ATTEST

Ref. Ares(2021)6740657 - 02/11/2021

WP5

Development of a smart environment for asset management in power grids

Tool for the characterization of Health Conditions for Electrical Assets

D5.2

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	D5.2 – Tool for the characterization of Health Conditions for Electrical Assets
TYPE	Tool Manual
DISTRIBUTION LEVEL	Restricted
DUE DELIVERY DATE	30 / 09 / 2021
DATE OF DELIVERY	30 / 09 / 2021
VERSION	V1.3
DELIVERABLE RESPONSIBLE	Comillas
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DOCUMENT HISTORY

VERSION	AUTHORS	DATE	CHANGES
0.1	Pablo Calvo COMILLAS	23 / 09 / 2021	First complete version
0.2	Martin Bolfek HEP	29 / 09 / 2021	Second revision
0.3	HOPS ATTEST TEAM HOPS	29 / 09 / 2021	Third revision

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Abbreviations and acronyms

CM	Condition Monitoring
DSO	Distribution System Operator
mse	Mean Squared Error
NaN	Not A Number
PT	Power Transformer
sem	Standard Error of the Mean

1. 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 in order to operate TSO & DSO power systems. This goal is reached through the evaluation of a set of indicators that cover different perspectives of the life and maintenance of assets. The strategy for obtaining these indicators and interpretate them will be implemented in three different tools that support the whole process of asset management in the context of the ATTEST project.

This deliverable is the User Manual of the first tool of Work Package 5. The goal of this tool is the identification of critical information/data to quantify the health condition of the assets. Typically, there is a great variety of data collected during the observed life of the assets with different granularity and formats. This information needs to be properly processed, converted, and ranked. This tool aims to provide a detailed characterization of the assets, to improve the decision-making process in managing multiple and heterogeneous types of assets.

2. DESCRIPTION OF TOOL 5.1

2.1. SCOPE

The goal of this tool is the characterization of the assets using indicators related to their specific properties. This tool allows for the identification of critical information/data to quantify so the health condition of the assets could be assessed.

2.2. METHODOLOGY

This section describes the methodologies that run behind this tool to explain how their results are obtained and can be interpreted.

2.2.1.CHARACTERIZATION OF HEALTH CONDITIONS FOR ELECTRICAL ASSETS

The characterization of Health Conditions for Electrical Assets aims to identify those assets with similar health condition. Patterns of assets with similar health condition are identified through clustering. Each pattern shows the most characteristic features of the clustered assets. Clustering allows the user to identify which assets share similar features improving the decision taking process regarding their health conditions.

2.2.1.1. 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 together. The total number of clusters (patterns) is determined through a well-known clustering algorithm: k-means; and two morphological assessment methods: elbow method and gap statistic method. One of uses for the field of unsupervised learning is cluster analysis. 'Unsupervised' learning methods aim to discover relationships between features without any prior knowledge about them. The clustering methods applied in this application are unsupervised K-means algorithm, used as part of the selection process for determining the optimal number of clusters, and Self-Organizing Maps (SOM) for 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, while SOMs are more precise than K-means.

In this application, two different heuristic methods are used are used to identify the optimal number of clusters automatically. These two heuristics are the Elbow method and the Gap statistic method. The first approach is based on the distortion (within-cluster dispersion value) defined by average squared Euclidean distance of each sample to the center of the cluster to which each observation belongs. The second approach compares the dispersion value obtained for the input dataset and an expected one for an equally distributed ideal dataset. (Tibshirani, 2001)

The Elbow method states that the optimal number of clusters is located at the point of inflection (elbow-shaped) 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 1 shows how both algorithms provide similar results (6 and 7, respectively) for the detection of optimal number of clusters, which are marked with a red cross.

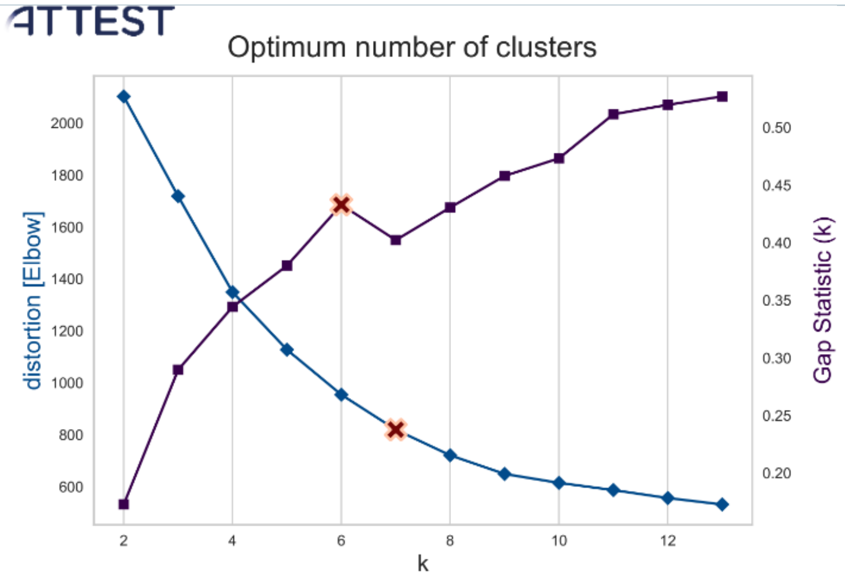

FIGURE 1 OPTIMUM NUMBER OF THE CLUSTERS (PATTERNS) ACCORDING TO ELBOW AND GAP STATISTIC METHODS

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

In the case that the optimal number of clusters is a prime number (larger than 3), the optimal number is rounded to the previous largest non-prime number. (Figure 2)

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

FIGURE 2 SOM LAYOUT DEPENDING ON THE OPTIMAL NUMBER OF CLUSTERS

2.2.1.2. 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 values. The min-max normalization is defined by the following equation:

$$v_{y,norm} = \frac{v_y - min(V_y)}{max(V_y) - min(V_y)} \qquad 1$$

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.

2.2.1.3. Clustering process. SOM training process.

The optimal number of clusters is not a deterministic indicator. Its estimated value is optained through an iterative process. This means that there might be some variations between the initial expected optimal number and the final number of clusters. These variations appear because the initial optimum number of clusters might be too large, producing some empty clusters. An empty cluster means that the layout is not optimal, therefore in this case the number of clusters is reduced by one until all the clusters are full. This iterative process is depicted in Figure 3:

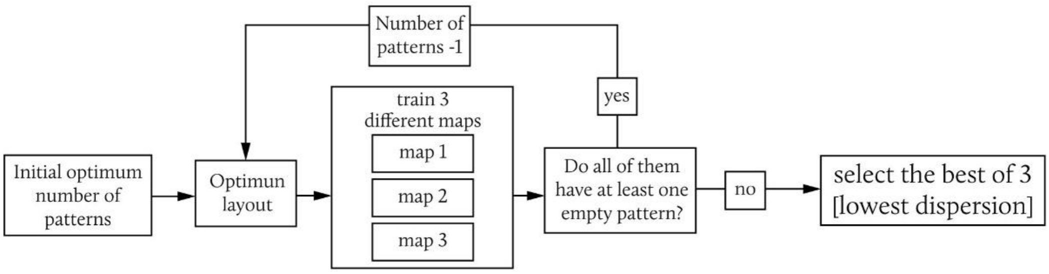

FIGURE 3 FLOW CHART OF THE TRAINING PROCESS OF THE SOM

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. An example of how the dispersion value evolves throughout the training process is shown in the following Figure 4

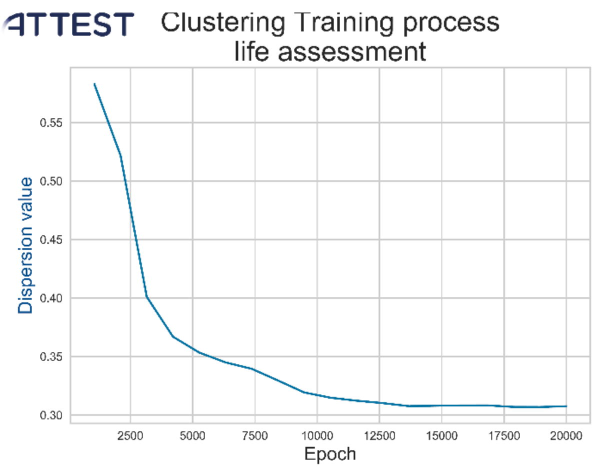

FIGURE 4 DISPERSION VALUE DEPENDING ON THE TRAINING EPOCH OF THE SOM

2.2.1.4. 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.

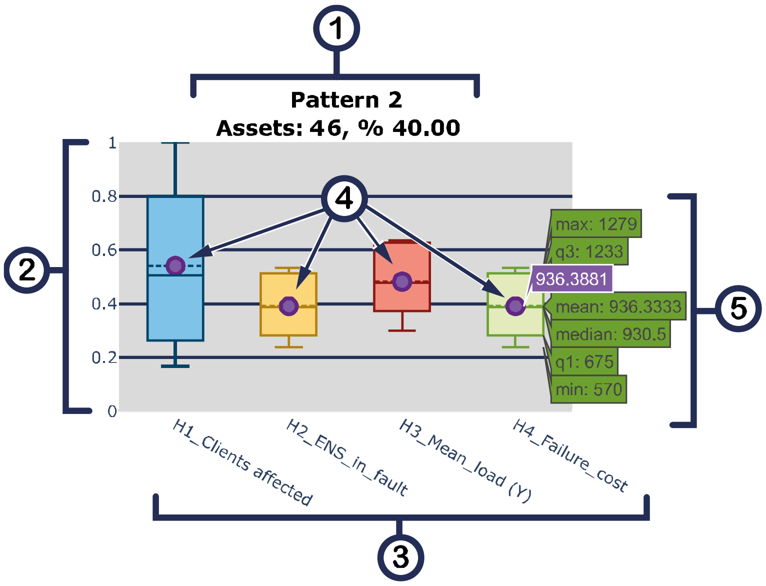

FIGURE 5 ELEMENTS OF THE BOX PLOTS

The main elements of each plot are the following.

1) The header of the pattern. It includes the ID number of the pattern (2 in the figure), the number of assets within the pattern(46 in the figure), and the proportion of assets included within the pattern with regards to the whole set of assets (40% in the figure).
2) The main scale. This scale allows the user to compare variables with different maximum and minimum values.
3) The name of variables, indicators, and 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.

2.2.2. CONDITION MONITORING FOR TRANSFORMERS

2.2.2.1. Condition model

This option aims to detect abnormal temperatures in the behavior of transformers fitted with temperature sensors in windings and oil insulation. These two temperatures are correlated with the current levels registered to build a behavior model of the transformer. This case is only an example about managing information that could be collected in real time. More cases are possible to consider for monitoring other different caracteristics of the assets. All of them will be built before the tool is used for condition monitoring and their main role is to be references for observing if the normal behavior previously observed during the model construction, is observed after this in the current operation observed.

The condition monitoring plan is conceived as the prediction of the winding temperature as a function of the load of the power transformer and the oil temperature. If the condition of the power transformer is adequate, the evolution of the winding temperature should follow the dynamics of the load measured in the power transformer as well as the oil temperature. Any hot spot -or cooling problem of the oil will appear as a discrepancy and trigger a warning about the degradation of the power transformer.

To reach this goal, a model of normal behavior expected in these three variables was built using part of the data available (one year), taking into account, in particular, 7000 samples per hour. The model proposed was winding_temperature = f(load, oil_temperature) . One model was fitted for PT-1 and another one for PT-2. Being PT-1 and PT-2, two different behaviors registered from two different transformers. A multi-layer perceptron neural network was used as an approximator for the function *f*. Schematic representation of the model is shown in Figure 6.

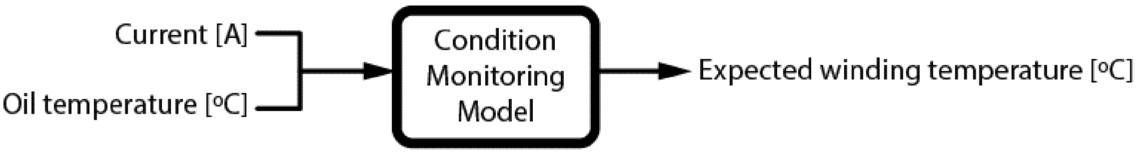

FIGURE 6 SCHEMATIC REPRESENTATION OF THE CONDITION MONITORING MODEL

Figure 7 presents available data for the power transformer PT-1:

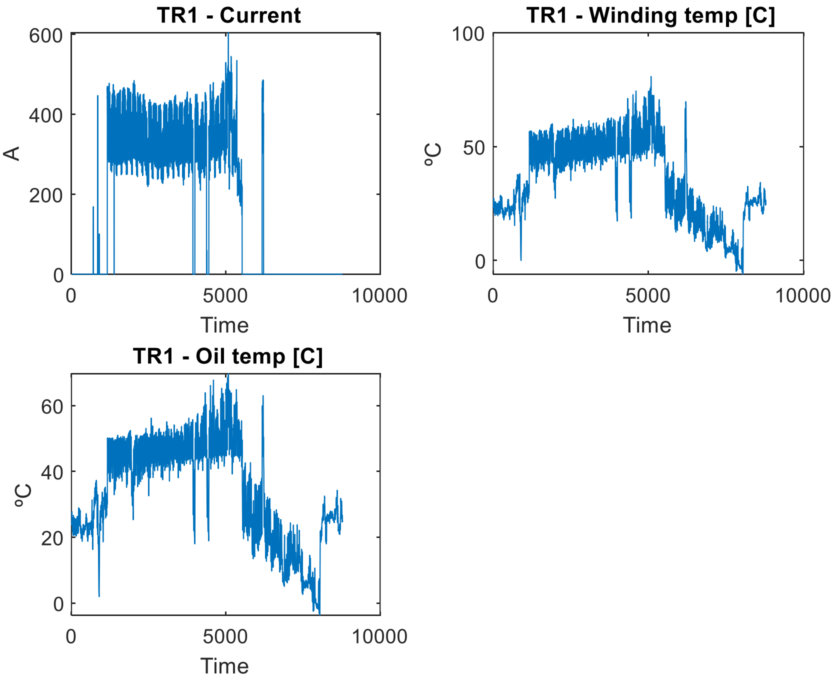

FIGURE 7 DATA FOR POWER TRANSFORMER PT-1

And Figure 8 presents available data for the power transformer PT-2:

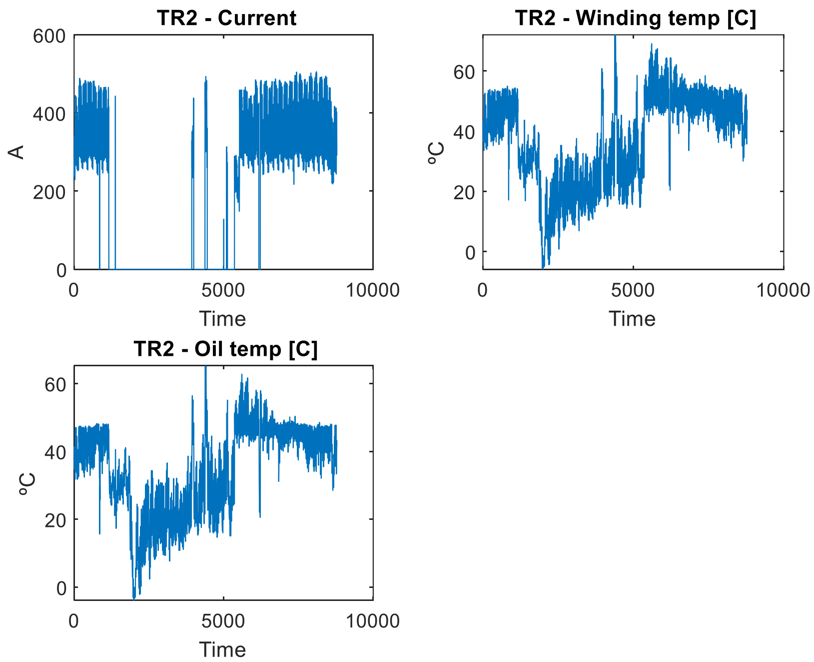

FIGURE 8 DATA FOR POWER TRANSFORMER PT-2

A model based on a multi-layer perceptron is designed with 20 neurons in its hidden layer for modeling the normal behavior of PT-2. The accuracy of the model is 99%. Figure 9 shows the temperature values estimated by the model, which overlap the actual values.

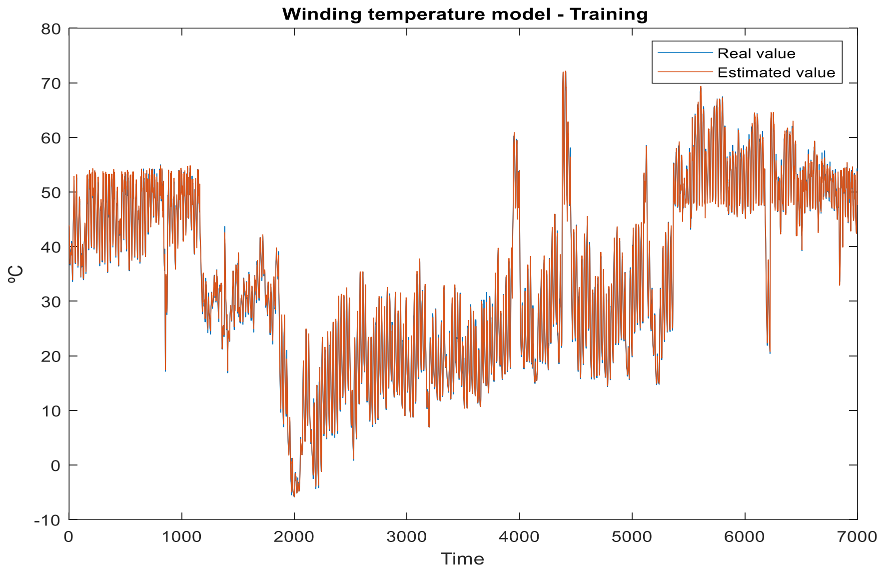

FIGURE 9 RESULTS OF THE WINDING TEMPERATURE MODEL FOR PT-2

Figure 10 shows the performance of the model with a set of inputs that is not part of the training and a confidence band, showing which results are outside of the expected error band.

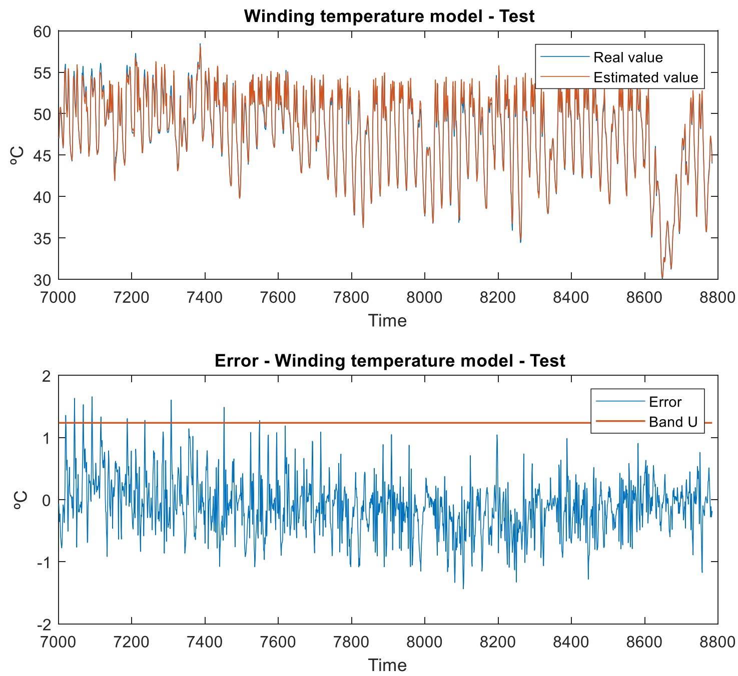

FIGURE 10 EVALUATION OF THE WINDING TEMPERATURE MODEL FOR PT-2

A similar analysis is developed for the power transformer PT-1. A model based on a multi-layer perceptron is designed with 20 neurons in a hidden layer for modelling the normal behavior of PT-1. The accuracy of the model is 99% (Figure 11).

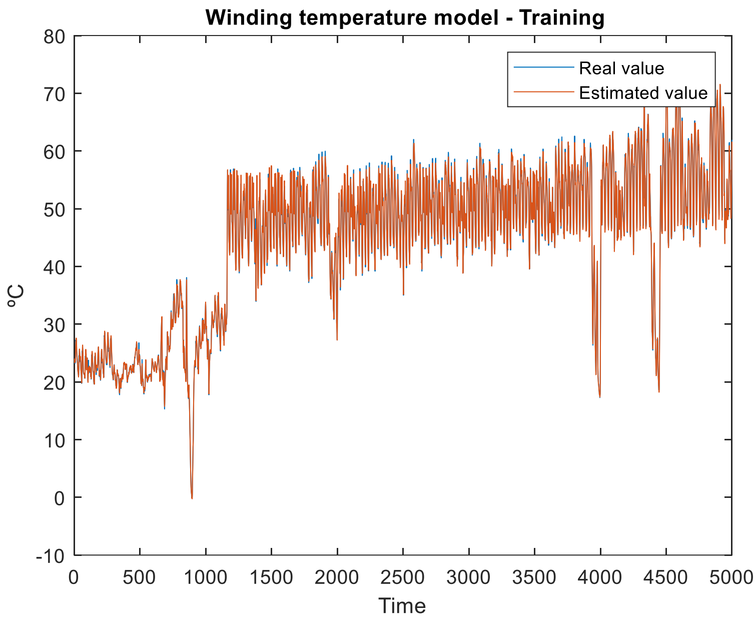

FIGURE 11 RESULTS OF THE WINDING TEMPERATURE MODEL FOR PT-1

Figure 12 shows the performance of the model with a set of input values excluded from the training set and a confidence band, showing what cases are outside of the expected error threshold.

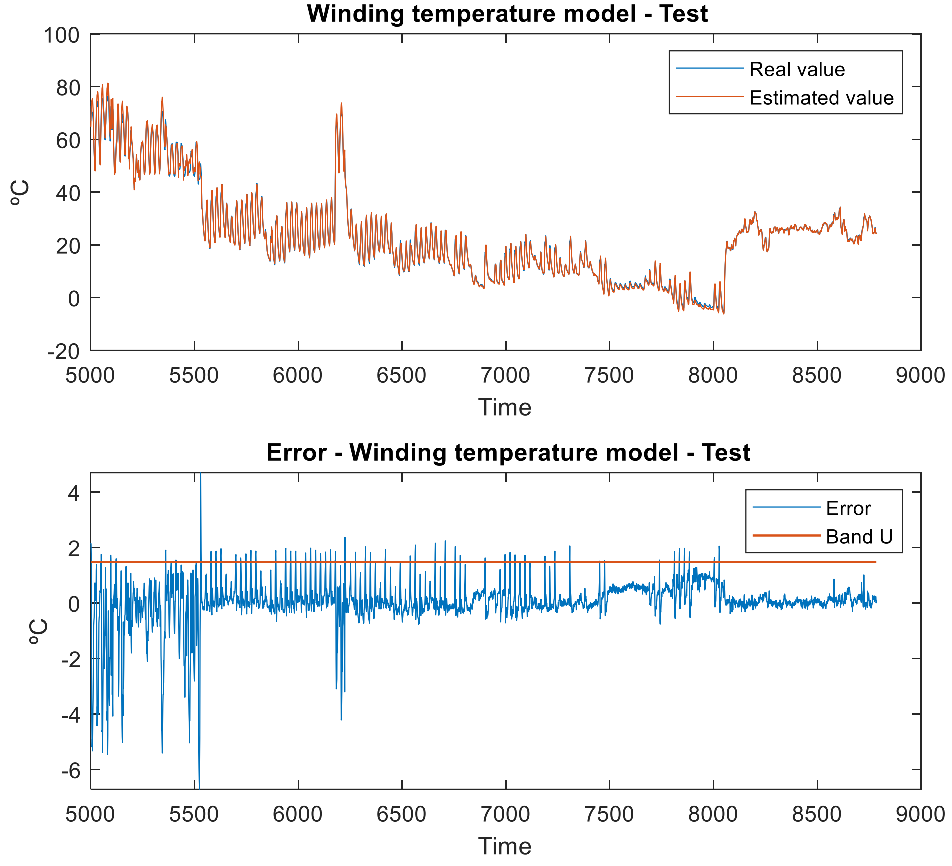

FIGURE 12 EVALUATION OF THE WINDING TEMPERATURE MODEL FOR PT-1

2.2.2.2. Health Condition Indicators

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

- H1_SOCB_OP. This indicator represents the percentage of samples outside the confidence band in the Old Past period which is made up of thefirst 50% samples.
- H2_SOCB_MP. This indicator represents the percentage of samples outside the confidence band in the Mid Past period which is made up of the next 30% samples.
- H3_SOCB_NP. This indicator represents the percentage of samples outside the confidence band in the Near Past period which is made up of the last 20% samples.
- H4_SOCB_TP. This indicator represents the percentage of samples outside the confidence band in the whole period.

An example of how these indicators are obtained is shown in Figure 13.

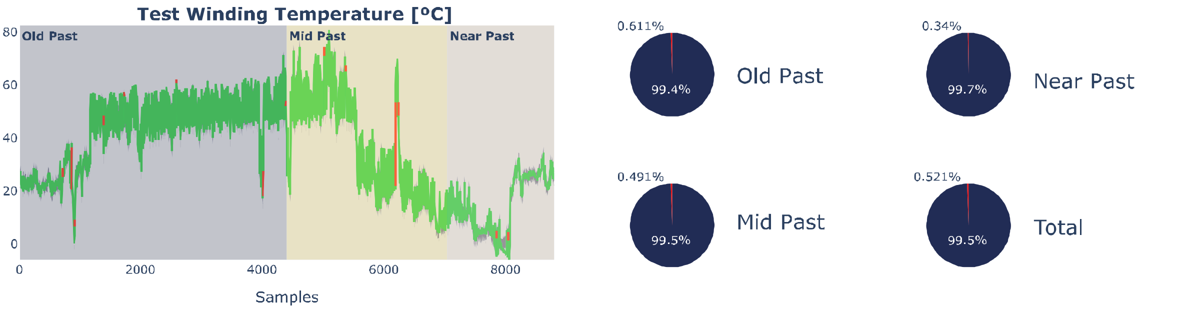

FIGURE 13 EXAMPLE OF THE CONDITION MONITORING GRAPH AND HEALTH CONDITION INDICATORS.

A condition is considered anomalous when the actual winding temperature is above the threshold value determined by its expected value. See Figure 14.

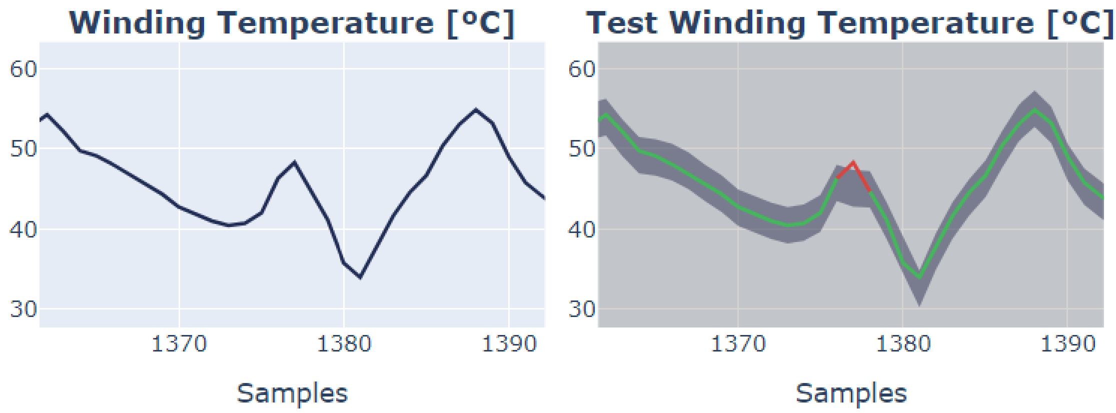

FIGURE 14 DETECTION OF ANOMALOUS CONDITIONS

A condition is not considered anomalous when the actual winding temperature is within or below the threshold value determined by its expected value. See Figure 15.

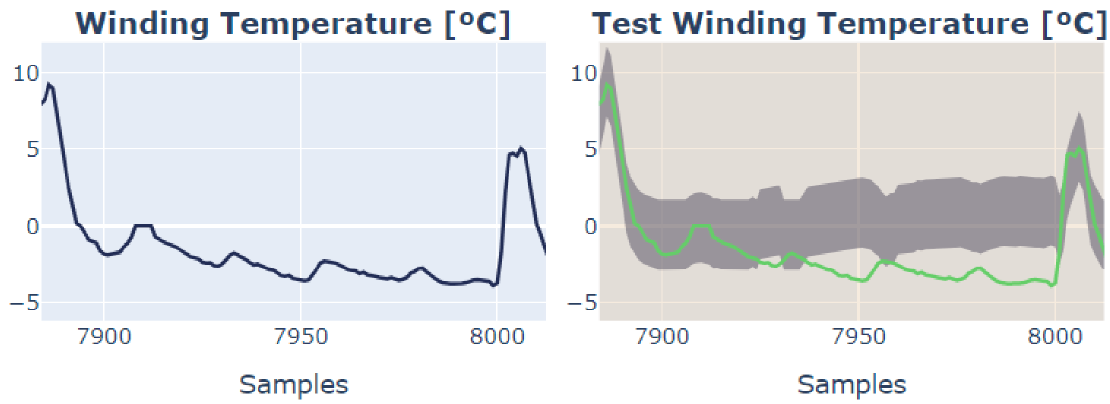

FIGURE 15 NOT ANOMALOUS CONDITIONS

3. INPUTS AND OUTPUTS

This section describes the formats of the input and output files of the tool. The description of signals, indicators and input variables can be found in deliberable D5.1.

3.1. INPUTS

3.1.1. CHARACTERIZATION OF HEALTH CONDITIONS FOR ELECTRICAL ASSETS

The following are the input files of the AAMT.

- **Assessment file (Life assessment, Maintenance strategy, Economic Impact):** It includes the features that characterize the state of each asset. This input file might contain alpha-numeric variables but only numeric values are included within the patterns obtained from the clustering process.

  Comments:

  - Selected variables from input files must be numeric.
  - Dimension files must not contain empty or Not a Number (NaN) values. In such cases, it is recommendable to fill the empty values with Ø, in case of numbers; or "not available", in case of text strings.

  File format:

  - Compatible formats: .CSV

- **Auxiliary file:** It includes any additional alpha-numeric feature used to identify and differentiate assets.

  Comments:

  - Auxiliary files must share a common identifier column with the Dimension file.

  File format:

  - Compatible formats: .CSV

CSV format comments:

CSV files can present different formats. This can hinder the parsing process of the file, producing errors in the reading process of the file. Therefore, it is important to take into account that this application only supports the following CSV coding:

- Two types of **delimiter characters** are accepted: **semicolon** (;) or **comma** (,)
- One type of **decimal separator** is accepted: **dot** (.)

3.1.2. CONDITION MONITORING FOR TRANSFORMERS

The following are the input files of the CMTT.

- **Monitoring model file**: This file isthe behavior model used to estimate the winding temperatures of the transformer. Inputs are the electric current intensity and oil temperature of the transformer.
  - File format: HDF5 (.h5)

- **Error threshold file**: This file includes the value of the mean and the standard deviation of the error obtained from the training set. These two values define the features of the anomaly detection threshold. The columns/keys of the Error threshold file must be: “**mse**” for the mean squared error and “**sem**” for the standard error of the mean.
    - Compatible formats: .CSV, .JSON, Excel files (.XLSL, .XLSX)

3.2. OUTPUTS

3.2.1. OUTPUT FILE FORMATS

The outputs of the characterization of the health condition application are the following.

- Pattern dashboard. The patterns obtained for each type of asset are shown in separate dashboards for each of the dimensions included in the assessment. Such dashboards are visualized as an interactive webpage in HTML format.
- Clustering and Training process visualization. These two graphs show how the optimal number of patterns is obtained and how the clustering error evolves throughout the training process. Both graphs are saved in PDF format to be visualized independently.

The output of the condition monitoring application is the following.

- Condition monitoring dashboard. This dashboard shows the results obtained from comparing the expected and real winding temperatures, including the time series of oil temperature and electric current, and the values obtained from the four indicators previously explained. Dashboards are also generated in HTML format.

3.2.2. OUTPUT FILE LOCATIONS

The outputs of the characterization of health application are located within the folder: *static\results_asset_management*

The output of the condition monitoring application is located within the folder: *static\results_condition_monitoring*

3.2.3. OUTPUT VISUALIZATION

Output files of the characterization of health application can only be visualized through the application; by contrast, output files of the condition monitoring application can be visualized outside the application by opening the generated HTML file.

4. USER INTERFACE

This section describes the main elements of the user interface, including the steps for importing the input files for each of the two tools.

4.1. MAIN MENU

This menu allows the users to select which application they want to use. Each button loads the application indicated by its name. In case help is needed, the user can open the Help document by clicking on the button: "User Manual". This menu is shown in Figure 16.

FIGURE 16 USER INTERFACE OF THE MAIN MENU

4.2. CHARACTERIZATION OF HEALTH CONDITIONS FOR ELECTRICAL ASSETS

The steps for importing the input files of this application are the following.

1) Optional. Type of asset. The user can write in this field the type of asset. This field will be the title of the dashboard that will be generated.

----------------- Configuration of a dimension -----------------
Repeat these steps for each dimension.

2) Path to the dimension input file.
3) Select the corresponding dimension to the input file.
4) Select numeric variables that will define the pattern features of the selected dimension.
5) Optional. Path to the auxiliary file. Each dimension can include a file of additional features that can be numerical or categorical. These features are used to identify and group the inported assets.
6) Optional. Variable for grouping assets. The variable selected in the auxiliary file will be used to group the assets. If the variable is numerical, the assets will be grouped in quartiles. If the variable is categorical the assets will be grouped in groups of assets with the same value.
7) Selection of the results. The user can choose which results will be generated by the application.

8) Save dimension configuration. Once each dimension is configured it has to be saved clicking on this button.

----------- End of the configuration of a dimension -----------

9) Generate results. Starts the process of results generation with the selected configuration.
10) Show results. Starts the local server and shows the corresponding dashboards.

FIGURE 17 USER INTERFACE OF THE CHARACTERIZATION OF HEALTH CONDITIONS APPLICATION

The results generated are shown as dashboards. One example of dashboard is shown in Figure 18. Each dashboard is made up of:

1) Menu of grouped assets. Through the variable selected in the auxiliary file, it is possible to group the assets according to the type of variable selected.
2) Dimension menu. Through this menu it is possible to access multiple imported dimensions. Dark blue indicates the current dimension, dark gray indicates the available dimensions, and light gray indicates that the dimension is not available.
3) Filter menu. Through this menu, it is possible to filter the assets depending on their feature value.
4) Restore button. It allows restoring the original state of the dashboard, discarding any filter applied.
5) Pattern graph. Each of the patterns contains information about how the assets of such pattern are distributed. Clicking on the title of the pattern shows a table with the available information for all the assets that belong to that pattern (see Figure 19). The title also includes the number and the total percentage of assets included in the pattern.
6) Close button. This application needs to be disconnected before closing the browser window, otherwise the tool process will remain active.

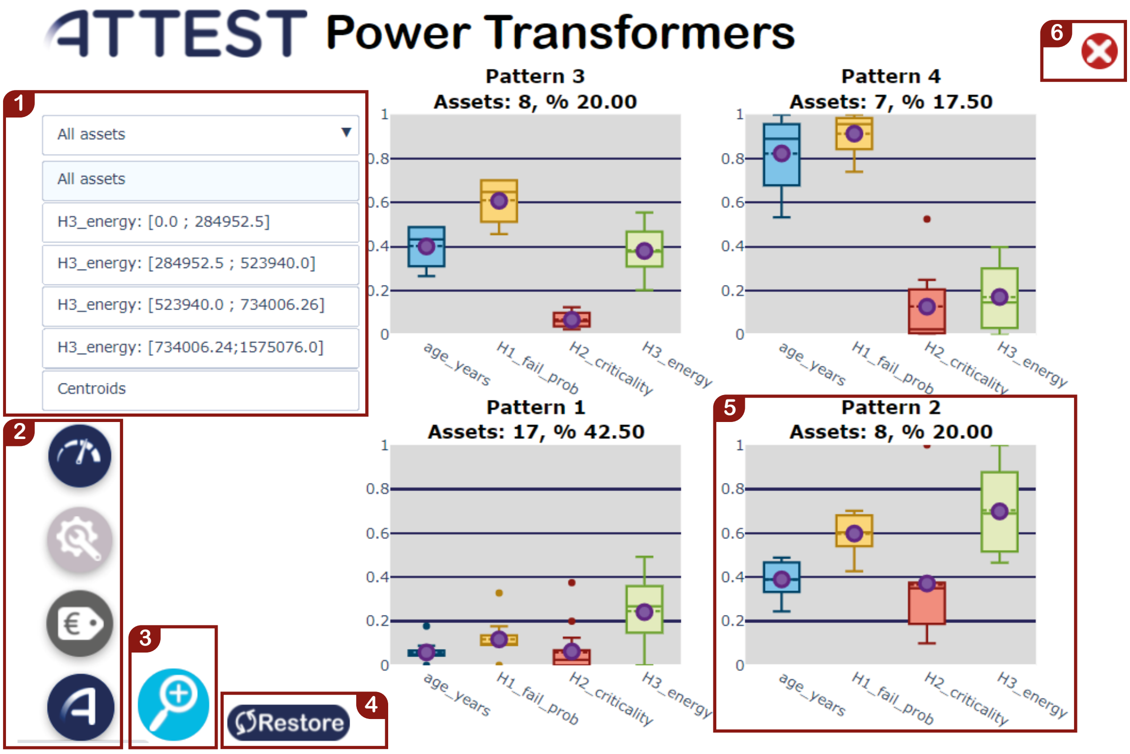

FIGURE 18 EXAMPLE OF DASHBOARD

A table of assets is shown in Figure 19. The main elements of this dashboard are:

1) Group sets. Each header indicates the group to which each asset belongs.
2) Interactive header. By clicking on the header it is possible to sort the asset values in descending or ascending order.
3) Return button. This button returns to the main dashboard of the corresponding dimension.

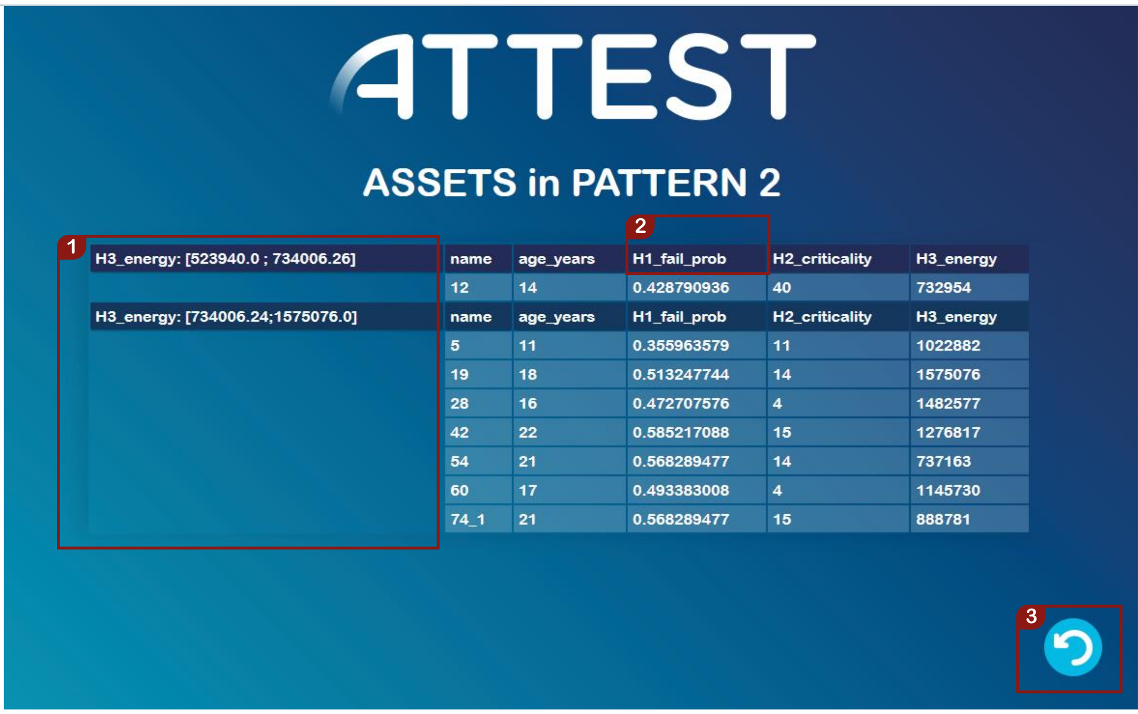

FIGURE 19 EXAMPLE OF TABLE OF ASSETS WITHIN A PATTERN

The main elements of the search tool menu, see Figure 20, are:

1) Include / Exclude: This option allows for searching assets excluding or including the configuration selected.
2) Load / Download filer configuration: The configuration can be saved to a .JSON file to be loaded afterwards.
3) Apply / Reset filter: Once the configuration has been set, it can be applied, or it can be set to its default values.
4) Enable / Disable filter. When this option is not checked, the condition is not included as part of the search function.
5) Numerical search. For numeric variables it is possible to apply four different conditions: greater than, lower than, equal to, and within two numeric values.
6) Categorical search. For categorical variables it is possible to select specific values are added for the search function.

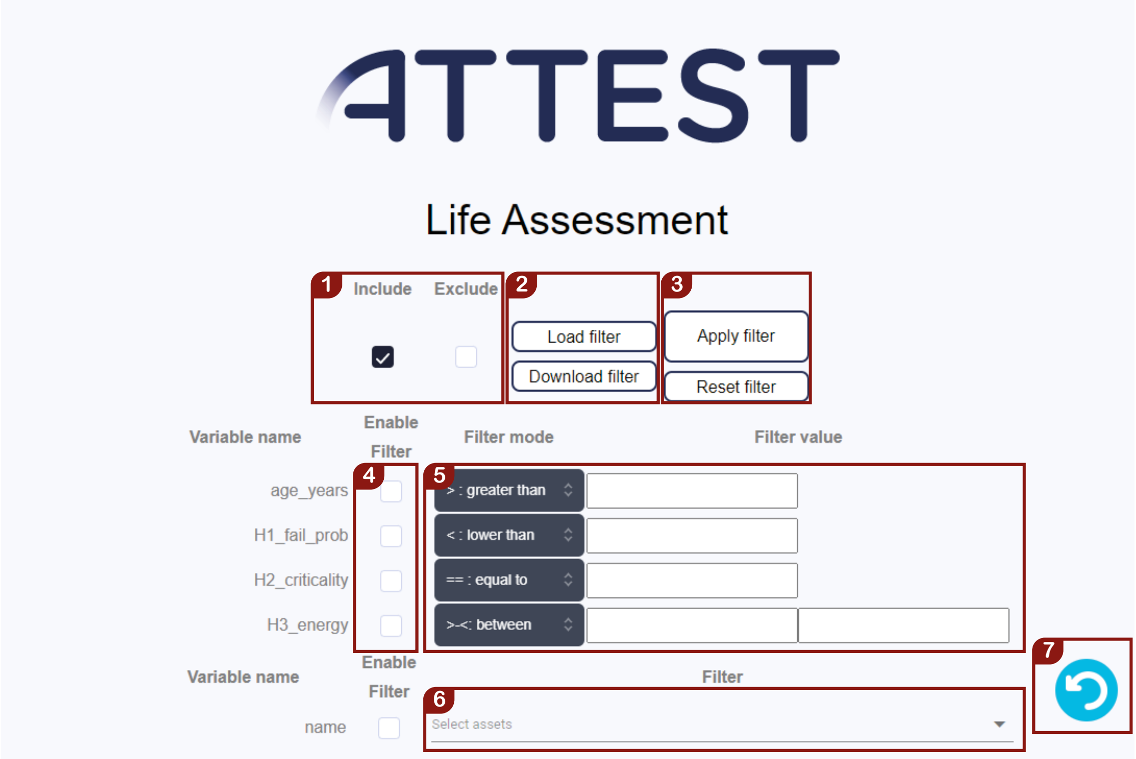

FIGURE 20 EXAMPLE OF SEARCH TOOL MENU

Categorical searchs are configured through the following menu, see Figure 21:

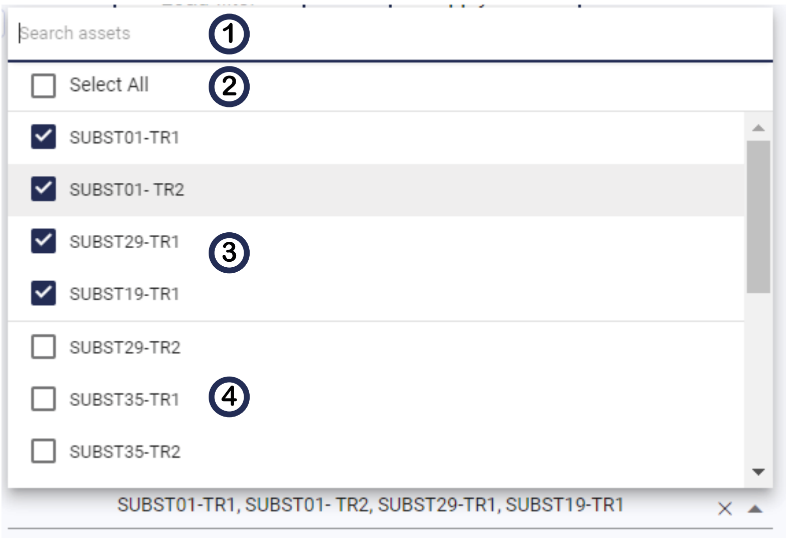

FIGURE 21 CATEGORICAL VARIABLE SEARCHING TOOL

The elements of this menu are:

1) Search box. Allows searching of any name within the list of categorical values.

2) Select all buttons. Allows selecting all the values corresponding to the inputted categorical variable.
3) List of selected values.
4) List of unselected values.

4.3. CONDITION MONITORING FOR TRANSFORMERS

The steps to load the input files in the Condition Monitoring for Transformers application are the following.

1) Select the model that contains the characterization of the behavior of power transformers.
2) Select the threshold configuration file.
3) Select the input dataset with the monitored values of electric current, oil temperature, and winding temperature.
4) Select which variables within the input dataset correspond to the current, oil temperature and winding temperature.
5) Generate results.
6) Show the results in a web browser.

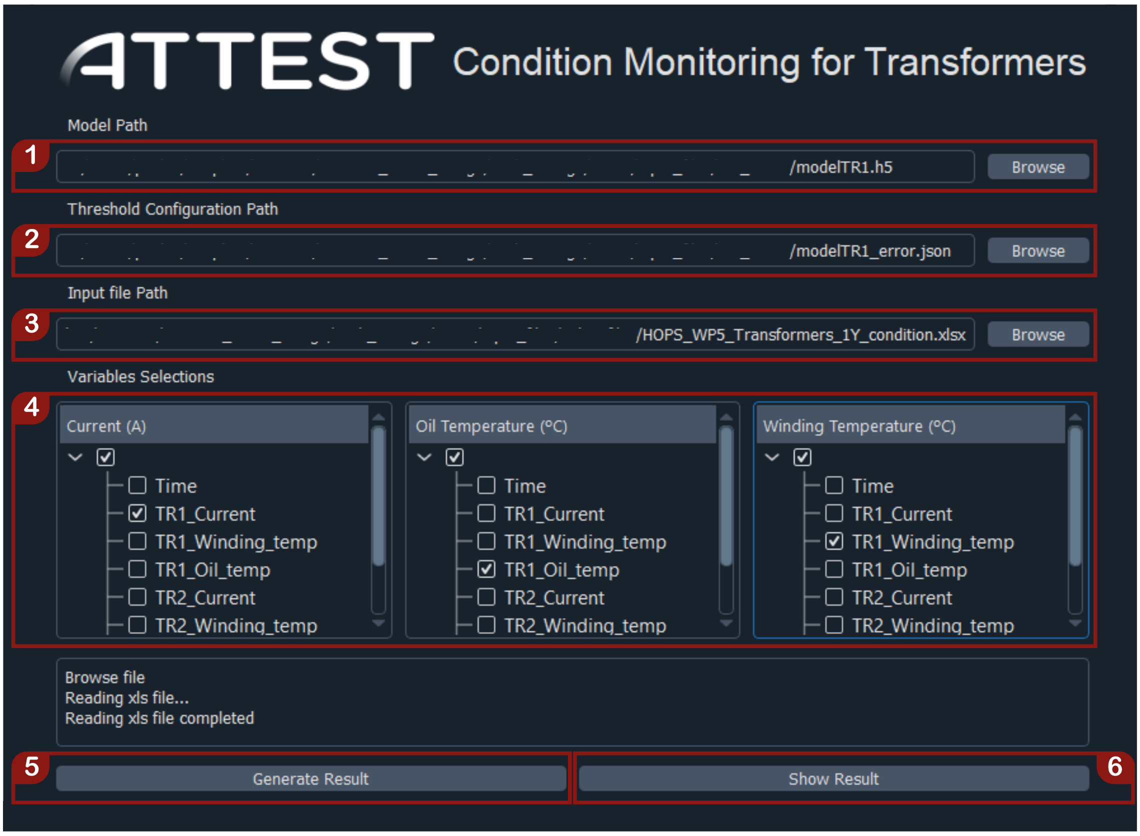

FIGURE 22 USER INTERFACE OF CONDITION MONITORING FOR TRANSFORMERS APPLICATION

An example of a dashboard obtained with this application can be seen in Figure 23. The main elements in this dashboard are:

1) Current values of the transformer

2) Oil temperatures of the transformer
3) Real winding temperatures of the transformer
4) Real vs estimated winding temperatures. This plot includes all the samples outside of the acceptance threshold highlighted in red.
5) Health Indicator that corresponds to the old past, mid past, near past and total. These indicators include the percentage of normal samples (dark blue) and the percentage of anomalous samples (red).

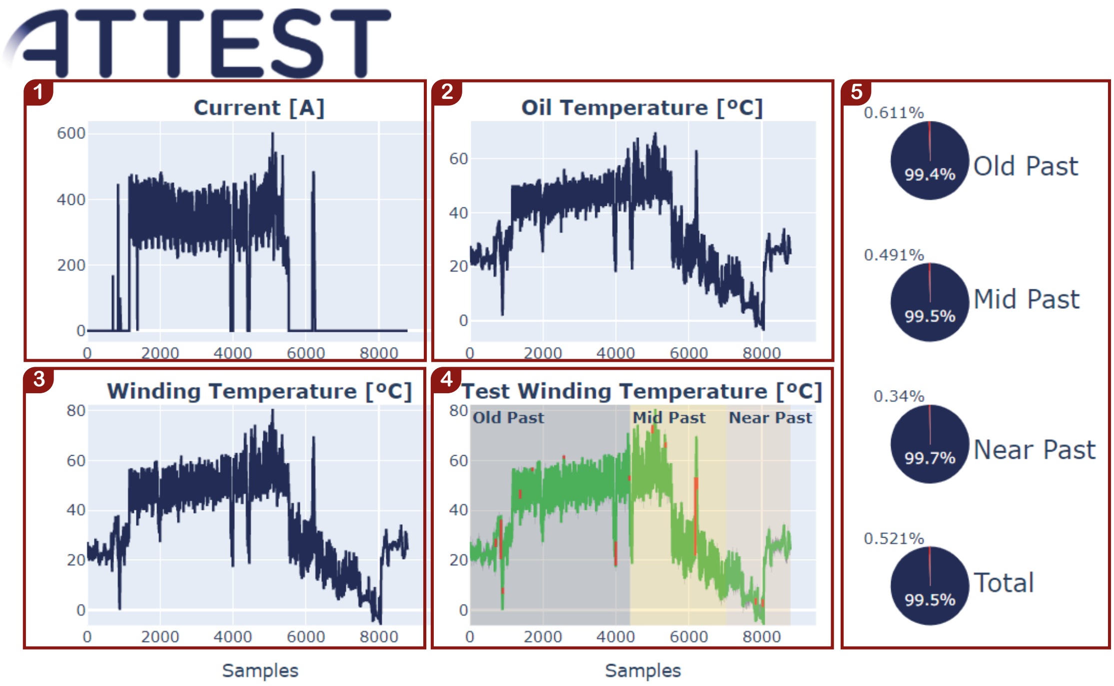

FIGURE 23 EXAMPLE OF DASHBOARD FOR THE CONDITION MONITORING FOR TRANSFORMERS

5. INSTALLATION

The software is a portable tool. It only has to be unzipped within the desired folder. The files and folders contained in the zip file are shown in Figure 24.

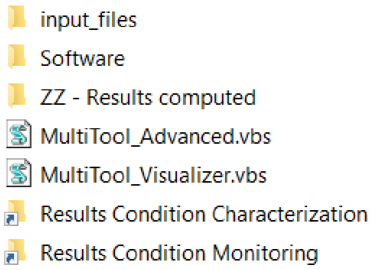

FIGURE 24 MAIN FILES OF THE TOOL

- Input_files: folder with the case studies included in this manual.
- Software: folder with all the Scripts and Virtual Environment files of the tool.
- MultiTool_Advanced.vbs: Script to call the advanced tool that generates and visualizes the results contained in the corresponding results folder.
- MultiTool_Visualizer.vbs: Script to call the tool to visualize the results contained in the corresponding results folder.
- Results Asset Management: Opens in a new window the folder that contains the results generated by the application of Condition Characterization.
- Results Condition Monitoring: Opens in a new window the folder that contains the results generated by the application of Condition Monitoring.

The PDFs of the clustering process for each dimension (Optimal number of clusters and training process) are not opened automatically, but they are accessible through the path:

- Results Condition Characterization >> clustering_graphs (Figure 25)

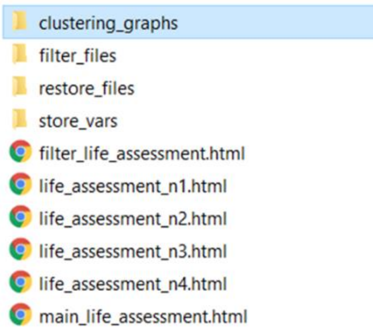

FIGURE 25 FOLDER WITH THE RESULTS OF THE CLUSTERING PROCESS

5.1. Software – Hardware requirements

- This software has been developed for a system with these minimum requierements:
    - OS: Windows 7 SP1/8.1/10 - 64bit.
    - Screen resolution. 1920 x 1080.
    - Python 3.8
    - RAM: 4GB
    - Hard Drive Space Required: 3 GB

6. CASE-STUDIES

In order to illustrate the type of results obtained, several real cases and a synthetic grid were analyzed through this tool.

6.1. CHARACTERIZATION OF HEALTH CONDITIONS FOR ELECTRICAL ASSETS

6.1.1. HEP - ASSETS

6.1.1.1. TRANSFORMERS

- Life assessment
    - Number of assets: 40 transformers
    - Features considered:
        - Age
        - Failure probability
        - Criticality
    - Results:
        - 4 patterns identified.

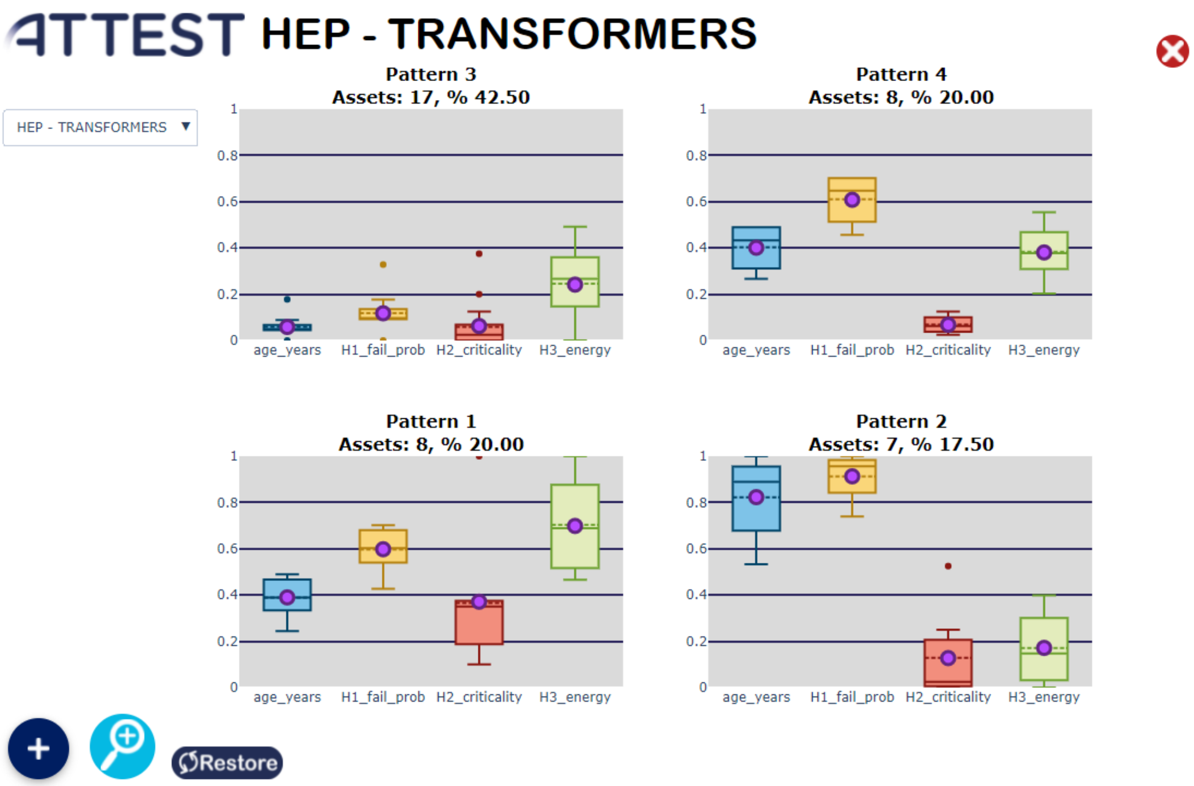

FIGURE 26 RESULTS: HEP TRANSFORMERS – LIFE ASSESSMENT

- Maintenance strategy
  - Number of assets: 40 transformers
  - Features considered:
    - External condition
    - Cost of failure
  - Results:
    - 4 patterns identified.

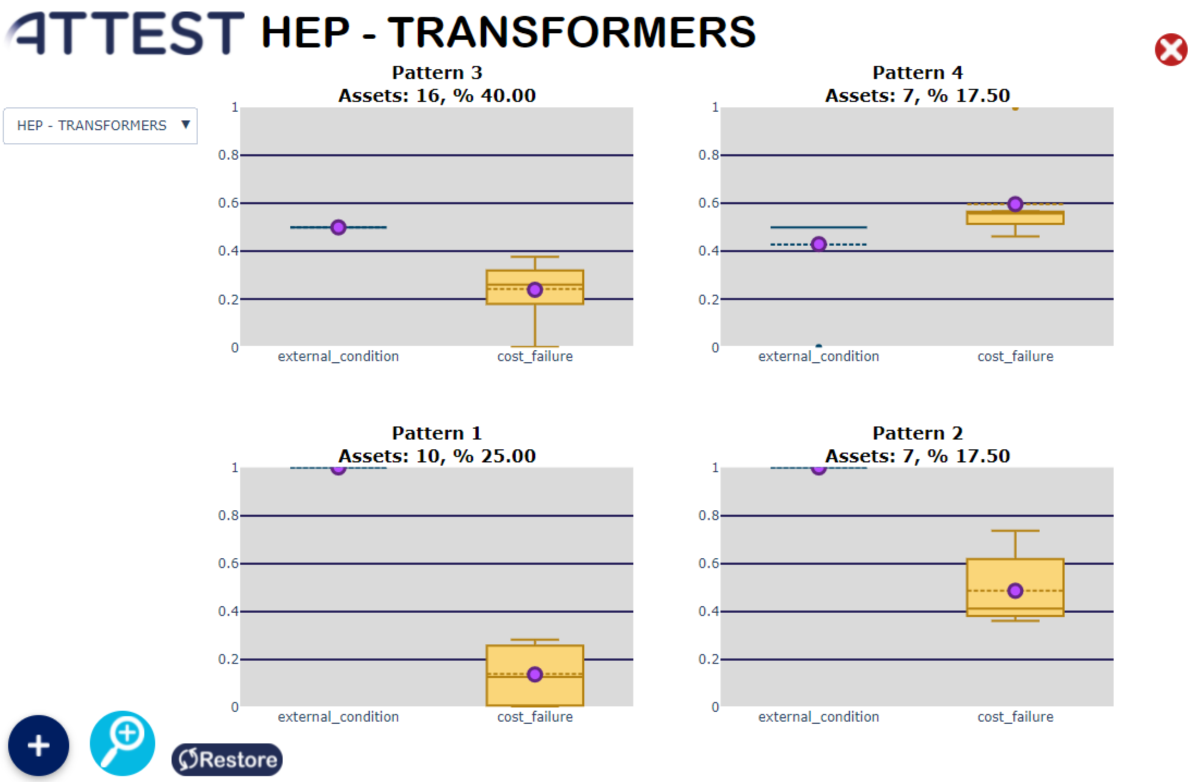

FIGURE 27 RESULTS: HEP TRANSFORMERS – MAINTENANCE STRATEGY

- Economic impact
    - Number of assets: 40 transformers
    - Features considered:
        - Cost of failure.
        - Number of customers affected.
        - Value of lost load.
    - Results:
        - 3 patterns identified.

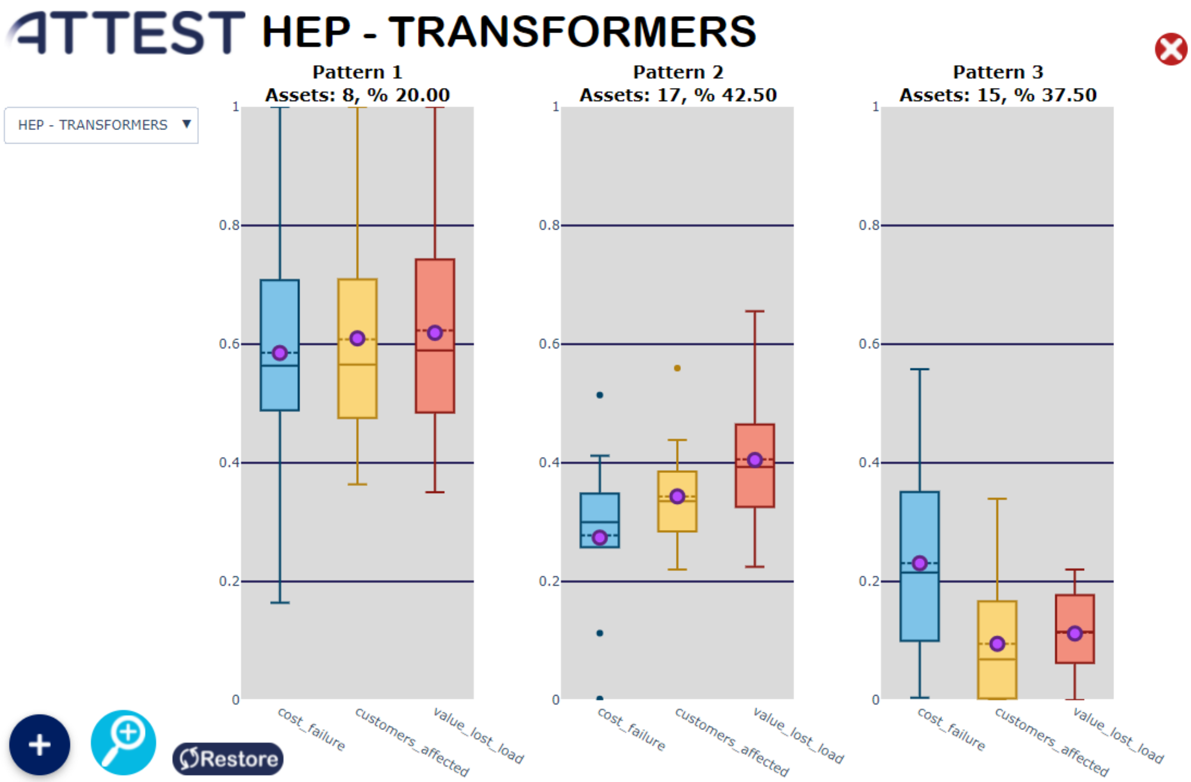

FIGURE 28 RESULTS: HEP TRANSFORMERS – ECONOMIC IMPACT

6.1.1.2. TRANSMISSION LINES

- Life assessment
  - Number of assets: 52 lines
  - Features considered:
    - Age.
    - Failure probability.
    - Criticality of the asset.
    - Energy supplied.
  - Results:
    - 6 patterns identified.

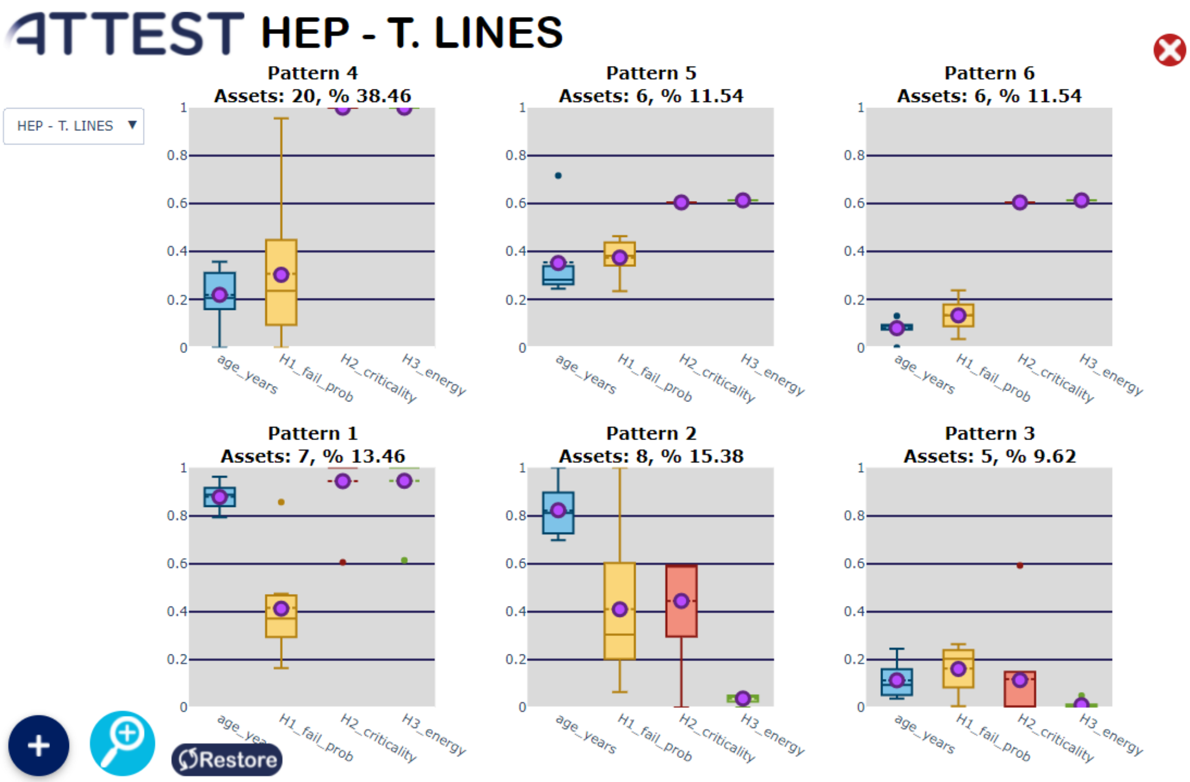

FIGURE 29 RESULTS: HEP TRANSMISSION LINES – LIFE ASSESSMENT

- Maintenance strategy
  - Number of assets: 52 lines
  - Features considered:
    - Repair time.
    - Cost of failure.
  - Results:
    - 3 patterns identified.

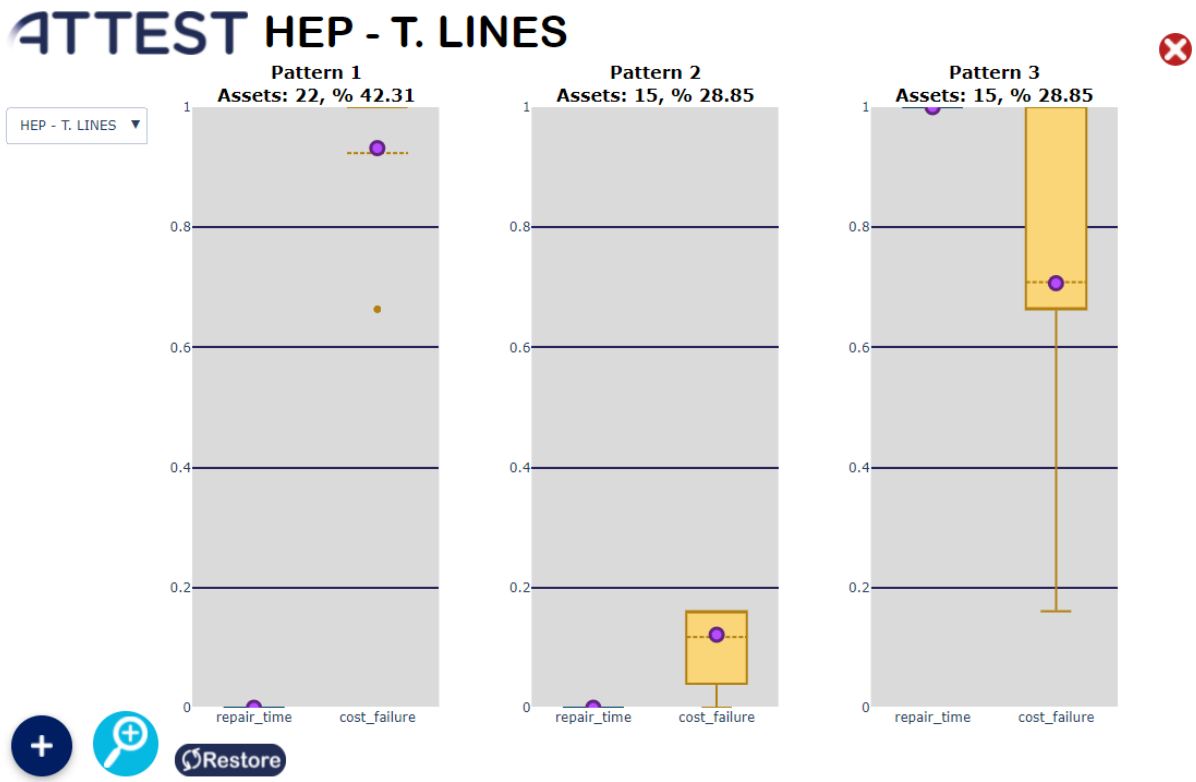

FIGURE 30 RESULTS: HEP TRANSMISSION LINES – MAINTENANCE STRATEGY

- Economic impact
  - Number of assets: 52 lines
  - Features considered:
    - Cost of failure.
    - Number of customers affected.
    - Value of lost load.
  - Results:
    - 4 patterns identified.

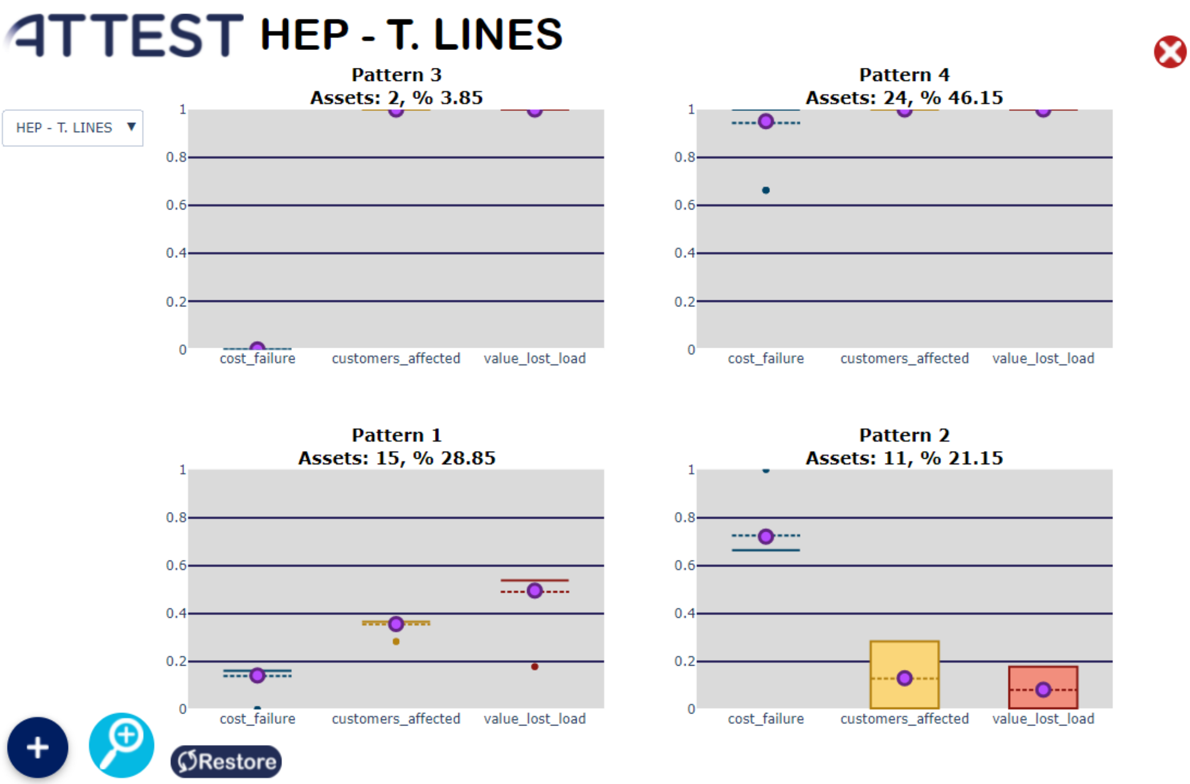

FIGURE 31 RESULTS: HEP TRANSMISSION LINES – ECONOMIC IMPACT

6.1.2. HOPS – ASSETS

6.1.2.1. TRANSFORMERS

- Life assessment
    - Number of assets: 15 transformers
    - Features considered:
        - Age.
        - Failure probability.
        - Unavailability dependent on age.
        - Load over the 50% of its power rating.
    - Results:
        - 3 patterns identified.

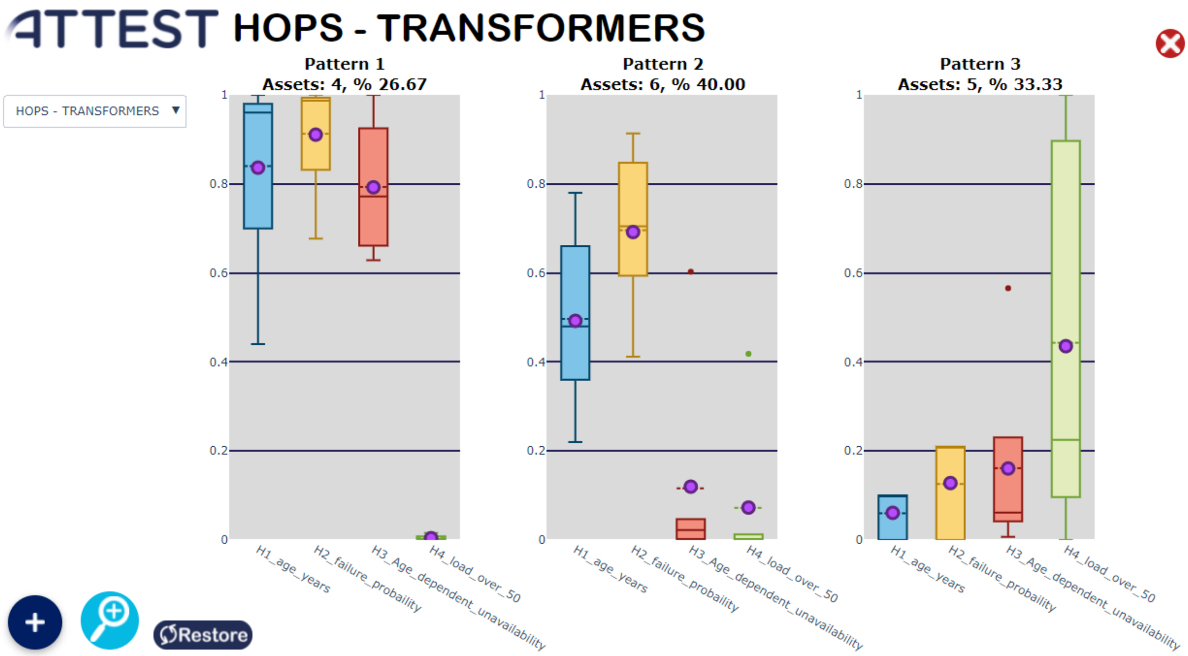

FIGURE 32 RESULTS: HOPS TRANSFORMERS – LIFE ASSESSMENT

- Maintenance strategy
    - Number of assets: 15 transformers
    - Features considered:
        - Maintenace cycles A (y)
        - Maintenace cycles B (y)
        - Maintenace cycles C (y)
        - Review A (man/day)
        - Review B (man/day)
        - Review C (man/day)
    - Results:
        - 1 pattern identified.

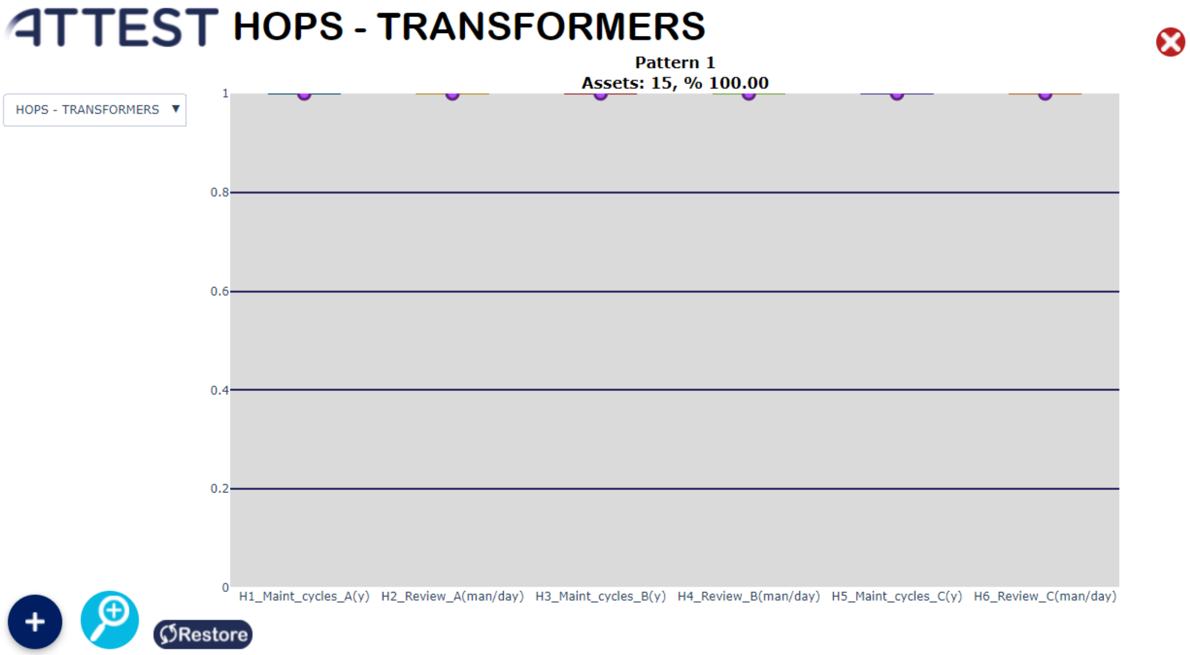

FIGURE 33 RESULTS: HOPS TRANSFORMERS – MAINTENANCE STRATEGY

- Economic impact
  - Number of assets: 15 transformers
  - Features considered:
    - Number of clients affected.
    - Energy not supplied in fault.
    - Mean load.
    - Cost of failure.
  - Results:
    - 3 patterns identified.

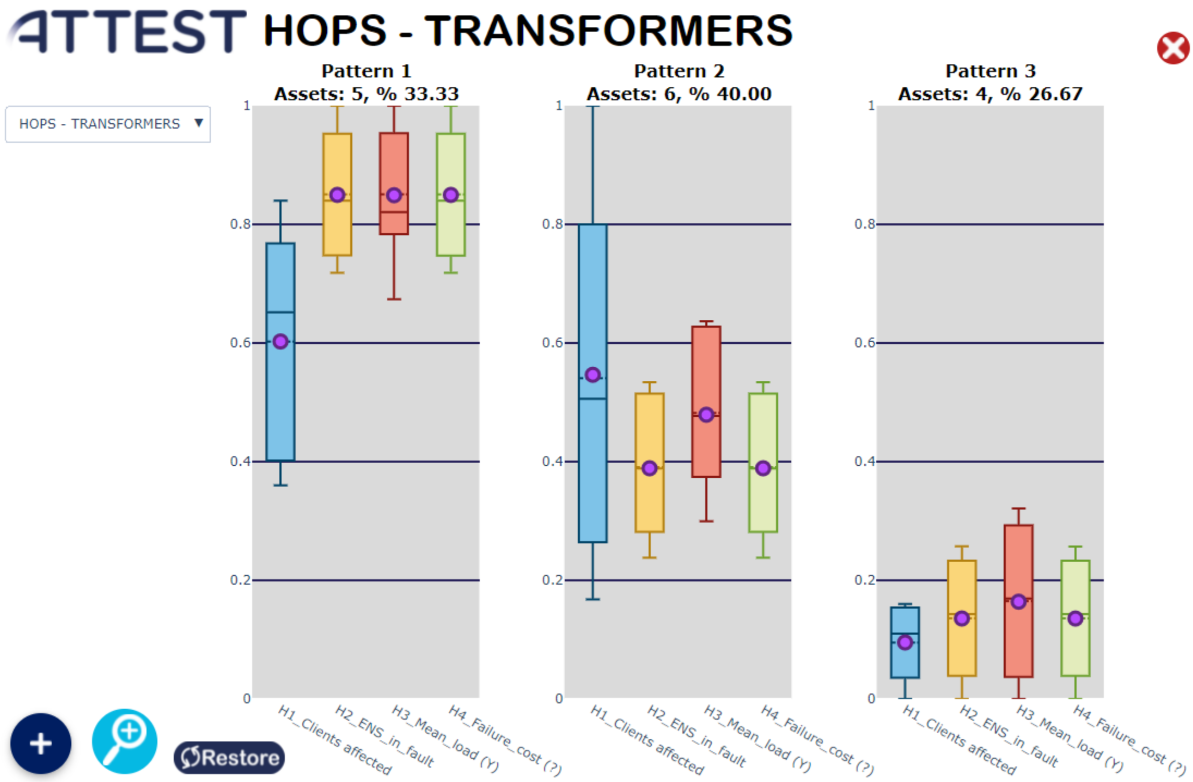

FIGURE 34 RESULTS: HOPS TRANSFORMERS – ECONOMIC IMPACT

6.1.2.2. TRANSMISSION LINES

- Life assessment
    - Number of assets: 10 tansmission lines.
    - Features considered:
        - Age.
        - Failure probability.
        - Unavailability dependent on age.
        - Load over the 50% of its power rating.
    - Results:
        - 4 patterns identified.

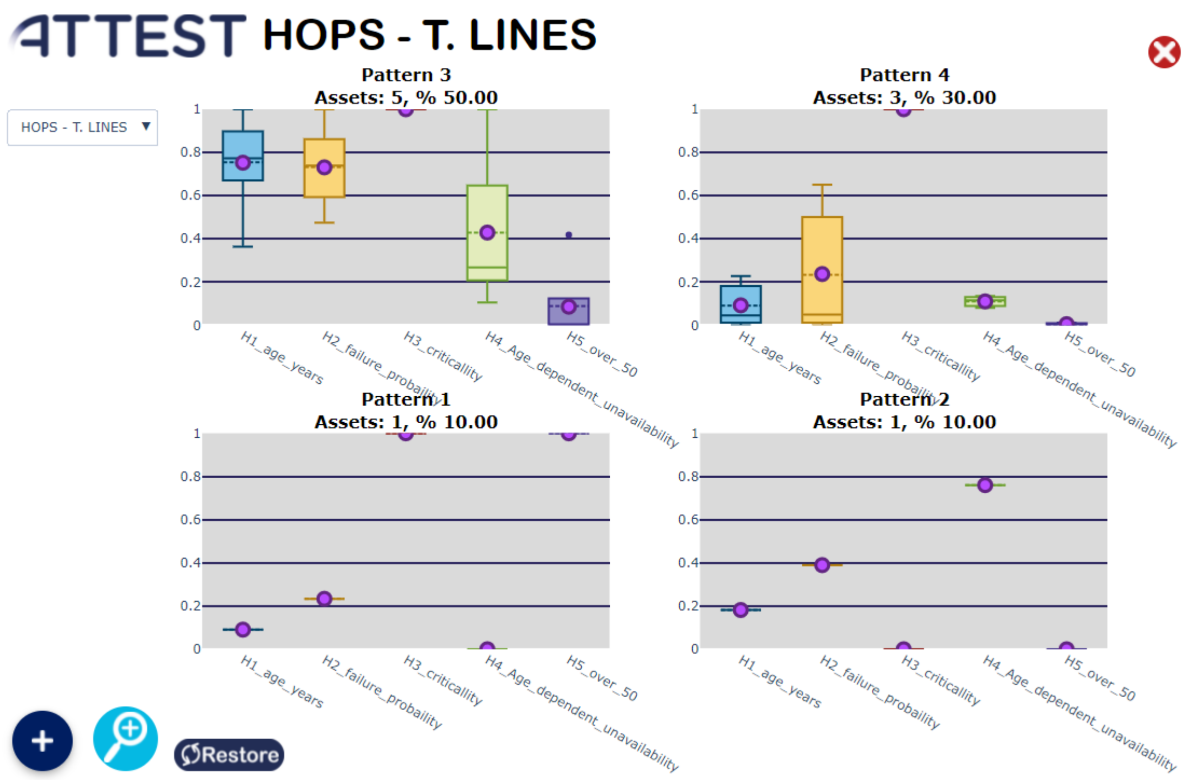

FIGURE 35 RESULTS: HOPS TRANSMISSION LINES – LIFE ASSESSMENT

- Maintenance strategy
  - Number of assets: 10 transmission lines.
  - Features considered:
    - Maintenace cycles A (y)
    - Maintenace cycles B (y)
    - Maintenace cycles C (y)
    - Review A (man/day)
    - Review B (man/day)
    - Review C (man/day)
  - Results:
    - 3 patterns identified.

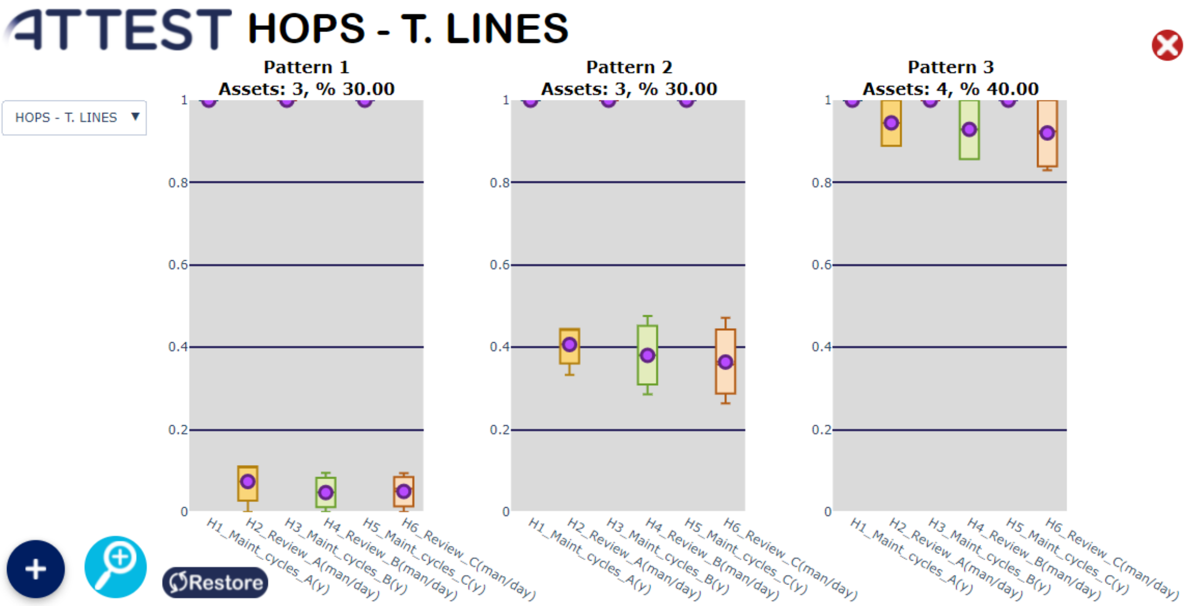

FIGURE 36 RESULTS: HOPS TRANSMISSION LINES – MAINTENANCE STRATEGY

- Economic impact
  - Number of assets: 10 transmission lines
  - Features considered:
    - Number of clients affected.
    - Energy not supplied in fault.
    - Mean load.
    - Cost of failure.
  - Results:
    - 3 patterns identified.

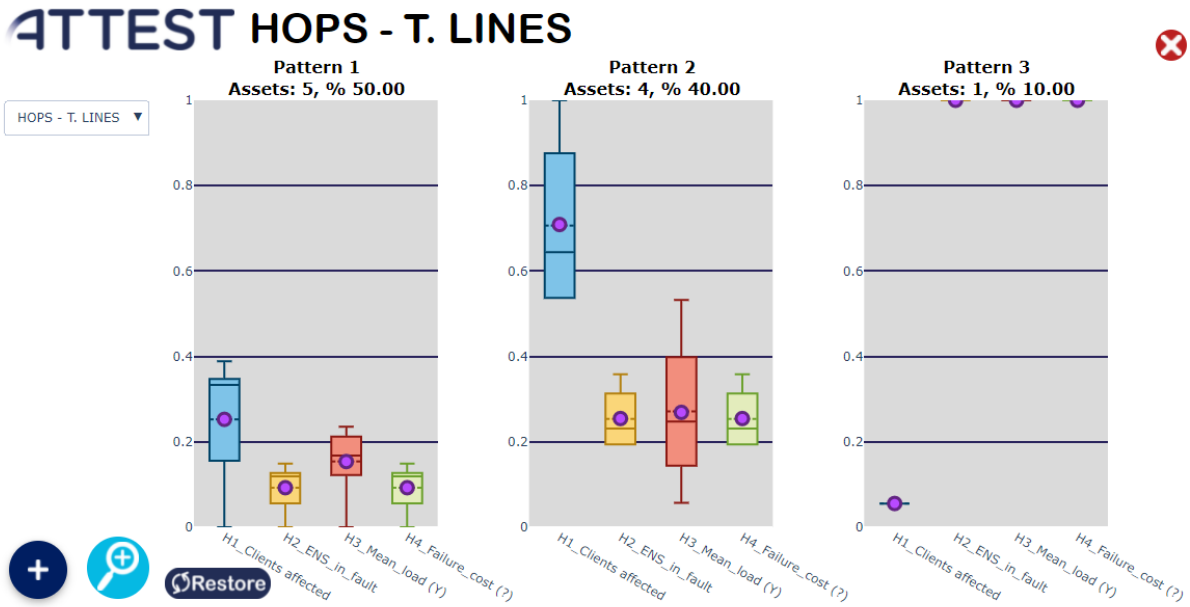

FIGURE 37 RESULTS: HOPS TRANSMISSION LINES – ECONOMIC IMPACT

6.1.2.3. CIRCUIT BREAKERS

- Life assessment
  - Number of assets: 39 circuit breakers
  - Features considered:
    - Field type.
    - Age.
    - Nominal voltage.
    - Rated short-circuit breaking current.
    - Switching operations in 2020
  - Results:
    - 6 patterns identified.

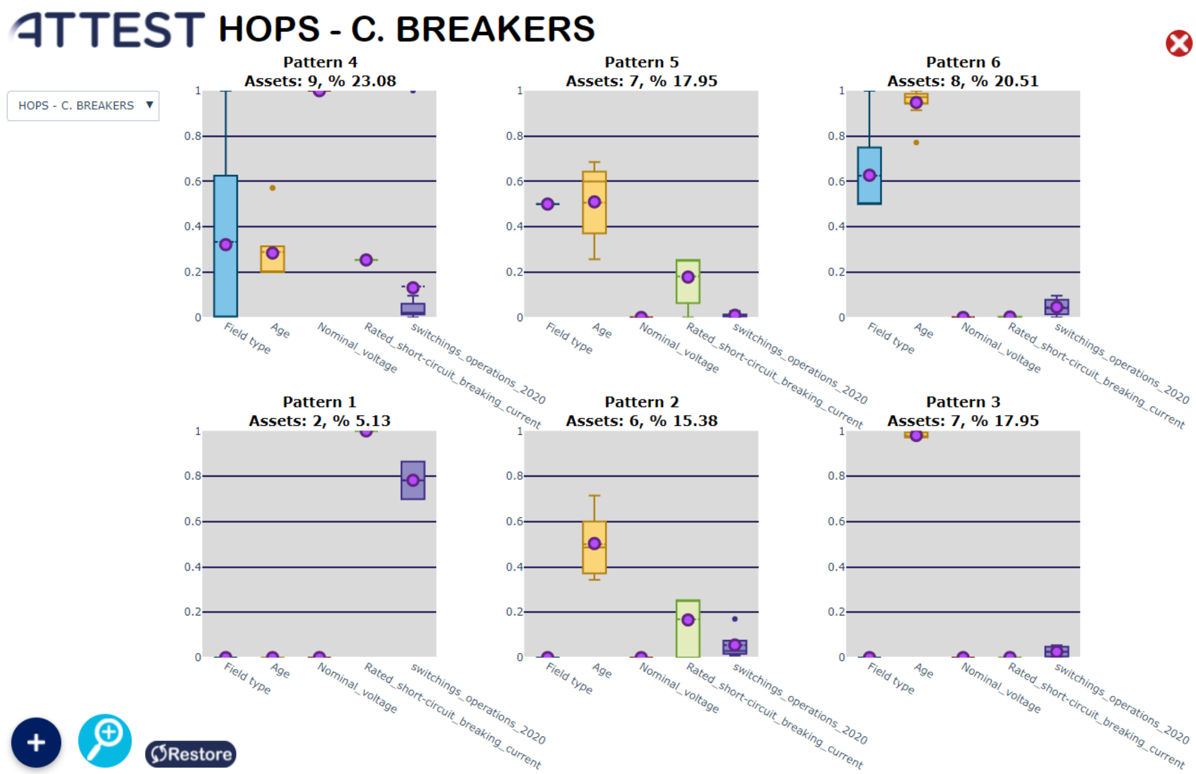

FIGURE 38 RESULTS: HOPS CIRCUIT BREAKERS – LIFE ASSESSMENT

- Maintenance strategy
    - Number of assets: 39 circuit breakers
    - Features considered:
        - Maintenace cycles A (y)
        - Maintenace cycles B (y)
        - Maintenace cycles C (y)
        - Review A (man/day)
        - Review B (man/day)
        - Review C (man/day)
    - Results:
        - 3 patterns identified.

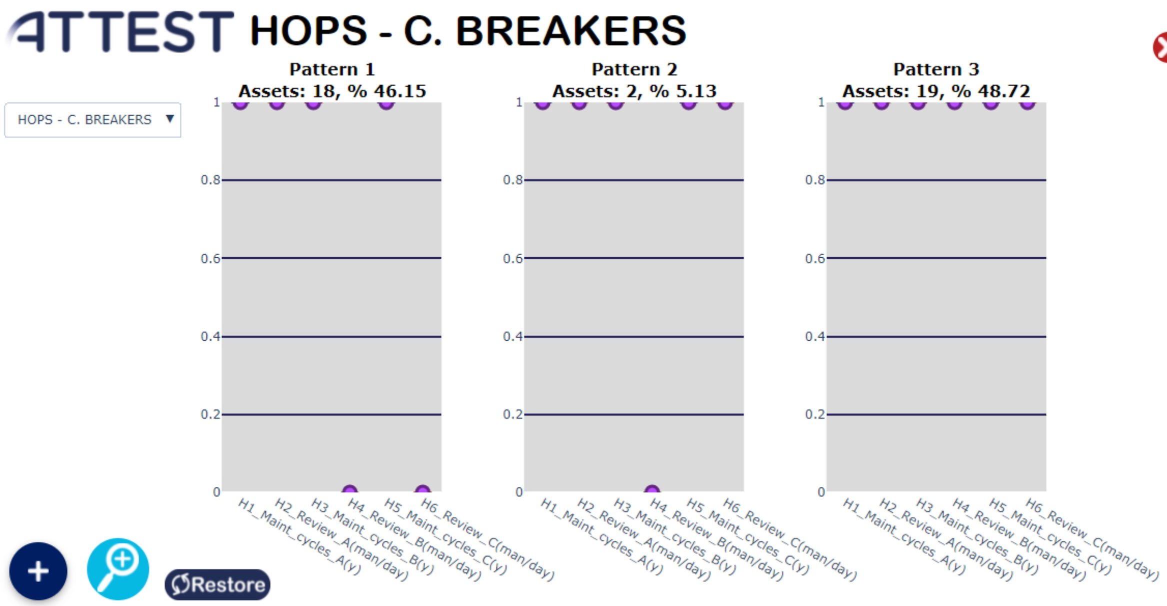

FIGURE 39 RESULTS: HOPS CIRCUIT BREAKERS – MAINTENANCE STRATEGY

6.1.3. SPANISH GRID – ASSETS

6.1.3.1. TRANSFORMERS

- Life assessment
    - Number of assets: 92 transformers.
    - Features considered:
        - Age.
        - Power rating.
        - Number of faults.
        - Number of customers.
        - Number of low-voltage connections.
    - Results:
        - 6 patterns identified.

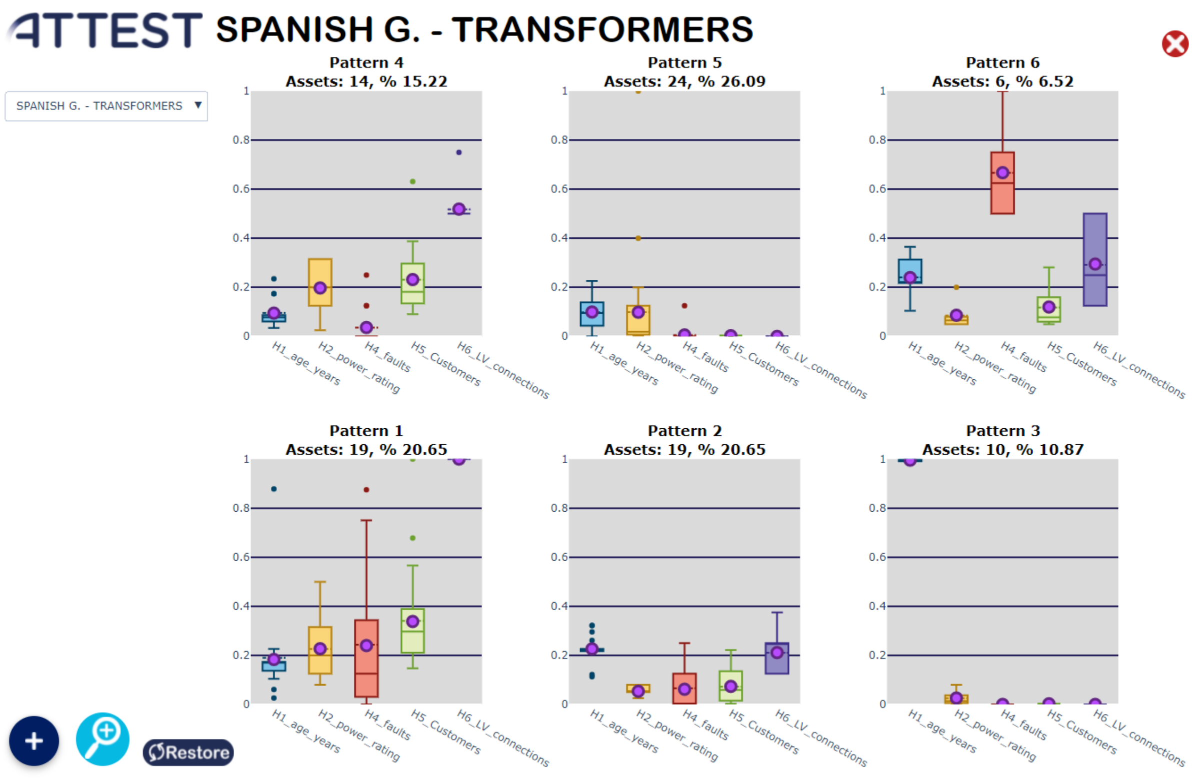

FIGURE 40 RESULTS: SPANISH GRID TRANSFORMERS – LIFE ASSESSMENT

- Maintenance strategy
  - Number of assets: 92 transformers.
  - Features considered:
    - Fault duration.
    - Number of faults.
    - Number of defects.
    - Severity of defects.
  - Results:
    - 4 patterns identified.

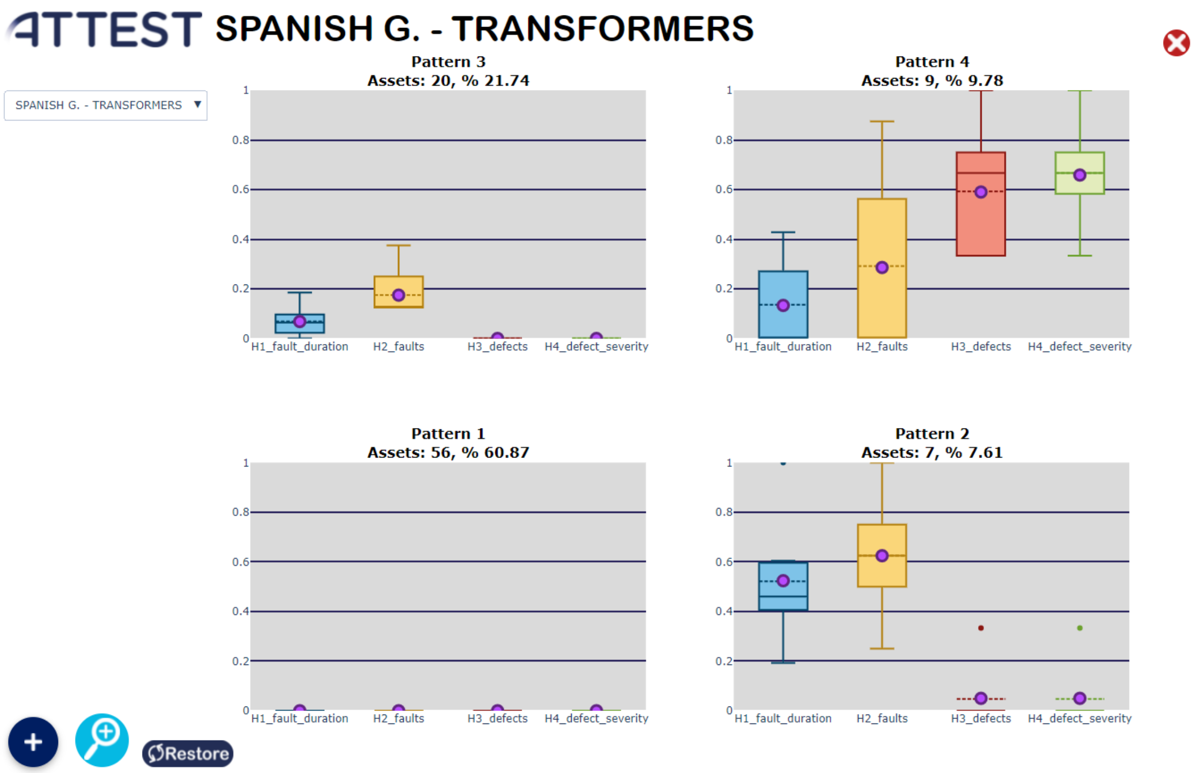

FIGURE 41 RESULTS: SPANISH GRID TRANSFORMERS – MAINTENANCE STRATEGY

- Economic impact
  - Number of assets: 92 transformers.
  - Features considered:
    - Number of important/critical customers.
    - Number of customers.
    - Power crontracted.
    - Cut power.
  - Results:
    - 6 patterns identified.

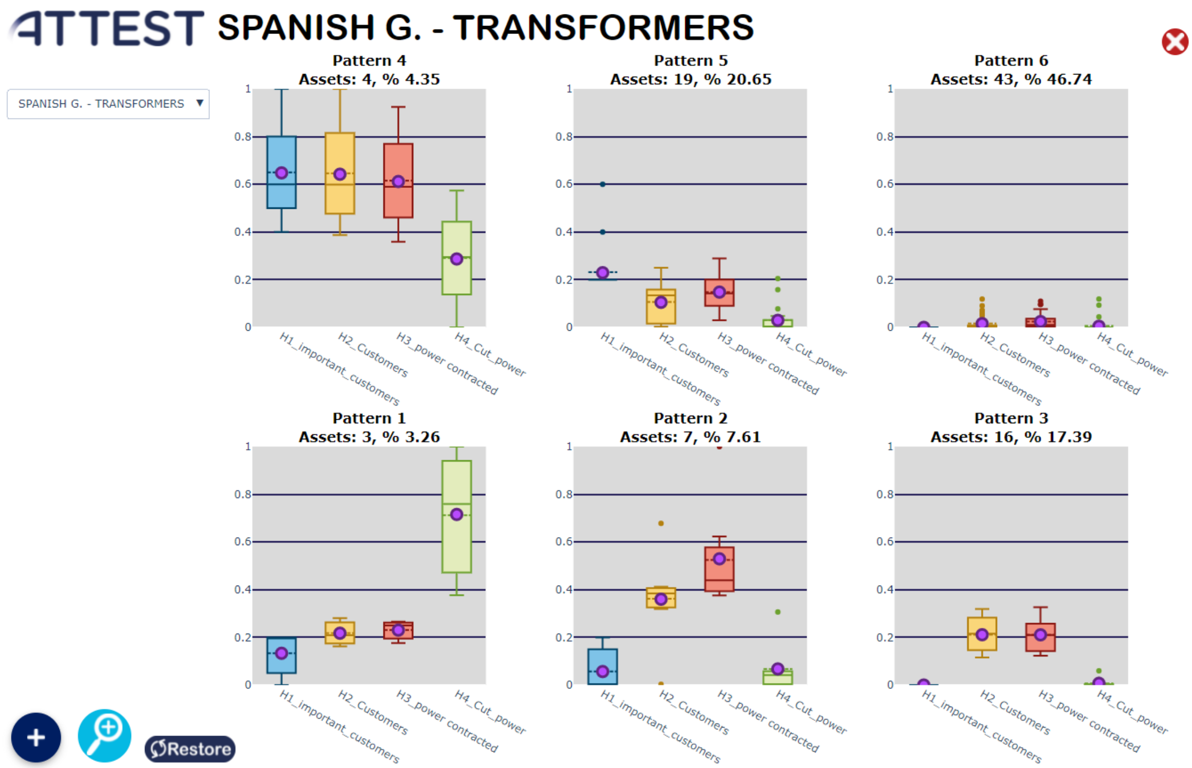

FIGURE 42 RESULTS: SPANISH GRID TRANSFORMERS – ECONOMIC IMPACT

6.1.3.2. TRANSMISSION LINES

- Life assessment
  - Number of assets: 219 transmission lines.
  - Features considered:
    - Age.
    - Failure probability.
    - KPI – weighted power.
    - Condition of the transmission line.
    - Risk.
    - Number of faults.
  - Results:
    - 4 patterns identified.

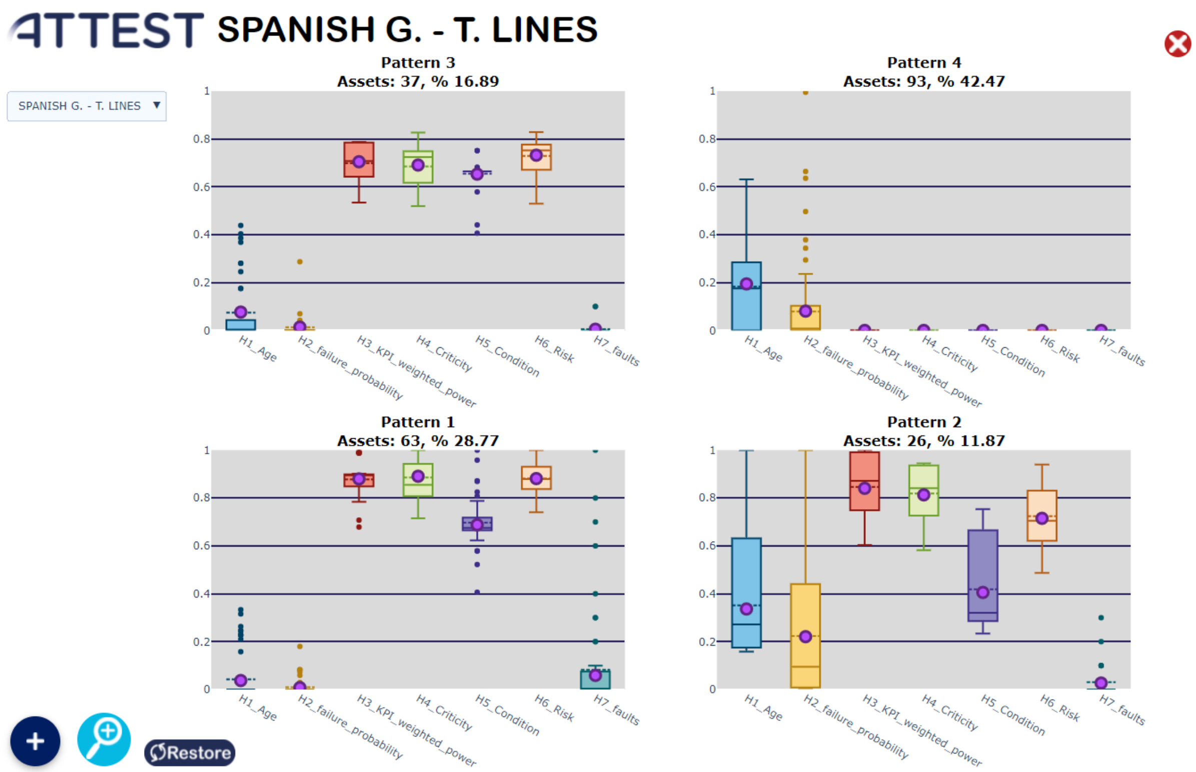

FIGURE 43 RESULTS: SPANISH GRID TRANSMISSION LINES – LIFE ASSESSMENT

- Economic impact
  - Number of assets: 219 transmission lines.
  - Features considered:
    - KPI – weighted power.
    - KPI – birdlife in surroundings.
    - KPI – severity of the defects found.
  - Results:
    - 3 patterns identified.

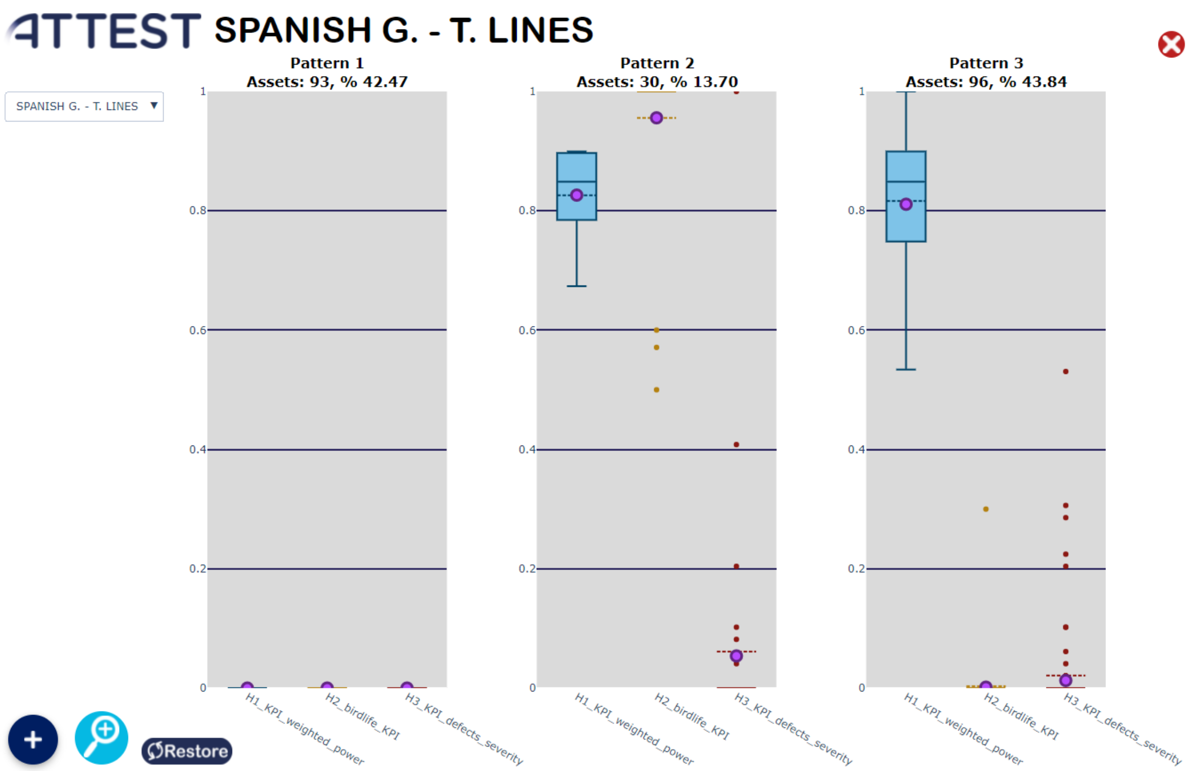

FIGURE 44 RESULTS: SPANISH GRID TRANSMISSION LINES – ECONOMIC IMPACT

6.1.3.3. SUPPORTS

- Life assessment
  - Number of assets: 380 towers/supports.
  - Features considered:
    - KPI – weighted power.
    - Criticity.
    - Condition.
    - Risk
  - Results:
    - 4 patterns identified.

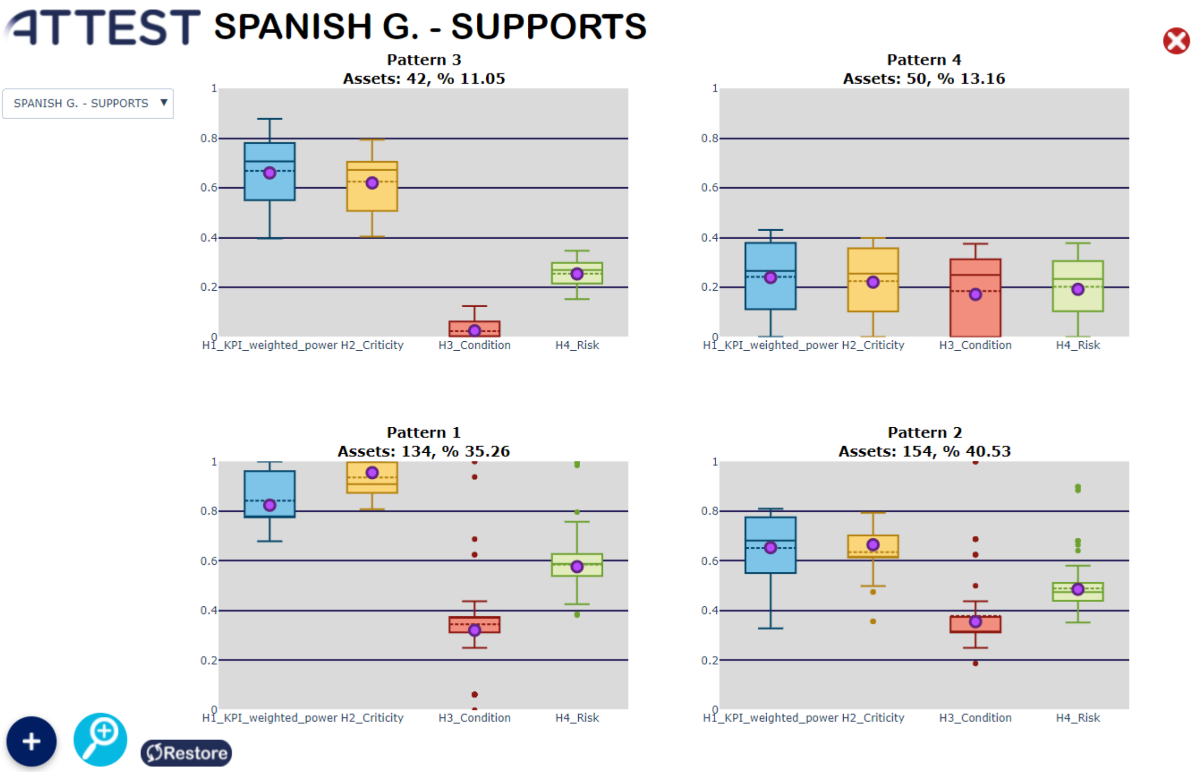

FIGURE 45 RESULTS: SPANISH GRID SUPPORTS – LIFE ASSESSMENT

- Maintenance strategy
  - Number of assets: 380 towers/supports.
  - Features considered:
    - Defects.
    - Defects severity.
  - Results:
    - 3 patterns identified.

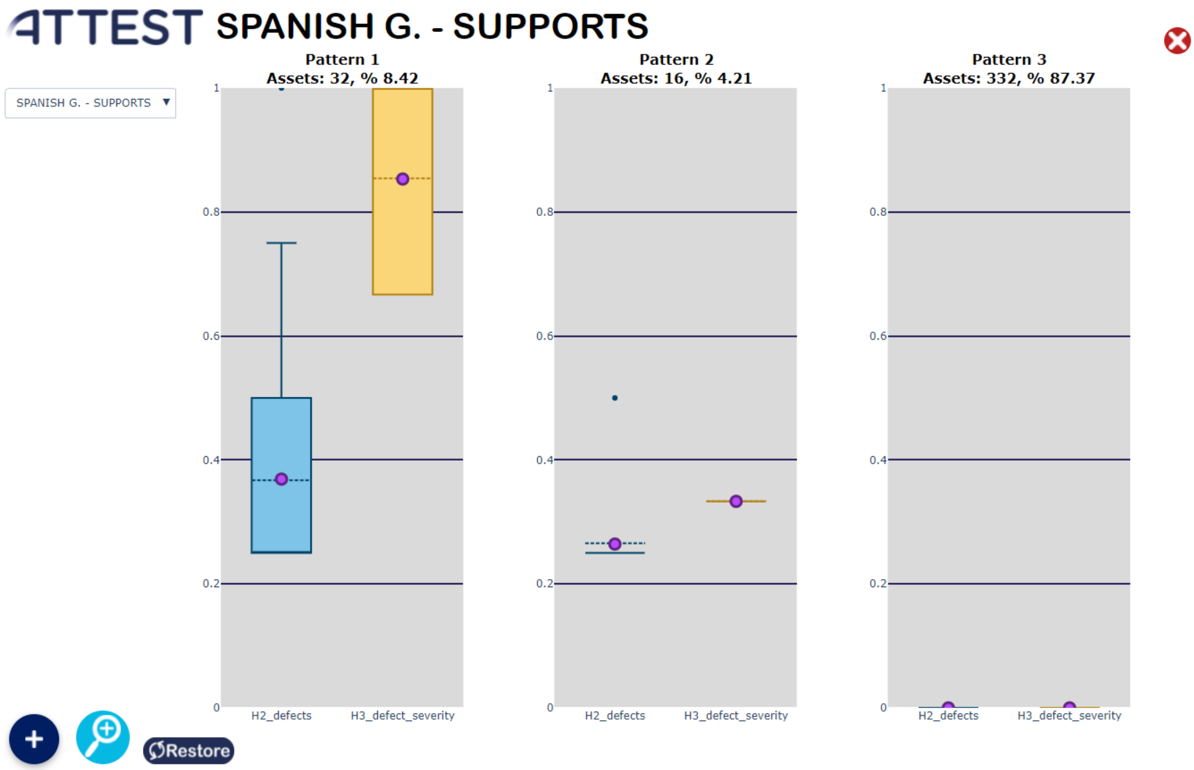

FIGURE 46 RESULTS: SPANISH GRID SUPPORTS – MAINTENANCE STRATEGY

- Economic impact
  - Number of assets: 340 towers/supports.
  - Features considered:
    - KPI – weighted power.
    - KPI – birdlife in surroundings.
    - KPI – defects severity.
  - Results:
    - 3 patterns identified.

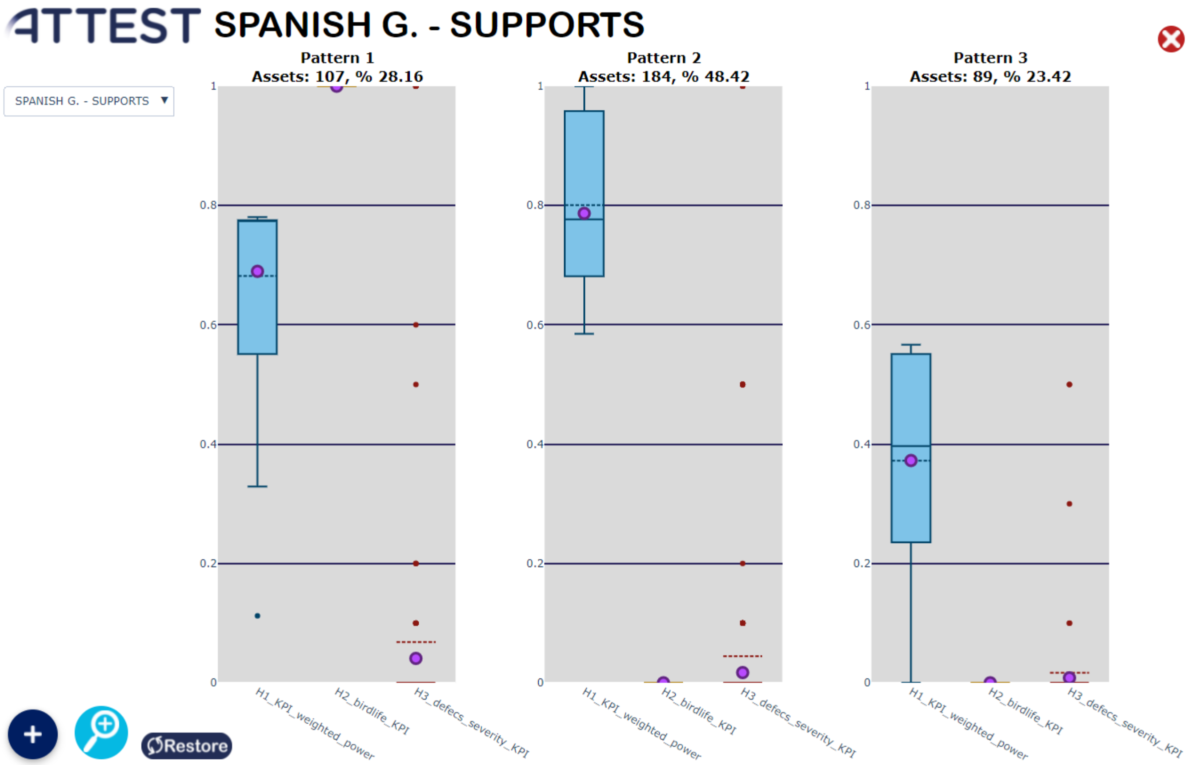

FIGURE 47 RESULTS: SPANISH GRID SUPPORTS – ECONOMIC IMPACT

6.1.4. SYNTHETIC GRID – ASSETS

6.1.4.1. *TRANSFORMERS*

- Life assessment
    - Number of assets: 391 transformers.
    - Features considered:
        - Age.
        - Failure probability.
        - Criticality.
        - % of the total hours under overloaded conditions.
    - Results:
        - 3 patterns identified.

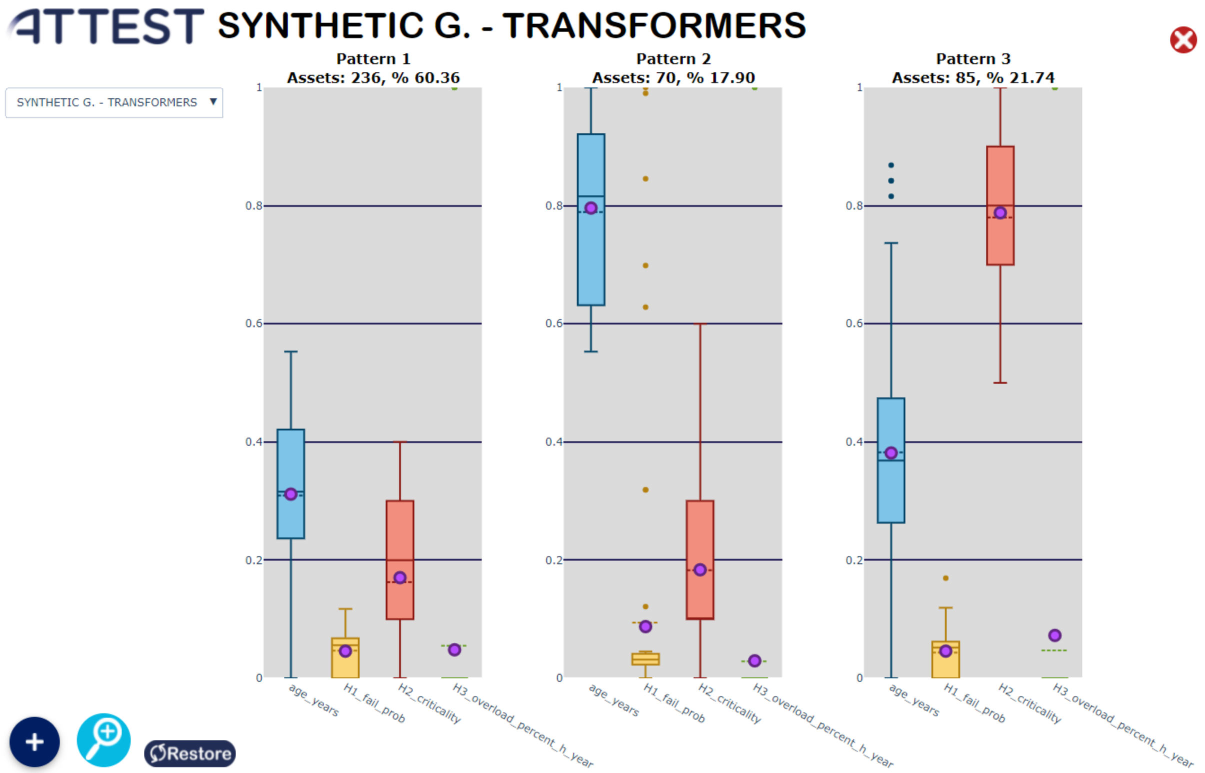

FIGURE 48 RESULTS: SYNTHETIC GRID TRANSFORMERS – LIFE ASSESSMENTS

6.1.4.2. TRANSMISSION LINES

- Life assessment
  - Number of assets: 8414 lines.
  - Features considered:
    - Age.
    - Failure probability.
    - Criticality.
    - % of the total hours under overloaded conditions.
  - Results:
    - 6 patterns identified.

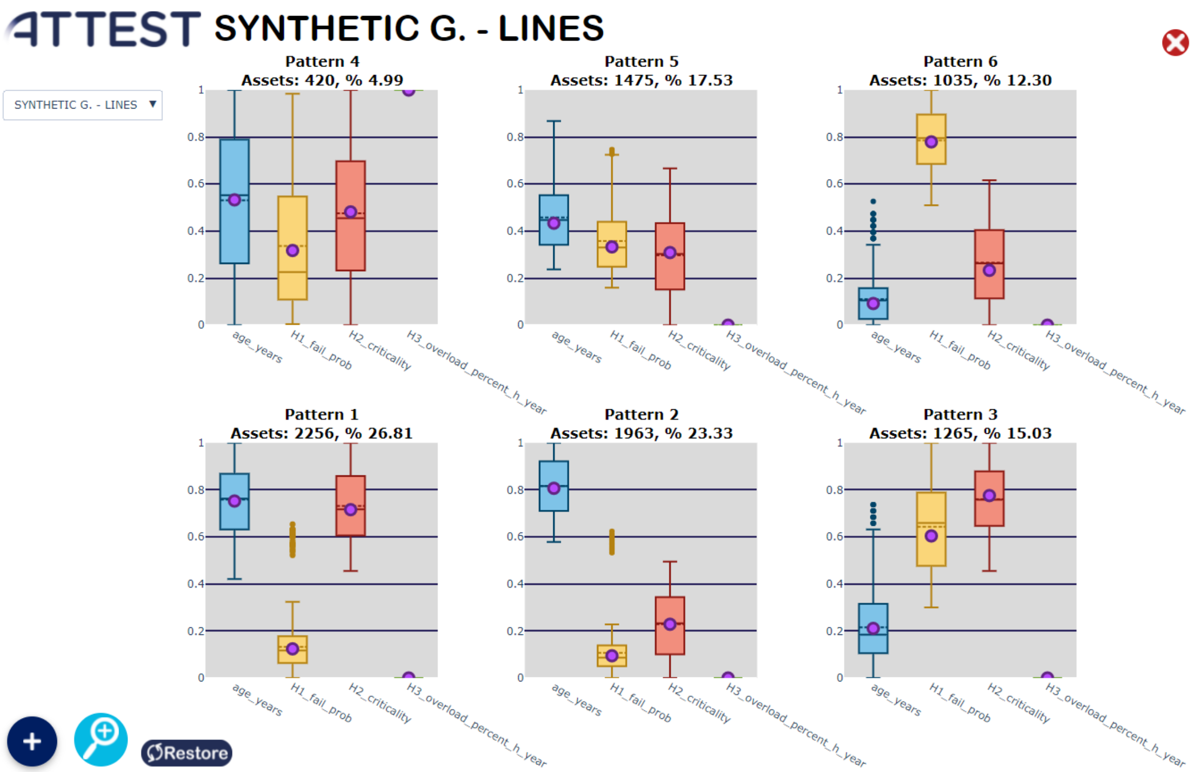

FIGURE 49 RESULTS: SYNTHETIC GRID TRANSFORMERS – LIFE ASSESSMENTS

6.2. CONDITION MONITORING FOR TRANSFORMERS

6.2.1. HOPS – POWER TRANSFORMER

- Results:
    - Number of hours: 8783h.
    - Condition Monitoring indicators:
        - Old Past [0 – 4392]h: 0.6 % anomalous behaviors.
        - Mid Past [4392 – 7027]h: 0.49% anomalous behaviors.
        - Near Past [7027 – 8783]h: 0.52% anomalous behaviors.
        - Total: 0.52% anomalous behaviors.

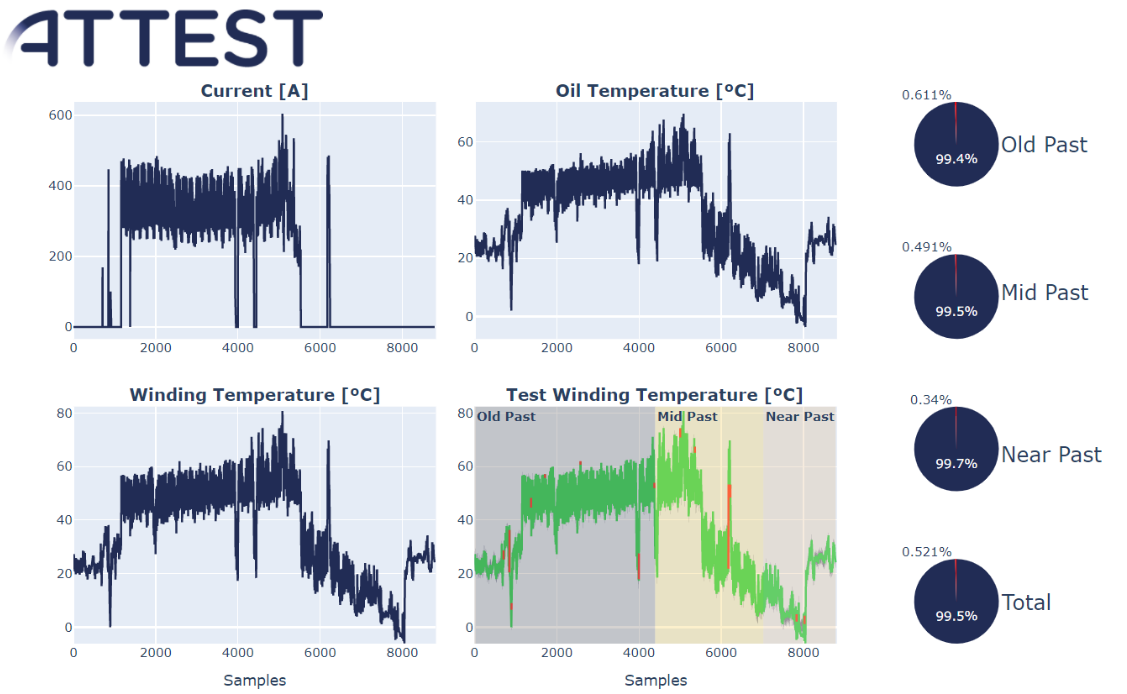

FIGURE 50 RESULTS: HOPS TRANSFORMERS – CONDITION MONITORING

7. ANEX

7.1. INPUT FILES

Examples of input files for each dimension of the characterization of health conditions of the assets.

- HEP – Transformers – Life assessment

```
name,age_years,H1_fail_prob,H2_criticality,H3_energy
2   ,22       ,0.585217088 ,5             ,873781
5   ,11       ,0.355963579 ,11            ,1022882
8   ,2        ,0.076883654 ,1             ,620858
11  ,43       ,0.820933852 ,3             ,532193
13  ,24       ,0.617107114 ,21            ,0
14  ,18       ,0.513247744 ,4             ,644969
15  ,4        ,0.147856211 ,0             ,217202
19  ,18       ,0.513247744 ,14            ,1575076
21  ,40       ,0.798103482 ,0             ,194173
24  ,35       ,0.753403036 ,0             ,298830
25  ,2        ,0.076883654 ,1             ,302141
28  ,16       ,0.472707576 ,4             ,1482577
32  ,21       ,0.568289477 ,4             ,613216
33  ,2        ,0.076883654 ,1             ,425791
38  ,2        ,0.076883654 ,0             ,237797
39  ,2        ,0.076883654 ,1             ,775018
42  ,22       ,0.585217088 ,15            ,1276817
44  ,8        ,0.273850963 ,1             ,590308
46  ,3        ,0.113079563 ,2             ,484916
47  ,2        ,0.076883654 ,0             ,558810
48  ,22       ,0.585217088 ,1             ,515687
51  ,15       ,0.451188364 ,2             ,575210
52  ,13       ,0.405479452 ,1             ,828648
53  ,2        ,0.076883654 ,0             ,256505
54  ,21       ,0.568289477 ,14            ,737163
55  ,45       ,0.834701112 ,1             ,231310
56  ,2        ,0.076883654 ,0             ,206733
57  ,22       ,0.585217088 ,2             ,458878
58  ,2        ,0.076883654 ,5             ,592992
59  ,3        ,0.113079563 ,8             ,420479
60  ,17       ,0.493383008 ,4             ,1145730
61  ,29       ,0.686513819 ,1             ,928
62  ,3        ,0.113079563 ,5             ,514312
73  ,0        ,0           ,0             ,294435
74_1,21       ,0.568289477 ,15            ,888781
74_2,2        ,0.076883654 ,15            ,0
81  ,12       ,0.381216608 ,3             ,318572
88  ,4        ,0.147856211 ,0             ,76696
12  ,14       ,0.428790936 ,40            ,732954
72  ,43       ,0.820933852 ,10            ,627011
```

- HEP – Transmission Lines – Maintenance Strategy

```
name    ,repair_time,cost_failure
1KV13/1 ,4          ,15174.00
1KV13/2 ,4          ,15174.00
1KV13/3 ,4          ,15174.00
1KV13/4 ,4          ,15174.00
1KV17/1 ,4          ,34083.00
1KV17/10,6          ,34083.00
1KV17/11,4          ,34083.00
1KV17/12,6          ,34083.00
1KV17/2 ,6          ,34083.00
1KV17/3 ,6          ,34083.00
1KV17/4 ,4          ,34083.00
1KV17/4 ,4          ,34083.00
1KV17/5 ,4          ,34083.00
1KV17/6 ,6          ,34083.00
1KV17/7 ,6          ,34083.00
1KV17/8 ,6          ,34083.00
1KV17/9 ,6          ,34083.00
1KV22/1 ,4          ,19749.00
1KV22/10,4          ,19749.00
1KV22/11,4          ,19749.00
1KV22/12,4          ,19749.00
1KV22/13,6          ,19749.00
1KV22/2 ,4          ,19749.00
1KV22/3 ,4          ,19749.00
1KV22/4 ,4          ,19749.00
1KV22/5 ,4          ,19749.00
1KV22/6 ,4          ,19749.00
1KV22/7 ,6          ,19749.00
1KV22/8 ,4          ,19749.00
1KV22/9 ,4          ,19749.00
1KV3/1  ,4          ,43672.00
1KV3/10 ,6          ,43672.00
1KV3/11 ,4          ,43672.00
1KV3/12 ,4          ,43672.00
1KV3/12 ,4          ,43672.00
1KV3/13 ,4          ,43672.00
1KV3/14 ,4          ,43672.00
1KV3/15 ,4          ,43672.00
1KV3/16 ,4          ,43672.00
1KV3/17 ,4          ,43672.00
1KV3/18 ,4          ,43672.00
1KV3/2  ,6          ,43672.00
1KV3/2  ,4          ,43672.00
1KV3/3  ,4          ,43672.00
1KV3/4  ,6          ,43672.00
1KV3/5  ,4          ,43672.00
1KV3/6  ,4          ,43672.00
1KV3/7  ,4          ,43672.00
1KV3/8  ,4          ,43672.00
1KV3/9  ,4          ,43672.00
1KV18/7 ,6          ,43672.00
1KV18/6 ,6          ,43672.00
```

- HOPS – Transmission Lines – Economic Impact

```
name             ;H1_Clients affected;H2_ENS_in_fault;H3_Mean_load (Y);H4_Failure_cost
SUBST34-SUBST29  ;19000.00          ;17.00          ;23.16           ;1974.00
SUBST29-SUBST01  ;10100.00          ;9.00           ;11.20           ;1045.00
SUBST19-SUBST01  ;13500.00          ;12.00          ;11.37           ;1394.00
SUBST36-SUBST01  ;6000.00           ;71.00          ;38.28           ;8245.00
SUBST35-SUBST36  ;13500.00          ;12.00          ;13.55           ;1394.00
SUBST34-SUBST35  ;4500.00           ;4.00           ;5.94            ;465.00
SUBST05-SUBST01  ;24800.00          ;22.00          ;14.49           ;2555.00
SUBST42-SUBST05  ;19000.00          ;17.00          ;7.79            ;1974.00
SUBST01-SUBST55  ;15000.00          ;14.00          ;12.56           ;1626.00
SUBST26-SUBST55  ;31500.00          ;28.00          ;13.42           ;3252.00
```

- HOPS – Transformer – Condition monitoring
    - Input variables:

Time	TR1_Current	TR1_Winding_temp	TR1_Oil_temp	TR2_Current	TR2_Winding_temp	TR2_Oil_temp
0:00	0	23.74524	24.39286	283.8611	43.69762	41.46191
1:00	0	23.66905	24.41904	269.4784	42.70953	40.71191
2:00	0	23.23572	23.85	255.8042	41.01667	39.28095
3:00	0	23.35714	23.96428	246.9336	39.87381	38.31667
4:00	0	23.54762	24.17619	238.9382	39.13333	37.56667
5:00	0	23.20238	23.82857	242.8683	37.72857	36.2
6:00	0	23.49762	24.11667	250.486	37.58095	35.99286
7:00	0	23.33809	24.04762	254.4116	37.04048	35.40714
8:00	0	23.4381	24.26666	264.0877	36.60715	34.90714
9:00	0	24.51905	25.19286	285.0007	37.64047	35.37143
10:00	0	26.06905	26.06428	298.8581	38.92857	35.93571
11:00	0	27.28095	26.71429	310.0878	39.43333	36.17381
12:00	0	27.10476	27.14524	304.8309	39.39524	36.41429
13:00	0	26.84762	27.28572	292.7021	39.10476	36.51191
14:00	0	27.02619	27.7381	281.9036	38.84762	36.59762
15:00	0	27.17381	27.75952	276.0129	38.65476	36.58571
16:00	0	26.77619	27.40476	295.7589	38.43333	36.12619
17:00	279.3540039	25.93571	26.49048	342.2129	39.13809	35.99048
18:00	283.6527557	24.97857	25.75476	342.1523	39.64762	36.28095
19:00	297.6819611	24.7	25.39524	336.1774	40.27381	36.99048
20:00	301.6222611	24.25238	24.81667	335.3206	40.5119	37.12143
…	…	…	…	…	…	…

- Threshold configuration:

{"mse": 0.4294548034667969, "sem": 2.379789113998413}

- Model:

Binary format (hdf5)