfill extends above the drilled section – REMOVE! (8) Any other obvious defects.	12 years for healthy poles; 6 years for minor decay in previous inspection.
Measure and record the pole circumference at the ground level, remove the surface decay down to *healthy* wood, and record the new circumference of the pole.	12 years for healthy poles; 6 years for minor decay in the previous inspection.
For wood poles and cross arms, if pole top and cross arm defects cannot readily be assessed from the ground, climb the pole for a thorough analysis after determining that it is safe to do so every 12 years for sound poles and every 6 years for minor decay in the previous inspection.	12 years for healthy poles; 6 years for minor decay in the previous inspection.

4.3.11. Transducers, Meters, Switches

TABLE 24 MAINTENANCE TASKS OF TRANSDUCERS, METERS, SWITCHES

Maintenance Task	Frequency
Test and calibrate transducers, meters, and switches	3 years

4.3.12. Protective Relay

TABLE 25 MAINTENANCE TASKS OF PROTECTIVE RELAY

Maintenance Task	Frequency
Perform relay calibration and functional testing.	Every year in harsh conditions and every 2 years in controlled environments.
Verify that correct instrument transformer output signals are received at the protective relay.	6 years

4.4. Economic Impact (EI)

This dimension will include any economic and environmental aspects that could be important in the evaluation of the asset from a management perspective. Types of information expected in this dimension are undelivered energy in the event of a failure, cost of the repair, social impact through the number of customers affected by a fault, and/or type of business affected, among other variables that could be included in this dimension. Several references suggest the evaluation of this type of impact, for example (A.S. Nazmul Huda, 2019) or (R.F. Ghajar, 2006).

5. Definition of asset management tools

The asset management module in the ATTEST project will be an open-source toolbox developed according to three different levels of information about the asset conditions, that will contribute to improving the management of distribution and transmission networks. These three levels are the following:

- The first level consists of the identification of the critical information/data to quantify the health condition of the asset. Typically, there is a multiplicity of data collected during the observed life of the assets with different granularity and formats. This information needs to be properly handled, converted, and ranked according to its contribution to the condition indicators to be developed in the next level;
- The second level of the smart asset management environment entails the definition and development of methods for estimating condition indicators for the assets. These methods are based on the heterogeneous information/data sources selected in the first level. The idea is to obtain comparable condition indicators for different assets including a factor of certainty (or confidence) of the indicators created.
- The third and final level of this smart environment will create a tool to simulate and quantify the evolution of the condition indicator previously defined for the asset under different management strategies.

The asset management tool is based on three tools that cover the three levels previously mentioned. The tools are the following:

- **Tool for the characterization of the health condition of assets:** The goal of this tool is the characterization of the assets using indicators based on different aspects of their lives.
- **Tool for the definition of condition indicators based on heterogeneous information sources**: This tool defines an innovative approach to translate the results obtained from the previous tool into a set of harmonized, easily measurable, and comparable indicators for different types of assets, which will allow identifying which assets require special attention from an asset management point of view.
- **Tool for the definition of smart asset management strategies:** This tool permits the comparison of assets under different perspectives (operation, maintenance, cost, impact) resulting in priority lists. Smart strategies for asset management based on the previous asset evaluation and common life indicators will be also developed.

The main characteristics of the asset management module tools are summarized in the datasheet in figure 3.

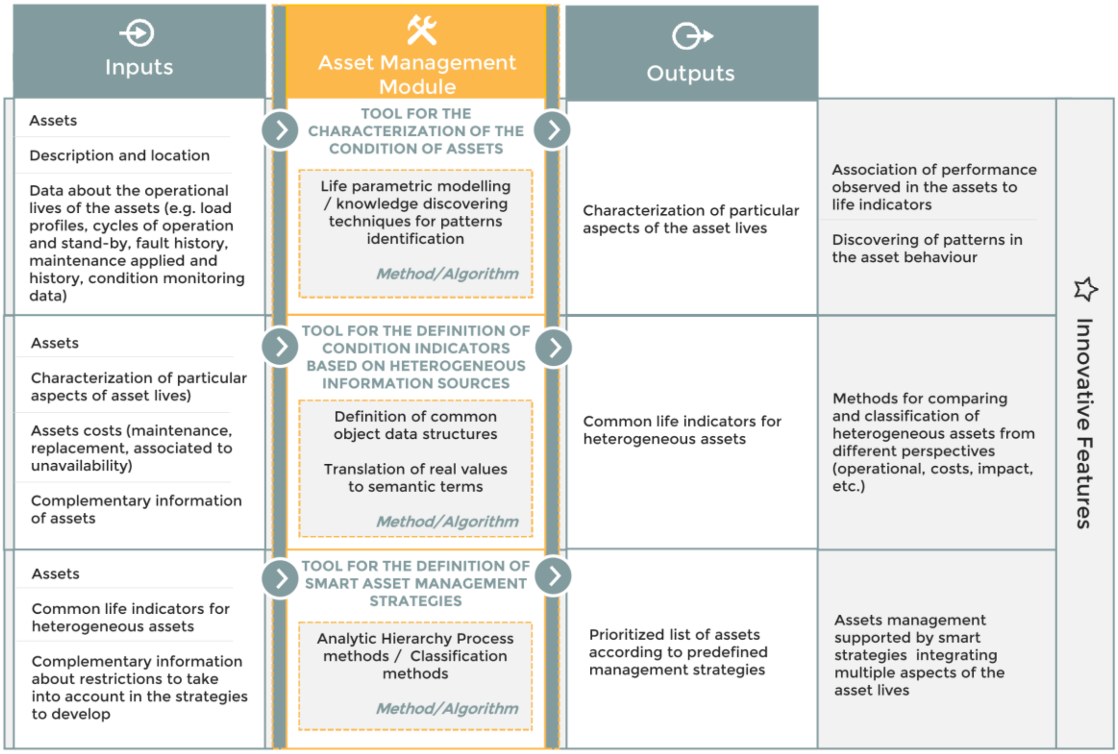

FIGURE 3 ASSET MANAGEMENT MODULE

The main features taken into account in the development of these tools are the following:

- All these tools have to be open source and easy to adapt to any new case where this module of ATTEST wants to be applied for guiding asset management.
- Complementing the previous feature, the tools have to be sufficiently generic to host most of the data scenarios in power companies, both in transmission and distribution.
- The design of the tools has to be modular to be able to adapt to the needs of users in assets management.
- The name of the assets usually will be obtained from files describing the power grids through interfaces specifically designed. The addition of new assets should always be possible according to some rules that will be specified later.
- The particular examples of applications used for demonstration could use part or the whole data structure designed in the tools.
- Python is the development language selected for the tool. This facilitates an easy implementation to any platform.

To test the tools developed, several cases have been studied. They are the following:

- Case of a power distribution grid proposed by the partner by HEP ODS in Croatia
- Case of a power transmission grid proposed by the partner by HOPS in Croatia
- Case of a power distribution grid proposed by an electrical company in Spain

In addition, another case has also been used. A synthetic distribution power grid with a very realistic representation based on a real scenario from which it was created. This case has a larger scope, and more variety in the types of assets, allowing for a wider demonstration of the possibilities and capabilities of the tools developed.

5.1. Foundations of the tools

The main principles that inspired the tools developed are focused on the consideration that each asset is evaluated by analyzing four different dimensions: ***life assessment***, ***health condition***, ***maintenance,*** and ***economic and environmental impacts***. These four dimensions are supported by basic indicators or variables selected by the power grid company according to the data that they collect during normal operation. This feature is considered to be very important to facilitate the use of the tools because they can be adapted easily to any context of data collection in an electrical company. Examples of possible types of data to be included in the four dimensions are as follows:

- Life assessment dimension. Some variables or basic indicators that could be included for the evaluation of this dimension are the following: age of the assets, estimation of failure probability, the importance of the asset based on the number of customers connected, the number of "special" customers connected, energy delivered or served per year and criticality index in the power grid of the assets. Other similar characteristics could be included in this dimension.
- Health condition. This dimension is to be used only if some periodic or online measurements are collected in the assets. The idea is to evaluate its current condition base on various recent observations. Some examples of measurements that could be used to implement this approach are a continuous measurement of internal temperature in the power transformer, dissolved gas analysis, or oil quality. Usually, these types of observations are not available in the assets of a distribution power grid but can be available in larger and more critical transmission transformers.
- Maintenance. This dimension evaluates the maintenance actions applied, and its effectiveness through some basic indicators such as Mean Time To Repair (MTTR) or similar indicator, Mean Time Between Failures (MTBF), the evolution of the number of work orders for this asset in a given period, and scheduled maintenance cycles.
- Economic and environmental impacts. This dimension considers the consequences of a failure of the assets according to different aspects such as maintenance costs, the cost of the failure, customers affected, value of the undelivered energy, and environmental damages.

The basic indicators cited for each dimension are examples of how to observe and evaluate them. They will be the core information to be managed at the first tool within the asset management toolkit, which corresponds to the "***Tool for the characterization of the condition of assets***". Additionally, each asset consists of information about its physical characteristics, such as the type of asset, manufacturer, or other non-dynamic information about the asset. Figure 4 presents a scheme summarizing the approach previously described in the context of the asset management work package (WP) of the ATTEST project.

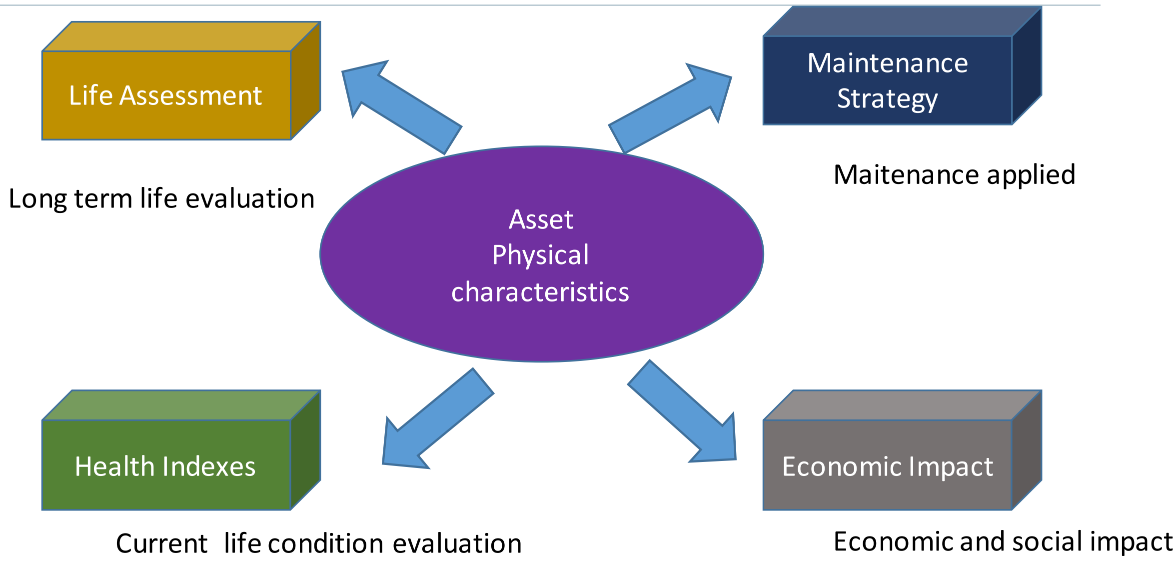

FIGURE 4 SCHEME OF THE BASIC DIMENSIONS OF THE ASSETS CONSIDERED IN THE DEVELOPMENT OF THE TOOLS

Once the basic indicators under each dimension are defined and assigned to each asset, machine learning algorithms are applied for clustering the assets according to their similarity, with respect to the basic indicators selected in each dimension. This allows the tool to reduce the dimensionality of the case being analyzed, by reducing the number of assets to a few groups of several assets with similar features (clusters). This facilitates the identification of the cluster that requires special attention from an asset management point of view, prioritizing the assets included in that cluster. This analysis can be performed flexibly either at the level of a single dimension or for all the dimensions.

The second tool to be developed corresponds to the "Tool ***for the definition of condition indicators based on heterogeneous information sources***". The main objective of this tool is to use simultaneously all four dimensions obtained in the previous level to integrate this information in comparable condition indicators for the assets. A new clustering algorithm is to be applied for combining the information collected from the four dimensions in a weighted formula. The user selects the weights according to the desired strategy of the electrical company. Each dimension contributes to the assessment of each asset according to predefined weights as shown in Figure 5.

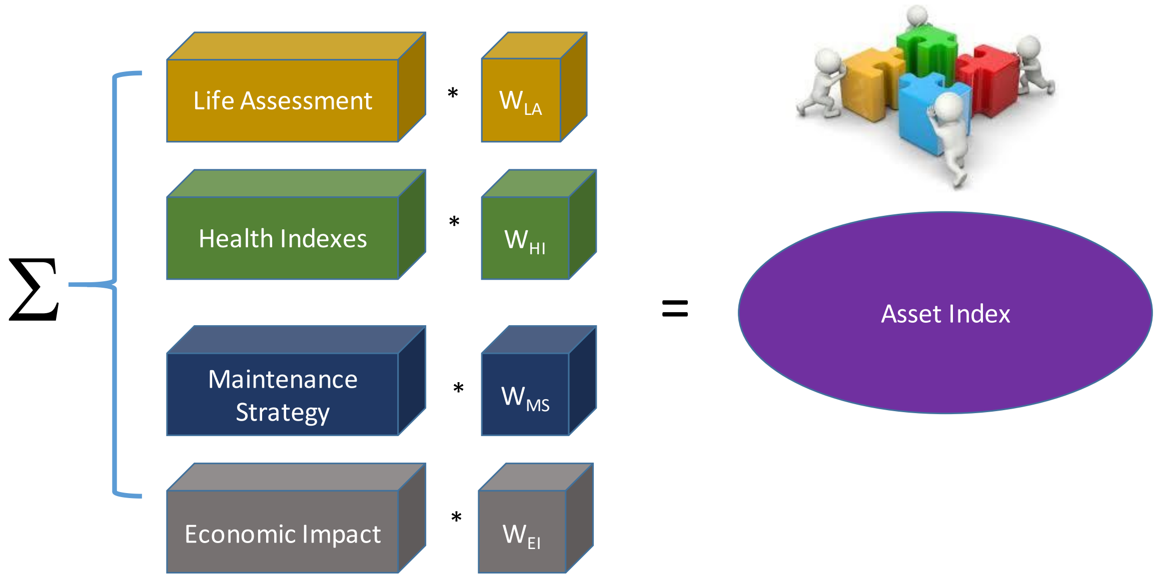

FIGURE 5 COMBINATION OF ALL DIMENSIONS

For each asset, each dimension ranges in a similar scale to compare different aspects observed and evaluated using different methods. In Figure 6 explain an idea of the results that should be obtained for each dimension of each asset.

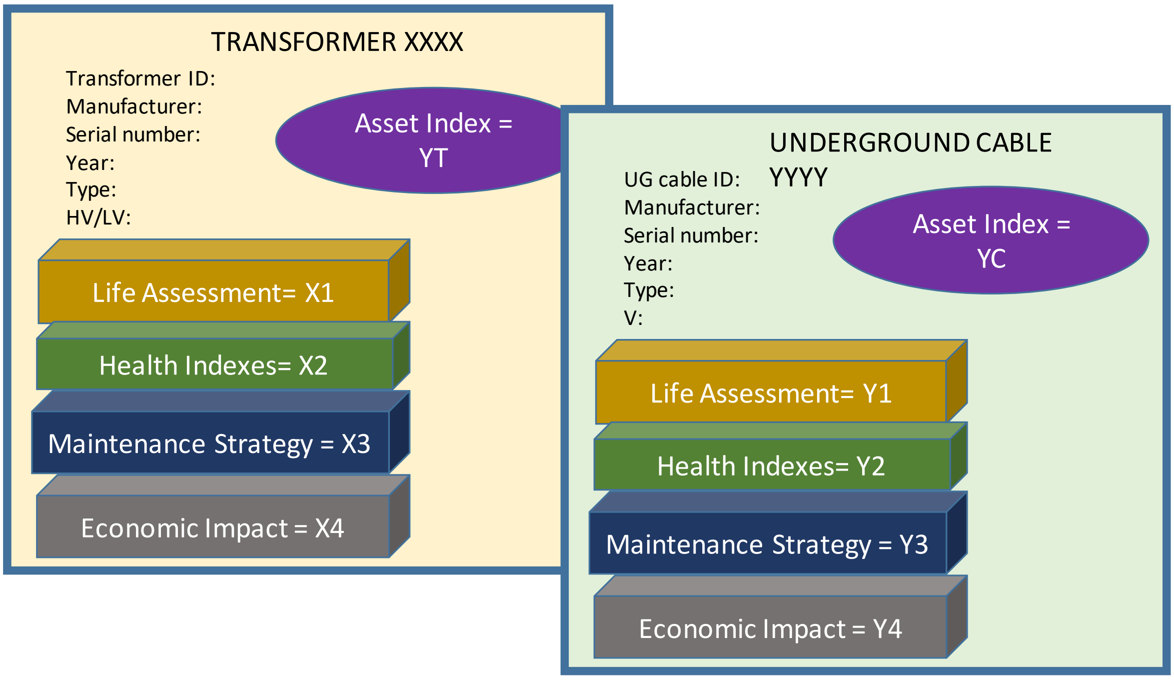

FIGURE 6 RESULTING INDICATORS FOR EACH ASSET

The results at this level should an inventory of assets by importance so that new maintenance, rescheduling, or replacement could be applied. This information further guides the asset management process at the third level.

The interaction among the different tools developed in this work package is illustrated in Figure 7. First, asset IDs and types are obtained from a power grid description. This leads to a definition of characteristics and data for life assessment, health indexes, maintenance strategy, and economic impact, which is used to characterize the condition of assets in the first tool. In the second tool, condition indicators are obtained for each asset. Finally, the third tool proposes asset management strategies.

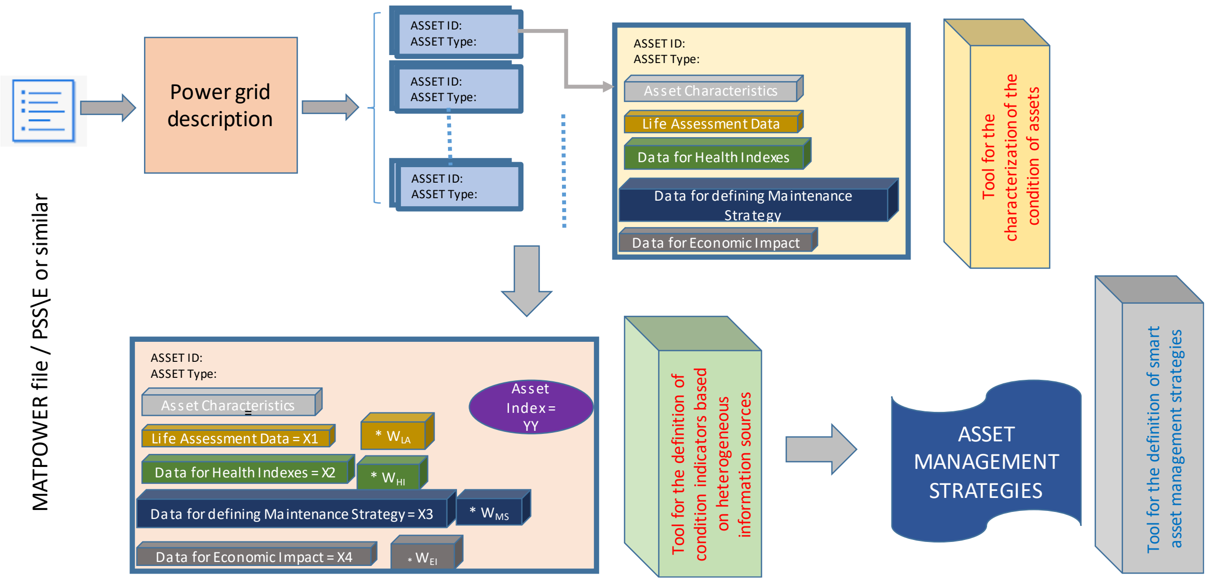

FIGURE 7 SCHEME OF INTERACTION OF DIFFERENT TOOLS

5.2. Input data for the tools

As was presented in the previous subsection, the tools developed in this work package are three-tier structures, where each tier corresponds to one asset condition characterization tool. Each tool uses results from previous levels supplemented by additional data. This means that the data required in this work package is that which is used in the access level

This subsection will describe the types of data used at the access level. The variables can be adapted to the data available in each power system company. This is the reason why it is not necessary to define a unique list of variables required as inputs for the tools of this work package.

The data described in the following paragraphs correspond to the different cases used as examples of the operation of the tools, but other variables could be used by different companies to use these tools.

As a general observation, it should be noted that all data used as tool-level inputs have to be ***.csv*** files with headings in each column, and a comma used to separate data in each row.

The assets are the main elements supporting the information coming in and out of the tools and for this reason, their identification is to be done using the same code that the company uses for them. This code can be obtained from descriptions of the power grid included in PSS/E files or directly from *.csv files. In the case the asset codes are obtained from PSS/E files, an external software developed for this purpose is required to create a .csv file that includes the asset identification codes and the additional features.

5.2.1. FILES REQUIRED

To start the asset management using the planned tools at the access level the following ***five .csv files*** are required The CSV files here are selected as the simplest way of interacting with the tool. In practice, in order to deliver the required data, the grid operator will most probably require to have a data infrastructure in place, preferably open and interoperable, and if possible compatible with established standards such as IEC CIM (IEC 61968/61970). The asset management tool would then interface with this data infrastructure. This does not affect the generality of the algorithms developed here.

- CSV file that includes the physical characteristics of the assets. This file can include any physical characteristic that could be useful for characterizing better the assets and heir distribution in clusters.
- CSV file that includes the basic indicators or variables to be used in the life assessment dimension. This file can include any number of columns as basic indicators to be used in the analysis. Each line corresponds to one asset and the heading of each column represents the name of the basic indicator.
- CSV file that includes the basic indicators or variables to be used in the maintenance plan dimension. This file is created according to the general rules described in the previous one.
- CSV file that includes the basic indicators or variables to be used in the dimension for economic and environmental impacts. This file is created according to the general rules described in the previous one.
- CSV file that includes the basic indicators or variables to be used in the health condition dimension. This file is created according to the general rules described in the previous one. At this moment there are no examples for this kind of file, but its structure should be the same as in cases shown before.

The next subsections describe the variables contained in the files described previously for the different cases of application developed in the project.

5.2.2. HEP ODS case. Croatian power distribution company.

This case includes the following assets:

- Power transformers: 40
- Underground cables: 52

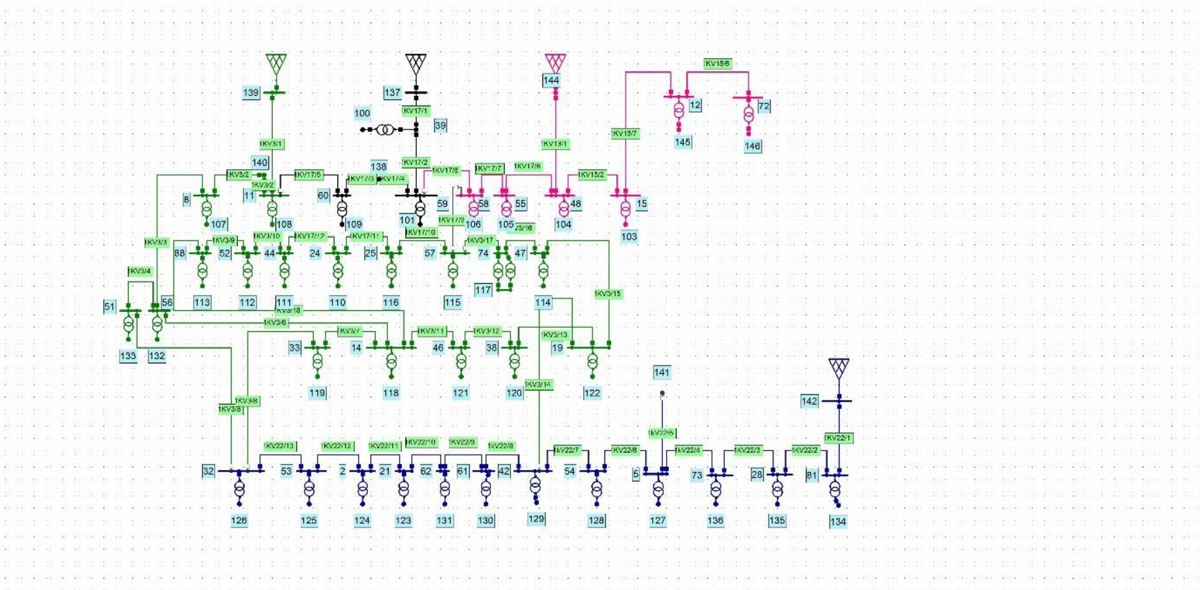

FIGURE 8 NETWORK SCHEME OF HEP ODS CASE

The files describing different asset characteristics contain the following items:

Physical characteristics

File for the power transformers:

- Power_transformer_id
- Voltage Ratio
- Insulation Medium
- Transformer Type
- Indoor/Outdoor
- Annual Maximum Loading (kVA)
- kVA Rating
- Backup Supply

File for the underground cables of the power line:

- Underground_cable_id
- Conductor Cross-Sectional Area
- Sheath Material
- Design Voltage

- Operating Voltage
- Insulation Type / Sheath
- Conductor Material
- Section Rating
- Type
- Number of cores

Life assessment dimension

The basic indicators included in the file for the life assessment dimension of the power transformers are:

- Power_transformer_id
- H1_age_years. Age of the power transformer
- H2_failure_probabilty. A constant failure rate has been considered obtained from scientific resources and an exponential law has been used for the estimation of the reliability.
- H3_criticallity. This item has been based on the number of sensitive customers connected to the power transformer.
- H4_Energy. Energy in kWh/year is supplied from the power transformer.

The basic indicators included in the file for the life assessment dimension of the power lines are as follows:

- Underground_cable_id
- H1_age_years. Age of the underground cables
- H2_failure_probabilty. A different constant failure rate has been considered obtained from scientific resources according to the type of cable XLPE/PVC, XLPE/PE, or Impregnated paper/Bitumen and an exponential law has been used for the estimation of the reliability.
- H3_criticallity. This item has been based on the total number of customers serviced through the power line where the underground cable belongs to.
- H4_Energy. Energy in kWh/year through the power line where the underground cable belongs to.

Maintenance plan dimension

The basic indicators included in the file for the maintenance plan dimension of the power transformers are:

- Power_transformer_id
- H1_ Transformer_external_ondition. The qualitative external condition of the power transformer
- H2_ Cost_of_failure. Mean cost of the failure in [€]

The basic indicators included in the file for the maintenance plan dimension of the underground cables can be seen below:

- **Underground_cable_id**
- **H1_ Repair time**. Mean duration of the repair
- **H2_ Cost_of_failure**. Mean cost of the failure in [€]

Dimension of economic and environmental impacts

The basic indicators included in the file for the dimension of economic and environmental impacts for power transformers are as follows:

- **Power_transformer_id**
- **H1_ Cost of failure [€]**. Mean cost of the failure in [€] of the power transformer
- **H2_ Customers affected**. Number of customers connected to this power transformer
- **H3_ Value of Lost Load (VOLL) €**. Value of the power cut according to the type of energy consumption associated with the power transformer and according to the reference (CEPA, 2018)

The basic indicators included in the file for the dimension of economic and environmental impacts for the underground cables follow:

- **Underground_cable_id**
- **H1_ Cost of failure [€]**. Mean cost of the failure in [€] of the underground cable
- **H2_ Customers affected**. Number of potential customers affected due to a fault in this underground cable
- **H3_ Value of Lost Load (VOLL) €**. Value of the power cut according to the type of energy consumption associated with the power line according to reference (CEPA, 2018)

5.2.3. HOPS case. Croatian power transmission company.

This case includes the following assets:

- 10 HV Substations
- 2 Power plants connected to the 110 kV network (SUBST 34 and SUBST 36)
- 9 Substations (110/35 kV)
- 15 Power Transformers
- 10 transmission lines
- 39 circuit breakers

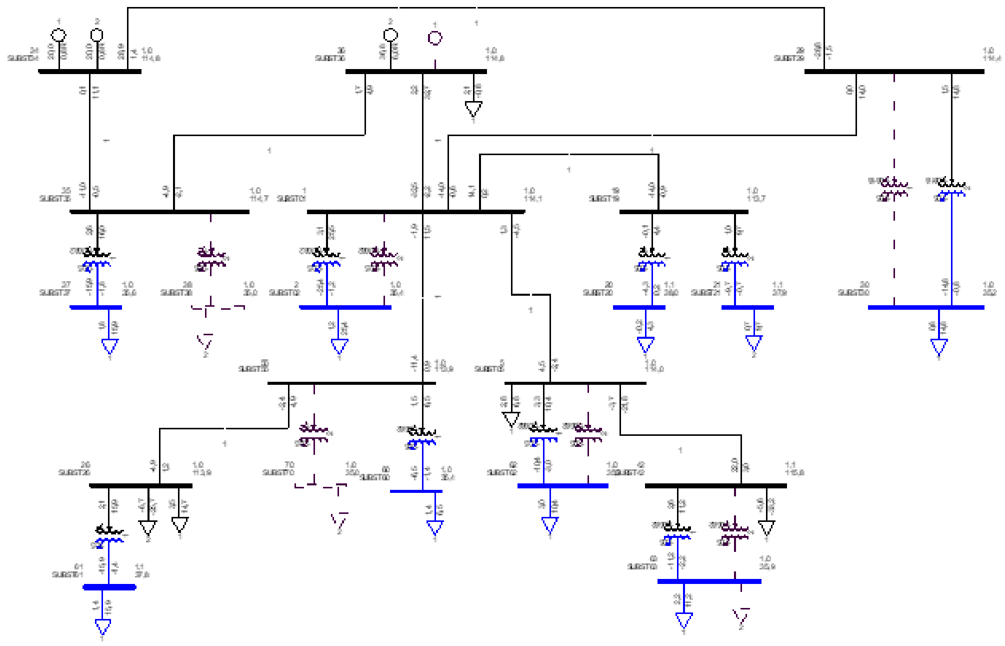

FIGURE 9 10 NETWORK SCHEME OF HOPS CASE

The files where the different characteristics of the assets are described contain the following items:

Physical characteristics

File for the power transformers:

- Power_transformer_id
- Voltage Ratio
- Insulation Medium
- Cooling system
- Transformer Type
- Winding connection
- Indoor/Outdoor
- MVA Rating

- Year of production

File for the overhead transmission line of the power lines:

- Transmission_line_id
- Conductor Cross-Sectional Area
- Design Voltage
- Operating Voltage
- Insulation Type
- Conductor Material
- R[OHM]
- X[OHM]
- B[µS]
- R0[OHM]
- X0[OHM]
- B0[µS]
- Current Capacity (A)
- Number of cores
- Year of construction

File for the circuit breakers:

- Circuit_breaker_id
- Field type
- Position
- Type
- Nominal voltage (kV)
- Nominal current (A)
- Rated short-circuit breaking current (kA)
- Year of production
- Number of circuit switching operations in 2020

Life assessment dimension

The basic indicators included in the file for the life assessment dimension of the power transformers can be seen below:

- Power_transformer_id
- H1_age_years. Age of the power transformer
- H2_failure_probabilty. A constant failure rate has been considered, which was obtained from scientific resources (failure rate of 0.04 failures/ year) and an exponential law has been used for the estimation of the reliability.
- H3_ age_dependent_unavailability. This item has been estimated by HOPS.

- **H5_time_over_rating_50%**. Percentage of time that the power transformer was over 50% of its rating in one year.

The basic indicators included in the file for the life assessment dimension of the transmission lines are as follows:

- **Transmission_line_id**
- **H1_age_years**. Age of the underground cables
- **H2_failure_probabilty**. A constant failure rate has been considered which was obtained from scientific references (1 failure per 100 Km in 10 years, 0,001/ per Km per year) and an exponential law has been used for the estimation of the reliability.
- **H3_criticallyty**. This item has been based on the total number of connections serviced through the underground cable.
- **H4_ age_dependent_unavailability**. This item has been estimated by HOPS.
- **H5_time_over_rating_50%**. Time over the 50% of maximum load reached during one year in this underground cable.

The basic indicators included in the file for the life assessment dimension of the circuit breakers are as follows:

- **Circuit_breaker_id**
- **Field type.** LB - line bay 1, TB - transformer bay 2, GB - generator bay, 3
- **Age**
- **Nominal_voltage**
- **Nominal_current**
- **Rated_short-circuit_breaking_current**
- **switchings_operations_2020.** Number of Switching operations in 2020

Health condition dimension

There is available data coming from two of the power transformers considered in this scenario and corresponding to substation 1. They are referred to as power transformers 1 and 2 (PT-1 and PT-2) in this section.

The condition monitoring plan is conceived as the prediction of the winding temperature as a function of the load in the power transformer and the oil temperature. If everything is correct in the condition of the power transformer the relation of the winding temperature should follow the dynamic of the load measured in the power transformer as well as the oil temperature. Any hot spot -or cooling problem of the oil will trigger the equilibrium expected warning about a degradation of the power transformer.

To reach this goal, a model of normal behavior expected in these three variables was created using part of the data available (one year), in particular 7000 samples taken each hour. The model proposed was *winding_temperature = f(load, oil_temperature)* . One model was fitted for PT-1 and another one for PT-2. A multilayer perceptron neural network was used as an approximator to the function *f*.

The data available for the power transformer PT-1 was:

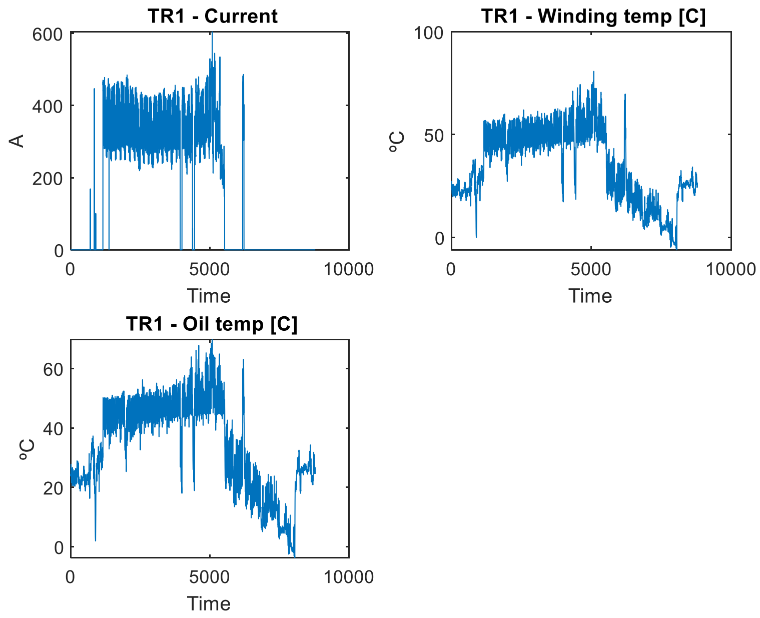

FIGURE 10 DATA FOR POWER TRANSFORMER PT-1

And for the power transformer PT-2:

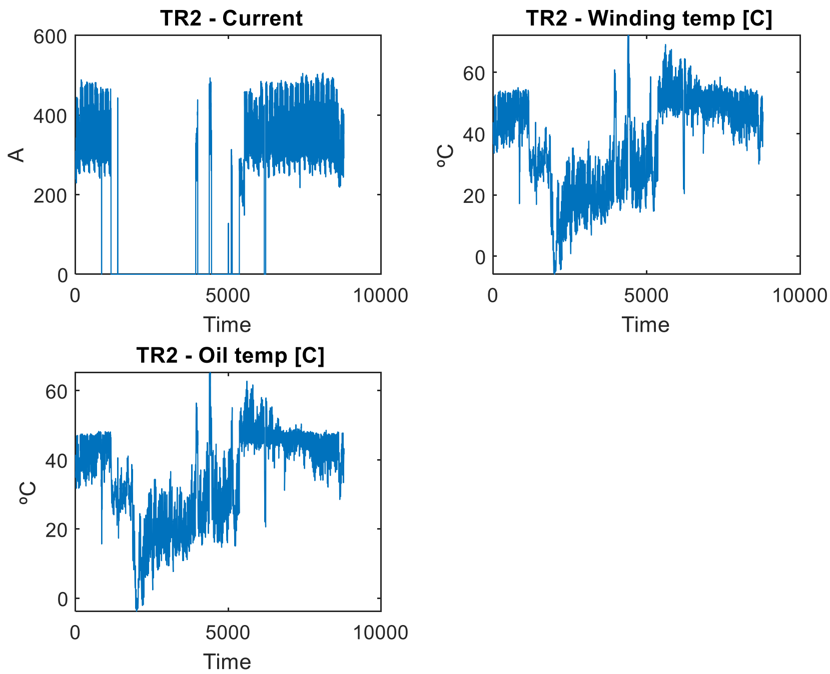

FIGURE 11 DATA FOR POWER TRANSFORMER PT-2

A model based on a multi-layer perceptron was designed with 20 neurons in a hidden layer for building a normal behavior model for the PT-2. The accuracy of the model obtained is 99%. Figure 14 shows the temperature values estimated by the model, overlapping the real values.

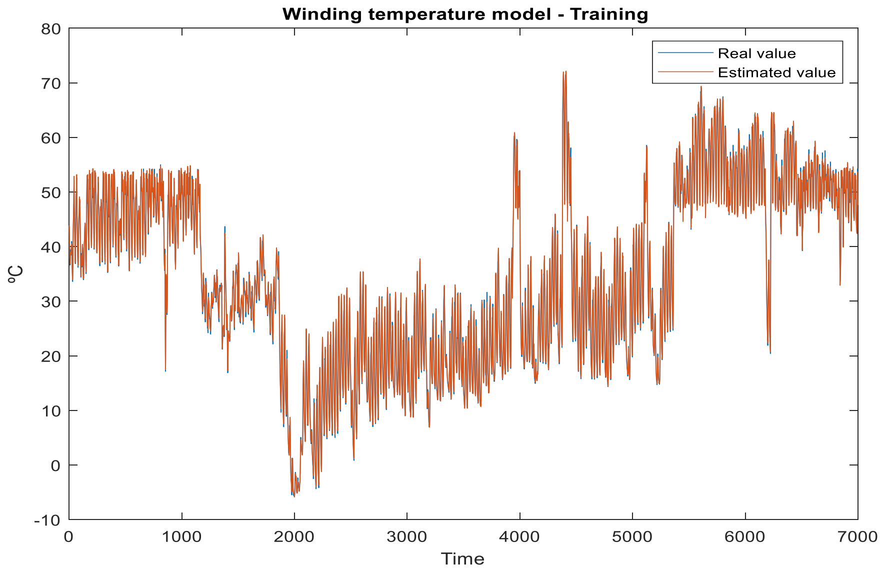

FIGURE 12 RESULTS OF THE WINDING TEMPERATURE MODEL FOR PT-2

Figure 13 shows the use of the model with inputs not included in the process of the model training and a confidence band indicating those cases outside of the expected error.

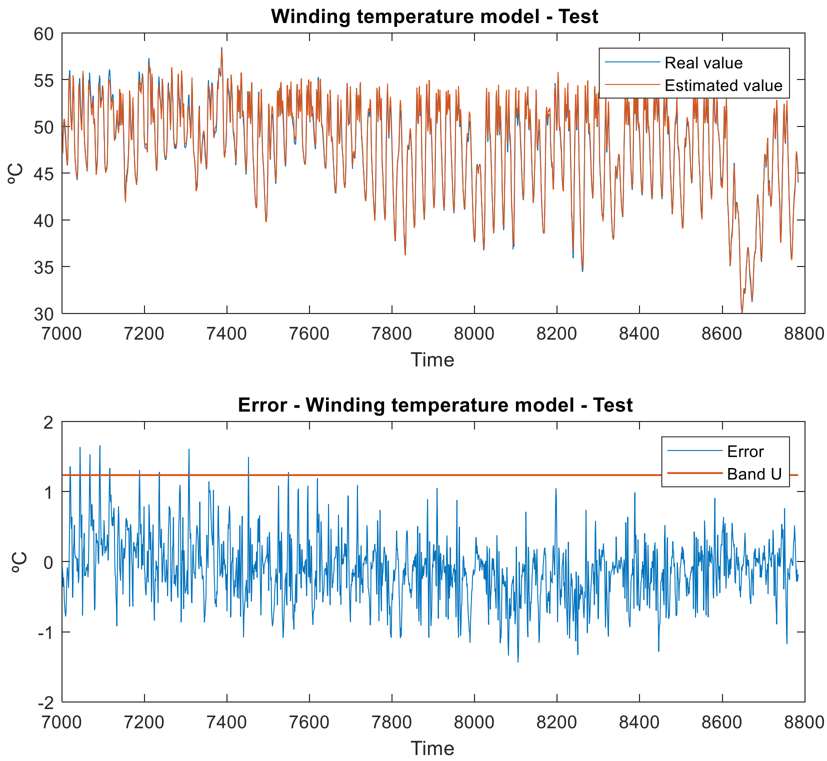

FIGURE 13 EVALUATION OF THE WINDING TEMPERATURE MODEL FOR PT-2

A similar analysis was developed for the power transformer PT-1. A model based on a multi-layer perceptron was designed with 20 neurons in a hidden layer for building a normal behavior model for the PT-1. The accuracy of the model obtained is 99%.

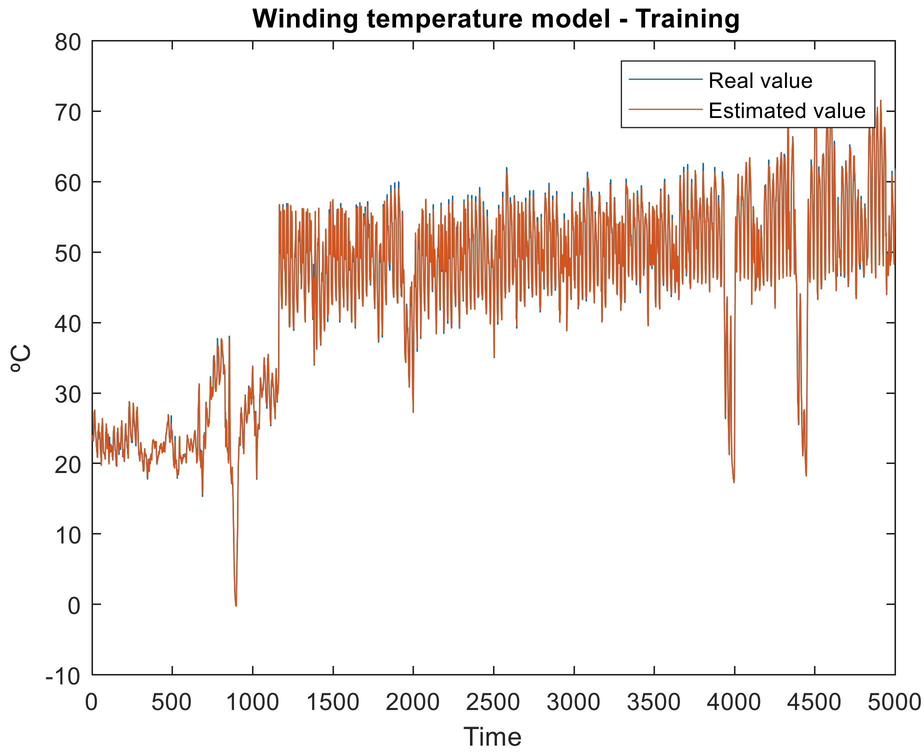

FIGURE 14 RESULTS OF THE WINDING TEMPERATURE MODEL FOR PT-1

Figure 15 shows the use of the model with inputs not included in the process of model training and a confidence band indicating those cases outside of the error expected.

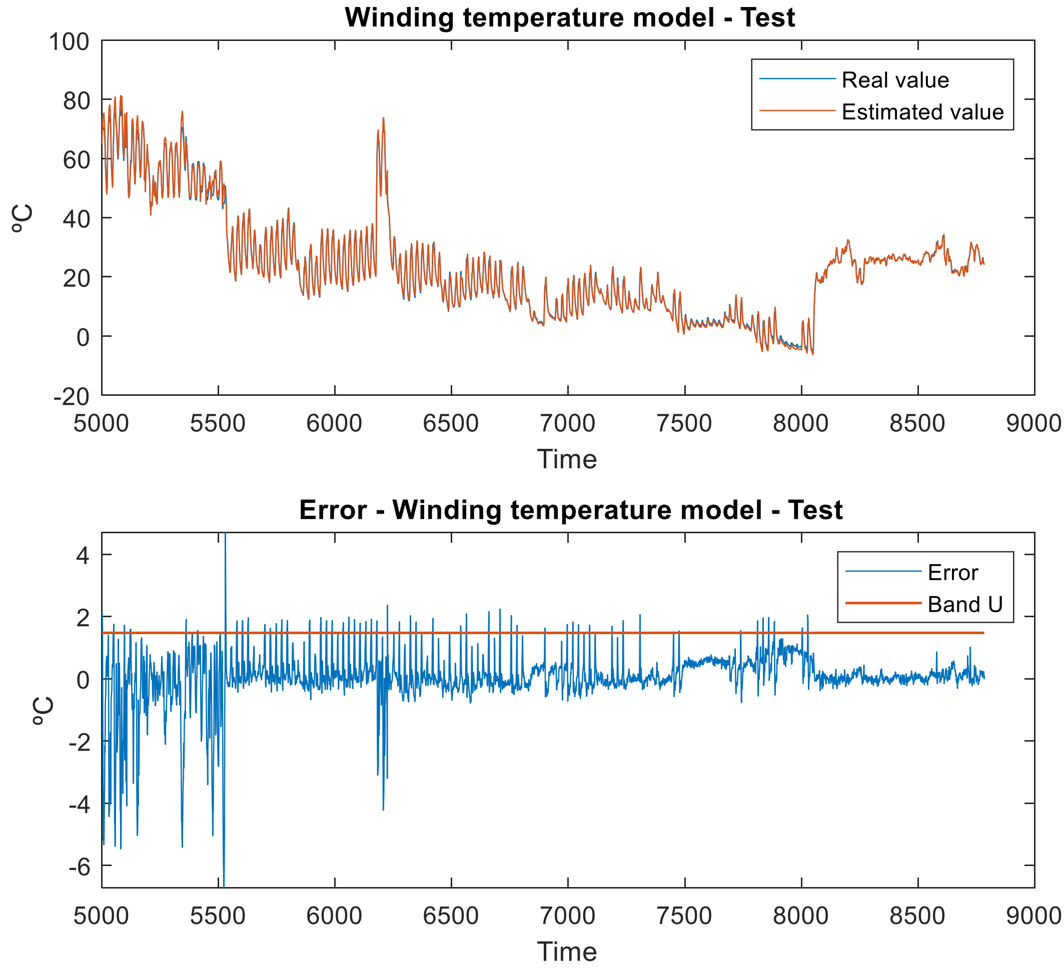

FIGURE 15 EVALUATION OF THE WINDING TEMPERATURE MODEL FOR PT-1

According to these models the basic indicators to be considered in the health condition file of the power transformers are the following:

- Power_transformer_id
- H1_SOCB_FP. This indicator represents the percentage of samples outside the confidence band in the whole period considered.
- H2_SOCB_HP. This indicator represents the percentage of samples outside the confidence band in the last half of the period considered.
- H3_SOCB_QP. This indicator represents the percentage of samples outside the confidence band in the last quarter of the period considered.

Maintenance plan dimension

The basic indicators included in the file for the maintenance plan dimension of the power transformers are as follows:

- Power_transformer_id

- **H1_Maintenance cycles** (year)
- **H2_Review** (man/day)
- **H3_Maintenance_cycles** (year)
- **H4_Review_and_inspection** (man/day)
- **H5_Maintenance_cycles** (year)
- **H6_Review_and_inspection** (man/day)

The basic indicators included in the file for the maintenance plan dimension of the transmission lines are shown below:

- **Transmission_line_id**
- **H1_Maintenance cycles** (year)
- **H2_Review** (man/day)
- **H3_Maintenance_cycles** (year)
- **H4_Review_and_inspection** (man/day)
- **H5_Maintenance_cycles** (year)
- **H6_Review_and_inspection** (man/day)

The basic indicators included in the file for the maintenance plan dimension of the circuit breakers are as follows:

- **Circuit_breaker_id**
- **H1_Maintenance cycles**_A (year)
- **H2_Review (**man/day). Regular review
- **H3_Maintenance_cycles_B** (year)
- **H4_Review_and_inspection_B** (man/day)
- **H5_Maintenance_cycles_C** (year)
- **H6_Review_inspection_and_overhaul_C** (man/day)

Dimension of economic and environmental impacts

The basic indicators included in the file for the dimension of economic and environmental impacts for power transformers are:

- **Power_transformer_id**
- **H1_Clients affected.** Number of customers connected to this power transformer
- **H2_ENS_in_fault.** Undelivered Energy in case of failure (MWh)
- **H3_Mean_load (Y).** Mean load in this power transformer per year
- **H4_Failure_cost (€).** Mean cost of the failure in [€] of the power transformer

The basic indicators included in the file for the dimension of economic and environmental impacts for the transmission lines can be seen below:

- **Transmission_line_id:**
- **H1_Clients affected.** Number of customers connected to this power line
- **H2_ENS_in_fault.** Undelivered Energy in case of failure (MWh)

- **H3_Mean_load (Y).** Mean load in this power line per year
- **H4_Failure_cost (€).** Mean cost of the failure in [€] of the power line

5.2.4. Spanish case I

This case includes the following assets:

- Feeders: 2
- Power transformers: 92
- Segments of the feeders: 219
- Supports (towers + insulators): 381

The files where the different characteristics of the assets are described contain the following items:

Physical characteristics

File for the power transformers:

- trafo_id
- power_line
- forced_cooling
- special_risk
- total power installed (kVA)
- Constructive model

File for the power segments of the feeders:

- segment_id
- segment type
- conductor type
- length (Km)
- resistance (ohms)
- reactance (ohms)
- constructive model
- impedance (ohms)
- type of power grid structure

File for the power segments of the feeders:

- support_id
- feeder
- support function
- birdlife
- frequented area
- insulator type
- number of insulators

- Tree zone
- Type of material

Life assessment dimension

The basic indicators included in the file for the life assessment dimension of the power transformers are the following:

- Power_transformer_id
- H1_age_years. Age of the power transformer
- H2_power_rating. The power rating of the power transformer
- H3_contribution_in_feeder. Percentage of power contracted in this power transformer in relation to the total power contracted in the feeder
- H4_faults. Number of faults registered over the last three years
- H5_Customers. Number of customers served by this power transformer
- H6_LV_connections. Number of low voltage connections

The basic indicators included in the file for the life assessment dimension of the segments of the feeder are the following:

- Segment_id
- H1_Age. Age of the segment
- H2_failure_probability. The process for obtaining the value is described in the next lines:

  A failure probability for the feeder where the segment is a part of it was estimated as the number of faults observed divided by the number of feeders, period of study (3 years) plus the length of the feeder. The failure rate obtained for the feeder was the number of failures observed per Km and year. The probability of failure for each segment is obtained as an exponential law using the failure rate of the feeder, the length of the feeder, and its age.
- H3_KPI_weighted_power. This variable is obtained from the key performance indicator for weighted power estimated by the electrical company.
- H4_Criticality. This variable evaluates the criticality of the segment. It is obtained from the company’s evaluation of risk for this segment.
- H5_Condition. This variable evaluates the condition of the segment. It is obtained from the company’s evaluation of risk for this segment.
- H6_Risk. This variable evaluates the risk of the segment. It is obtained from the company’s evaluation of risk for this segment.
- H7_faults. Number of faults registered in this segment over the last three years.
- H8_faults_per_Km. Faults registered in this segment per Km

The basic indicators included in the file for the life assessment dimension of the supports of the feeder are the following:

- Support_id

- **H1_KPI_weighted_power**. This variable is obtained from the key performance indicator for weighted power estimated by the electrical company.
- **H2_ Criticality**. This variable evaluates the criticality of the support. It is obtained from the company evaluation of risk for this segment.
- **H3_Condition**. This variable evaluates the condition of the support. It is obtained from the company evaluation of risk for this segment.
- **H4_Risk**. This variable evaluates the risk of the support. It is obtained from the company evaluation of risk for this segment.

Maintenance plan dimension

The basic indicators included in the file for the maintenance plan dimension of the power transformers are the following:

- **Power_transformer_id**
- **H1_fault_duration**. Mean fault duration in minutes
- **H2_faults**. Number of faults
- **H3_defects**. Number of defects
- **H4_defect_severity**. Severity of the defects observed (mean value)

The basic indicators included in the file for the maintenance plan dimension of the supports of the feeders are shown below:

- **Support_id**
- **H1_defects**. Number of defects
- **H2_defect_severity**. Severity of the defects observed (mean value)

Dimension of economic and environmental impacts

The basic indicators included in the file for the dimension of economic and environmental impacts for power transformers can be seen below:

- **Power_transformer_id**
- **H1_important_customers**. Number of special customers connected to the power transformer
- **H2_Customers**. Number of customers connected to this power transformer
- **H3_power contracted**. Power contracted in this power transformer
- **H4_cut_power**. Cut power in this power transformer in the last three years.

The basic indicators included in the file for the dimension of economic and environmental impacts for segments of the feeder are shown below:

- **Segment_id**
- **H1_KPI_weighted_power**. This variable is obtained from the key performance indicator for weighted power estimated by the electrical company.

- H2_birdlife_KPI. This variable evaluates the KPI of birdlife around the segment. It is obtained from the company evaluation for this segment.
- H3_KPI_defects_severity. This variable evaluates the KPI of the severity of defects in this segment. It is obtained from the company's evaluation for this segment.

The basic indicators included in the file for the dimension of economic and environmental impacts for the supports of the feeder are the following:

- Support_id
- H1_KPI_weighted_power. This variable is obtained from the key performance indicator for weighted power estimated by the electrical company.
- H2_birdlife_KPI. This variable evaluates the KPI of birdlife around the support. It is obtained from the company's evaluation for this support.
- H3_KPI_defects_severity. This variable evaluates the KPI of the severity of defects in this support. It is obtained from the company's evaluation for this support.

5.2.5. Synthetic distribution power grid case.

This case study is added as complementary to the previous ones, as an example managing a larger number of assets than the previous ones. This is useful to observe the performance of the tools when a large number of assets are managed. Due to the purposes of this example, only one dimension is processed, in particular, the Life Assessment dimension both in power transformers and power lines. This synthetic example is obtained from previous works developed in Comillas in this area. The case is inspired in a real distribution area and an important similarity between the actual data and the results of this synthetic case study was checked.

The case includes the following assets:

- Power transformers: 390
- Power lines: 8414

The files describing different asset characteristics contain the following items:

Life assessment dimension

The basic indicators included in the file for the life assessment dimension of the power transformers are the following:

- **Power_transformer_id**
- **H1_age_years**. Age of the power transformer
- **H2_failure_probabilty**. A constant failure rate has been considered obtained from scientific resources and an exponential law has been used for the estimation of the reliability.
- **H3_criticallity**. This value of this item was decided according to artificial distributions laws.
- **H4_overload_percent_h_year**. A profile of load in one year was selected among several created artificially and the time in hours per year in which the power transformer was operating above the related power was calculated.

The basic indicators included in the file for the life assessment dimension of the power lines are the following:

- **Power_ line _id**
- **H1_age_years**. Age of the underground cables
- **H2_failure_probabilty**. A constant failure rate has been considered obtained from scientific resources and an exponential law has been used for the estimation of the reliability.
- **H3_criticallity**. This value of this item was decided according to artificial distributions laws.
- **H4_overload_percent_h_year**. A profile of load in one year was selected among several created artificially and the time in hours per year in which the power transformer was operating above the related power was calculated

5.3. Specification of the tool for the characterization of the condition of the assets

This section presents the specifications of tool 5.1, the aim of which is the characterization of the condition of the assets based on the multiple dimensions previously described. This section describes the main aspects required to understand the main key of this tool.

5.3.1. Input requirements

The number of dimensions that characterize each scenario depends directly on the number of indicators, measurements, or registers available. Therefore, the number of dimensions might vary from one scenario to another. Each dimension is defined by two main inputs:

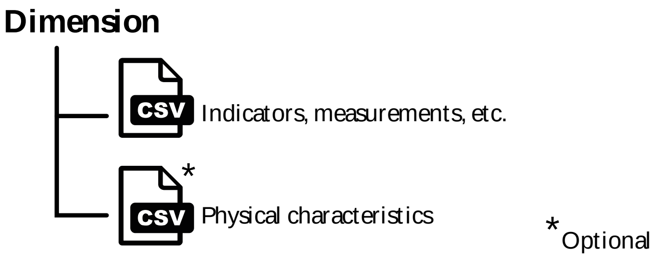

FIGURE 16 INPUT FILES FOR TOOL 5.1

The first input is made up of all the indicators, measurements, etc. that define the conditions of the asset for that particular dimension. The second input, which is optional, includes the main physical characteristics that can be used to identify and group assets with similar physical features. The information contained can be defined as auxiliary features not included as part of the characterization of the assets. Both inputs are included in two separate CSV files.

Our recommendation for the **name format of the input** files is the following:

Tool + Scenario + Asset Acronym + Dimension Acronym +(AUX)*.csv

*Optional.

Some examples:

Input file for the tool 5.1, scenario provided by HOPS corresponding to Power Transformers (PT) for the dimension of Economic Impact (EI).

tool51_HOPS_PT_EI.csv

In case that the physical characteristics were available, the corresponding auxiliary file would be:

tool51_HOPS_PT_EI_aux.csv

A CSV can be built in multiple formats, two formats are supported by this tool:

Recommended format:

Field delimiter: " , "

Decimal separator: " . "

Alternative compatible format:

Field delimiter: " ; "

Decimal separator: " , "

Both formats can be used without distinction. Other CSV formats are not supported by this tool, therefore, their use might lead to errors reading the input files.

Some other conditions also apply for the input files:

- The **features** included for the characterization of assets must be **numerical**, other formats such as text strings or mixed types are not supported.
- The features must **not contain** any empty field or **NaN** (Not a Number) values. In other cases, these blanks can be filled manually with zeros.
-
- In case that a particular **data** was **not available**, such information has to be filled with a value defined by the user. In most cases, it is recommendable to **fill** this missing data **with zeros**, in case of numerical values **or "not available"**, in case of text strings.
- The **auxiliary file** for each dimension must **include every asset** contained **in the main file**. In case that some physical characteristics are not available, they must be filled in applying, for instance, the previously mentioned rules.

The location of the input files is not fixed, but it is recommended to keep such files within the local folder of the project. The user can choose where to save and load the files.

5.3.2. The interface of Tool 5.1

This section explains the user interface of Tool 5.1. This UI has been created for user friendly experience with less technicalities and based on direct approach. Figure 17 shows the user interface. As we can see in the figure 17, user can select any file from the system in the section named as "select CSV/Excel file". In the section "Select component and variable" user can choose all the components and variables or the one they need/require for their analysis. After selecting the components and variables user need to select dimensions from "dimensions" section and algorithm from "algorithms" section in UI. The name of sections justifies the work of it.

After selecting all the parameter user can save all the setting by clicking on save setting button and can generate the result by clicking on generate result button. "show result" will allow user to see the result of analysis in web browser. "Clear" button helps to clear out all the previous selection done by user in order to perform another analysis with different selection.

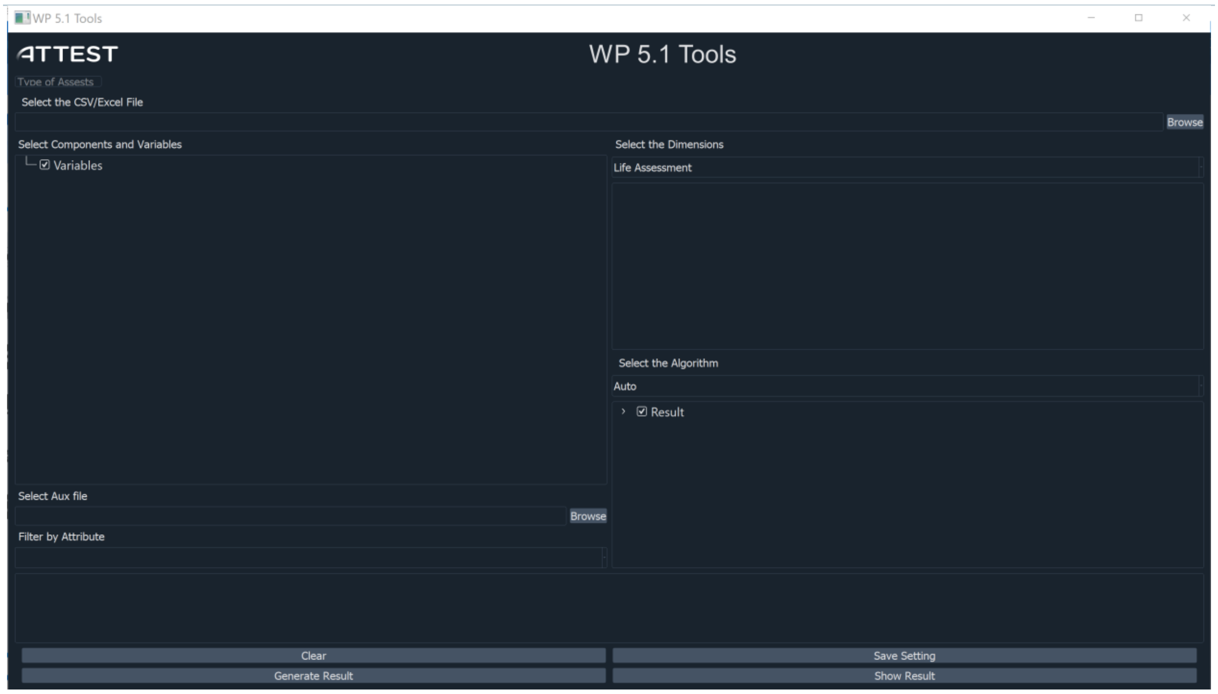

FIGURE 17 GRAPHICAL USER INTERFACE OF TOOLS 5.1

5.3.3. Clustering process. The number of clusters.

The characterization of the condition of the assets is carried out through a clustering process in which assets with similar features are grouped.

Clustering analysis belongs to the field of 'unsupervised' learning. 'Unsupervised' learning methods aim to discover relationships between features without any prior knowledge about them. The clustering algorithms applied in this tool are K-means, used as part of the determination process of the optimal number of clusters, and Self-Organizing Maps (SOM) or the clustering of the assets. The optimal number of clusters does not depend on the type of algorithm applied. The K-means algorithm is a fast clustering technique, and SOMs are more precise than K-means. Therefore, K-means is used for determining the optimum number of clusters, and SOMs are used for clustering the assets.

In this tool, two different approaches to automatically identify the automatic identification of the optimal number of clusters. These two approaches are the Elbow method and the Gap Statistic method. The first approach is based on the distortion (within-cluster dispersion value), based on the Euclidean distance of each sample to the center of the cluster, to which each observation belongs. The second approach is based on comparing the dispersion value obtained for the input dataset and an expected one for an equally distributed idealistic dataset. (Tibshirani, 2001)

The Elbow method states that the optimal number of clusters is located at the point of inflection (elbow-shaped point) on the curve of distortion values. The Gap Statistic method states that the optimal number of clusters corresponds to the first peak value of the Gap curve. The example in Figure 18 shows how both algorithms give similar results (6 and 7 respectively) for the detection of the optimal number of clusters, which are marked with a red cross.

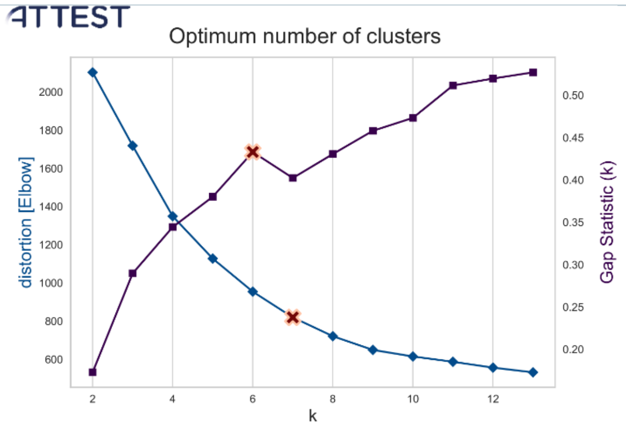

FIGURE 18 OPTIMUM NUMBER OF THE CLUSTER ACCORDING TO ELBOW AND GAP STATISTIC METHODS

Once the optimal number of clusters is determined, the assets are grouped using SOMs. In addition to the number of clusters, SOMs should define the layout of the clusters. The layout defines how the displacement of one cluster affects the location of its neighbors. For this purpose, the layout of the SOM has to be bidimensional. This condition can be only fulfilled if the number of clusters is greater than 4, otherwise, the layout will be defined as unidimensional.

In case that the optimal number of clusters was a prime number, the optimal number will be rounded to the previous largest non-prime number.

Optimal number of clusters	Layout
10 [2x5]	● ● ● ● ● ● ● ● ● ●
9 [3x3]	● ● ● ● ● ● ● ● ●
8 [2x4]	● ● ● ● ● ● ● ●
7 [2x3]	● ● ● ● ● ●
6 [2x3]	● ● ● ● ● ●
5 [2x2]	● ● ● ●
4 [2x2]	● ● ● ●
3 [1x3]	● ● ●
2 [1x2]	● ●

FIGURE 19 SOM LAYOUT DEPENDING ON THE OPTIMAL NUMBER OF CLUSTERS

5.3.4. Clustering process. Normalization and data preprocessing.

All the variables, indicators, and measurements are normalized before computing each of the clusters that define the SOM. This normalization is carried out using their maximum and minimum value. The min-max normalization is defined by the following equation:

$$v_{y,norm} = \frac{v_y - min(V_y)}{max(V_y) - min(V_y)} \quad 14$$

where $v_{y,norm}$, is the normalized value; y, is the variable to be normalized; v_y is an observation of the variable y and V_y is the set of observations of the variable y.

5.3.5. Clustering process. SOM training process.

The optimal number of clusters is not an exact indicator. This means that there might be some variations between the initial optimal number and the final number of clusters. These variations are because the initial optimum number of clusters might be too large, producing some empty clusters. An empty cluster means that the layout is not optimum, therefore the number of clusters will be reduced to one until all the clusters are full. This workflow is depicted in the following flowchart:

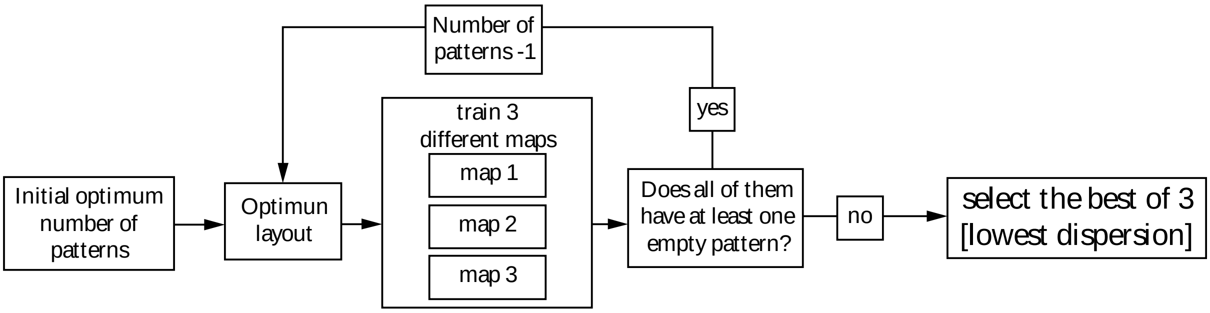

FIGURE 20 FLOW CHART OF THE TRAINING PROCESS OF THE SOM

The dispersion value, obtained throughout the training process, shows the converging characteristic of the SOM. When the SOM reaches a local or global optimum, the dispersion value stabilizes itself. This process is shown in the next figure:

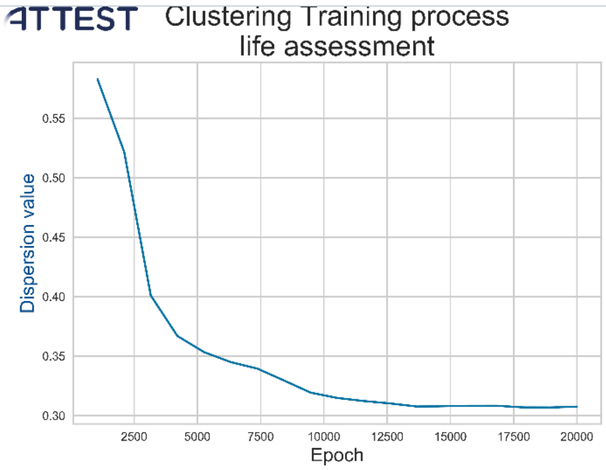

FIGURE 21 DISPERSION VALUE DEPENDING ON THE TRAINING EPOCH OF THE SOM

5.3.6. Clustering process. Denormalization and visualization.

The information contained in each pattern is denormalized to its original scale. The equation applied is the inverse of the previous one:

$$v_y = v_{y,norm} \cdot \left(\max\left(V_y\right) - \min\left(V_y\right) \right) + \min\left(V_y\right)$$

The information of each pattern is represented through box-plot diagrams like the one shown in the following figure:

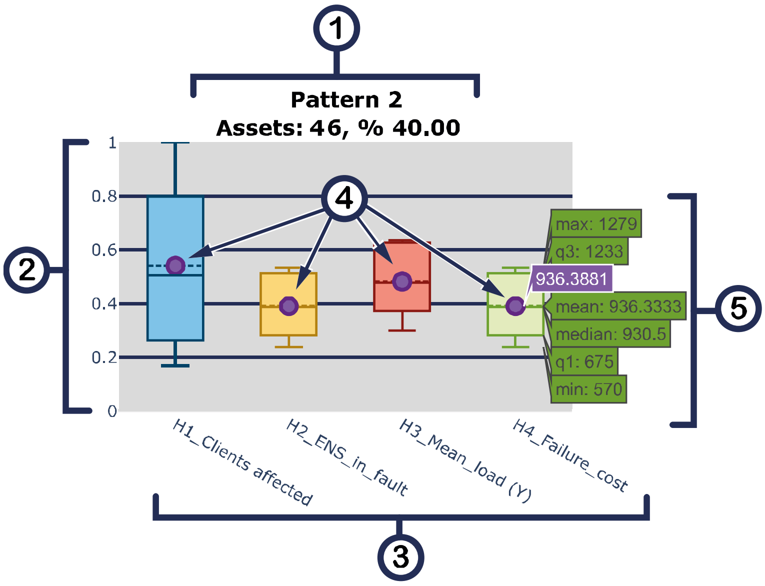

FIGURE 22 ELEMENTS OF THE BOX PLOTS

The main elements of each plot are:

1) The header of the pattern. It includes the number of the pattern, the number of assets within the pattern, and the percentage of assets included within the pattern regarding the whole set of assets.

2) The main scale. This scale allows the user to compare variables with different maximum and minimum values.
3) The name of variables, indicators, or measurements included in the study.
4) The centroid of the patterns. The centroids are the most representative values of each pattern.
5) Box-plot. They show how the assets are distributed within the same pattern. The values of the box plots are not normalized. Each box contains information about the minimum value, the first quartile, the mean value, the median, the third quartile, and the maximum value of each group of assets.

5.3.7. All the assets that belong to the same pattern are listed in tables. Each table contains detailed information about each asset. Results. Advanced search tool.

An advanced search tool allows the user to filter assets according to their variables, taking into account whether a variable is numerical or categorical.

FIGURE 23 INTERFACE OF THE ADVANCE SEARCH TOOL

The main elements are:

1) Numerical variables. This option allows the user to filter each variable applying different numerical filters such as Greater than, lower than, equal to, or between two values.
2) Categorical variables. This option allows the user to filter the variables by their categorical values.
3) Include or exclude the values set for the filter.
4) Action menu. In this menu the user can save or restore a previously defined filter configuration; apply the configuration set or reset the filter configuration.

Categorical variable filters are configured through the following menu:

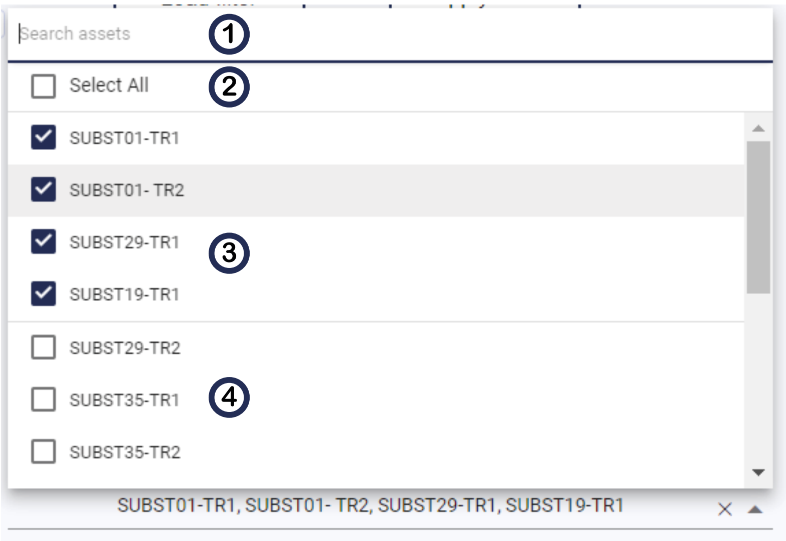

FIGURE 24 ELEMENTS OF A CATEGORICAL VARIABLE SEARCHING TOOL

The elements of this menu are:

1) Searching box. Allows to search any name within the list of categorical values.
2) Select all button. Allows to select all the values of this categorical variable.
3) List of selected values.
4) List of unselected values.

The results shown in a faded color correspond to the whole set of assets within the pattern. The results shown in the highlighted colors correspond to the values that fulfill the filter conditions applied. Now the percentage in each pattern header corresponds only to the total amount of assets that fulfill the conditions of the filter.

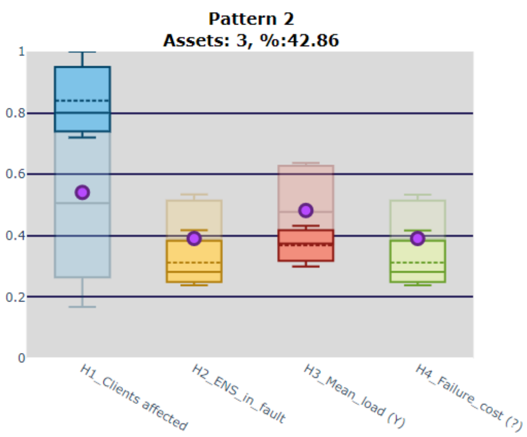

FIGURE 25 EXAMPLE OF HOW THE INFORMATION IS DISPLAYED AFTER APPLYING A SEARCHING FILTER

5.3.8. Results. Dimensions.

Each dimension can be accessed through the button located at the bottom right corner of the application. Hovering this button, it will show the dimensions loaded in the tool. To access to each dimension, the user can click on the desired dimension to show its corresponding results.

FIGURE 26 DIMENSION MENU. LEGEND OF COLORS.

The three dimensions included in this tool are:

FIGURE 27 DIMENSION MENU. LEGEND OF ICONS.

5.4. Specification of the Tool for the definition of condition indicators based on heterogeneous information sources

This section contains the specification for tool 5.2, its goal is to characterize the condition of indicators based on heterogeneous information sources using the previously stated numerous dimensions. This section explains the most important parts of how this tool was created and how it should be used.

3.4.1 Input Requirements

The input requirements for tool 5.2 are similar to the ones discussed in the input requirements of tool 5.1 (see section 3.3.1). Similar to Tool 5.1, the characterization of dimensions depends on the number of indicators, measurements, or registries present. CSV file is the supported format for input files.

Name format of input files is recommended as follows:

Tool + Scenario + Asset Acronym + Dimension Acronym +(AUX)*.csv

3.4.2 Normalization and data pre-processing

All the variables, indicators, and measurements are normalized before any computation. This normalization is carried out using their maximum and minimum value. The min-max normalization is defined by the following equation:

$$v_{y,norm} = \frac{v_y - min(V_y)}{max(V_y) - min(V_y)} \quad (15)$$

where $v_{y,norm}$, is the normalized value; y, is the variable to be normalized; v_y is an observation of the variable y and V_y is the set of observations of the variable y.

3.4.3 Weight process

Weighted values are assigned to each feature according to its importance. The weight of a particular feature will depend on the importance factor, the higher the importance, the higher the weight. The sum of all the weights is 1. For example, if there are 3 features such as x_1, x_2, x_3 where the importance of the feature goes in ascending order respectively. We assign weight to each feature such as w1 for x1, w2 for x2 and w3 for x3. So,

w= 1 = w1+ w2+ w3

and,

w1*x1+w2*x2+w3*x3 = indicator

the same process will be done for all dimensions and indicators are generated for each of them.

3.4.4 Table

After generating the indicator with the assigned weights, we will perform addition to all the indicators by rows, which creates an overall indicator. We will evaluate the performance of assets based on the total indicator value. If the total indicator is almost 1 or near to one, it means that the asset is in critical condition and needs priority attention and maintenance.

For convenience, it is recommended to sort the value of the total indicator is descending order.

As shown in table 28 asset 1 is in a very critical condition as the total indicator is very close to one. Now, this higher value of total indicator has been affected by all the dimensions because all the three dimensions have high values, which automatically results in a high total indicator.

Support_ID	LA_indicator	MS_indicator	EI_indicator	total_indicator
RQ9W9OJR//74-32	0.885	0.8	0.904	0.863
RQ8UCGAG//74-33-4	0.729	1.0	0.819	0.849
RQAUFPTH//74-33-2	0.729	0.9	0.819	0.816
RQBQDFTA//74-33	0.751	0.8	0.824	0.792
SAM60AF0//D59-70	0.912	0.5	0.933	0.782
RQA9HCG7//74-33-3	0.729	0.7	0.819	0.749
RQ3K0TFG//82	0.958	0.8	0.488	0.749

FIGURE 28 LIST OF TOTAL INDICATORS

3.4.5 Clustering process: number of clusters

Similar to section 3.3.3 of tool 5.1, this section has the same process for clusters of tool 5.2. the difference between both processes is the input. Here we are performing cluster analysis for indicators. Similar to section 3.3.3 we are using the K-means algorithm as a fast clustering technique. Similarly, the Elbow method and Gap Statistic Method have been used to determine the optimal number of clusters.

The indicators are grouped using SOMs once the appropriate number of clusters has been found. In addition to the number of clusters, the SOMs must specify how the clusters should be laid out. The layout specifies how one cluster's relocation affects the positioning of its neighbors. The SOM's layout must be bidimensional for this to work. The layout will be unidimensional if the number of clusters is less than 4.

3.4.6 Clustering process. SOM training process and Visualization.

SOM training process for tool 5.2 is similar to that of tool 5.1, as mentioned in section 3.3.5. The training process contains a similar process where we are optimizing our cluster until there are no empty clusters.

Indicator’s information is visualized by a box plot diagram, as shown in the figure 28:

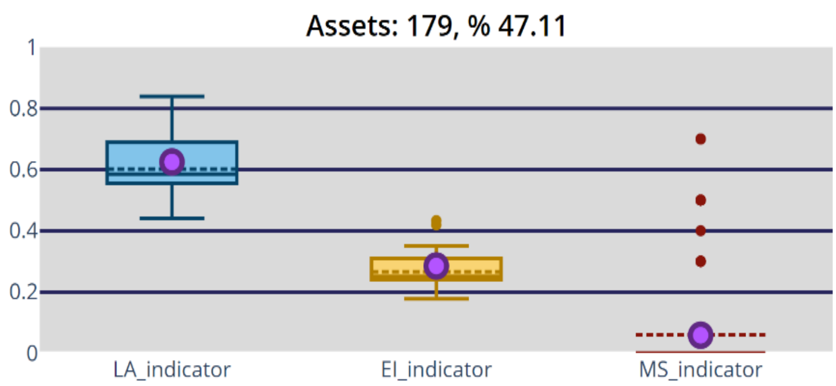

FIGURE 29 HEALTH INDICATORS OF ASSETS 179

5.5. Specification of the Tool for the definition of smart asset management strategies

The tools specified in sections 3.3 and 3.4 have permitted the characterization of the assets from four different dimensions from the asset management perspective and several indicators were evaluated. The tool for the definition of smart management described in this section at a more advanced level than the previous tools. Its main objective is to offer the user a framework to compare different strategies for asset management, attending to different criteria of possible changes in the current scenarios analyzed in the previous levels by the other tools. The tool will permit the management and decision of the following features:

- Creation of simulated scenarios taking as reference the one analyzed in the previous tools, but adding some changes or hypotheses on the basic information used in the tool for the definition of condition indicators based on heterogeneous information sources about the evolution over a period of time. Hypothetical changes in the current values observed in the assets for the evaluation of the basic indicators will be very useful to analyze different ***what-if*** cases according to possible planning strategies of asset management in the electrical company. Changes can be assumed in any basic indicator of any dimension at the level of the whole fleet of assets or the level of particular ones. For example, a change in the failure rate can be introduced assuming a deterioration of its current value for a set of assets, or on the contrary, some assets are expected to be renewed and an improvement of the failure rate is expected. Another example could be an increasing value of the load to be supplied due to increasing demand by electrical vehicles or increasing numbers of customers in a neighborhood. Another example could be to suppose an increasing value in the failure costs or maintenance costs in the mean or long-term part of the assets.
- Creation of simulated scenarios, taking as reference the results obtained in the tool for the definition of condition indicators based on heterogeneous information sources. This option will allow introducing values of indicators as input targets for one or more assets, the current values, and its results would be those basic indicators that must change to reach the target values. This option will be very valuable in the context of recommendations to be implemented in asset management.
- To enable the other tools in the open-source toolbox to include smart asset management strategies in network planning and operation.

The main features of this tool will be similar to those described in sections 3.3 and 3.5 but allowing the comparison of several simulated scenarios based on the results obtained in the reference scenario developed in the mentioned sections.

A user interface will permit to select the changes to be included over the reference scenario or the target indicators to be reached. The tool will work in simulation mode based on changes of data used for the tool described in section 3.3 or recommendation mode based on target indicators for the results obtained in the tool described in section 3.4. Both modes will be not compatible.

6. Interactions with other work-packages

Interactions between the tools developed in WP5 for asset management, and the tools developed for planning and operating the grids in WP3 and WP4, respectively, are planned.

From WP4, valuable information about the operation of the grids will be provided to the asset management tools fed. This information will cover indicators about:

- Criticality of assets. The analysis of the severity of N-1 contingencies will enable us to identify which assets are critical (those in which contingencies appear when they are removed) and those that are not critical (there is no congestion when removed). This information will be available with quantitative indicators, identifying the severity associated with each contingency. This will provide critical information for power transformers and power lines. For large-scale cases, it is expected that the contingency analysis will not cover the exhaustive list for all the assets, but will still provide useful information for the simulated scenarios.
- Load profile of assets. This information can come from the simulation of the operation of the grids, taking into account the outputs of the simulations. This information is valuable to assess the condition of the assets, in terms of how much they are exposed to overload conditions.

The outputs of WP5 dealing with asset management will be valuable for WP3 dealing with algorithms for planning the transmission and distribution systems. In particular:

- In WP5 it will be estimated the time in which the recommended thresholds for the life of assets will be exceeded. This will be defined depending on the type of assets. This can be valuable in WP3 to fine-tune the life of assets, to compute more accurately their net present value.
- WP5 will provide file assessment indexes, that will be valuable to determine the required preventive or corrective maintenance cost in WP3, and to guide the replacement of assets.

Finally, the most important interaction will be with WP6 as main framework designed for integrating the results of all the tools developed in WP3, WP4 and WP5.

7. Requirements of the tools

The tools developed in this work package do not require special computing needs except for the number of assets to be treated. The scenarios used to demonstrate the operation of the tools can be executed in conventional computers. However, at the moment of writing this report, the performance of the tools is unknown in the case of a massive number of assets. The case using more assets was the synthetic case previously described.

The programming language used by the tools in this work package is Python because it is freely available and can be easily installed in any computer. The files required are listed in section 3 of this report.

8. Concluding remarks

This deliverable includes the foundations and specification of the three tools planned to be developed in the ATTEST project for helping the process of making decisions in the context of asset management for TSO/DSO users. The tools will be designed using open source codes and under the principles of an easy adaptation to any specific context of data management in power companies. The three tools to be developed in this work package will offer information to the TSO/DSO users in a scaled way from the evaluation of basic indicators about the condition of the particular assets to an overall view of all of them where comparison can be done and simulation of possible future scenarios about their condition. The condition of the assets is obtained by consideration of four dimensions of each of them: life, maintenance, health condition and economic and environmental impacts where they are installed.

The main features to be developed in the tools where described in this deliverable but they could be considered only as a reference that could be improved, if this is consider convenient, during the development of the tools.

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