National University of Science and Technology
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SUMMARY OF THE DOCTORAL THESIS

Contributions to the study of the life cycle of power substations

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CHAPTER 1:

INTRODUCTION

1.1. MOTIVATION

The life cycle of electrical equipment refers to the length of time from planning, design, development, installation, to operation, maintenance, retrofitting, modernization and decommissioning. The retrofit/modernization stage is an asset renewal strategy aimed to optimize asset management results. Information about the condition of the assets, collected during the operation/maintenance phase, is used to ensure continuous improvement to increase the life cycle.

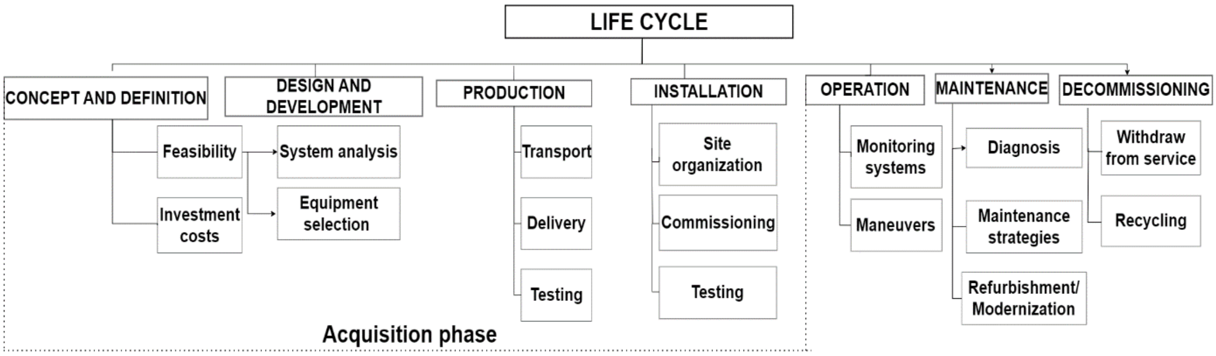

Fig. 1. Life cycle stages

Lean Six Sigma is a technique used in asset management. In the energy field, it can be used in the generation, transmission and distribution of electricity to manage assets and improve user satisfaction. This effective technique focuses on four essential aspects: profitability, quality, productivity and cost. However, Lean and Six Sigma strategies are not sufficient to meet the goals of waste minimization, pollution prevention, energy and resource storage, and cost reduction. Thus, a new methodology was identified, Green Lean Six Sigma, which uses aspects of traditional Lean and Six Sigma methodologies, while providing the necessary tools to decide, implement and sustain improvements that also have a positive impact on the environment.

1.2. SCOPE

The thesis analyses the solutions that cover the existing situation and aims to demonstrate the need and the opportunity to implement the concept of Green Lean Six Sigma for asset management in high-voltage electrical substations, as well as the feasibility of this goal, while respecting regulatory and consumption requirements, in an acceptable risk exposure.

1.3. PROBLEMS APPROACHED AND REPRESENTATIVE ORIGINAL CONTRIBUTIONS

This paper represents a contribution in the field of power substations maintenance management and proposes solving problems by implementing the Green Lean Six Sigma methodology.

Chapter 1 is a brief introduction to the theme of the paper, presenting its objectives and motivation. Also, this chapter provides a brief presentation of the content of the thesis.

Chapter 2 is dedicated to an bibliographic study to determine the current state of research on the life cycle of power substations and to recognize the role of maintenance management in the smartgrid context.

Chapter 3 presents a theoretical study on the mathematical models of the life cycle and their applicability in power substations. 39 mathematical life cycle estimation models approached over time are analyzed.

Chapter 4 presents a theoretical and practical study on the opportunity to extend the life cycle of power substations by approaching traditional *Lean*, *Six Sigma* and *Lean Six Sigma* asset management methodologies.

The concept of *Green Lean Six Sigma* in the field of power substations is approached for the first time and observations are made on the use of *GLSS* tools in the different phases of the *Define, Measure, Analyze, Improve and Control (DMAIC)* method to highlight how maintenance contributes to *LCC*.

Phase I: The problem was formulated, the constraints were identified and methods of data collection for design, construction, commissioning, operation and maintenance have been established.

Phase II: Measurement/monitoring and data collection from 491 high voltage electrical equipment in operation in the 3 substations. The objective was to identify the main factors that affect technical performance and analyse the consequences of their failure on the dynamic behavior of electrical installations.

Phase III: The asset maintenance process in power substations was examined and all operations and activities directly and indirectly associated with maintenance were analysed in order to improve processes: a questionnaire was created to assess the impact of electrical equipment failure on health and environmental safety, it was proposed to improve the questionnaires for assessing the impact of the failure on the technical condition and importance, technical condition (i_{st}), importance (i_{imp}), environmental protection, health and safety (i_{mss}) indices were proposed, numerical simulations and the calculation of the 3 indices were carried out based on data obtained from measurements/monitoring for the considered electrical equipment.

Phase IV: The proposal of a solution to improve substation maintenance by generating a global priority index of maintenance activities (i_g) was carried out for the implementation and monitoring of the solutions adopted during the analysis stage. It was determined, through graphic simulations in Matlab, the priority of maintenance activities according to the size of the global performance index, for all 491 electrical equipment from the analyzed substations.

Phase V: The aim of the control is to ensure the sustainability of the results obtained at the substation level and the financial benefits at the company level, benefits due to the increase of life cycle of electrical equipment.

Finally, the main scientific and technical contributions were identified.

Chapter 5 presents the prospects for further research by carrying out a SWOT analysis in order to identify the strengths and weaknesses of internal factors (at the company level) and external factors (attributed to the environment).

CHAPTER 2:

THE CURRENT STATE OF RESEARCH ON THE LIFE CYCLE OF POWER SUBSTATIONS AND THE IDENTIFICATION OF TRENDS IN THE CONTEXT OF SMART GRIDS

2.1. SYNTHESIS OF ADVANCED LIFE CYCLE RESEARCH METHODS AND TECHNIQUES

In the technical literature, numerous approaches are identified for the life cycle analysis (*LCC - Life Cycle Cost*) of a power substation. Figure 2.1 presents the evolution of publications over time according to the type of the research method approached.

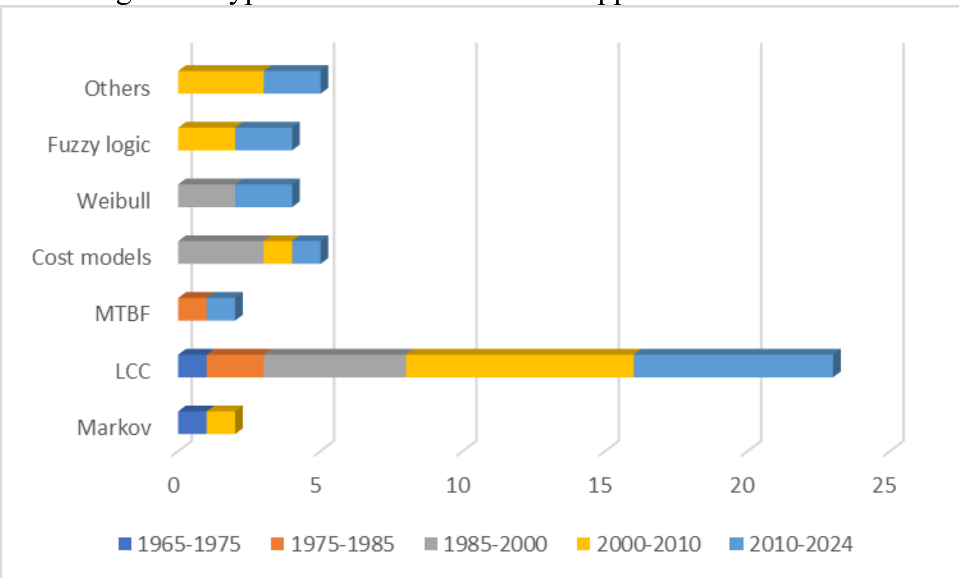

Fig. 2.1. Documentation results on the evolution of publications according to the LCC research method approached

In *LCC* analysis, the optimization process is applied to each alternative considered in the study [1]. So, the optimization process means finding a set of parameters that minimizes LCC and can be applied in specific LCC activities, such as design optimization, equipment replacement optimization, maintenance optimization, spare parts optimization, considering specific restrictions, etc.

2.2. MONITORING AND DIAGNOSIS OF POWER SUBSTATIONS

Current monitoring and/or automated diagnostics systems improve real-time electrical equipment supervision and maintenance planning. The technical condition assessment and diagnosis methods, the development of maintenance policies, as well as asset management, allow increased access to valuable information regarding the critical parameters of power substations, require the identification and evaluation of trends in the field and a detailed analysis of them.

The communication methods and protocols, together with the cyber security measures implemented within the monitoring system, allow the power system operator to visualize the general operation of the power substation in real time. The sampled data provides detailed information for the analysis of the technical state of the system in order to avoid the occurrence of incidents.

2.3. POWER SUBSTATIONS MAINTENANCE

Maintenance management in the context of the life cycle is characterized by two factors: the constraints of non-continuity of electricity supply to consumers and LCC. Based on the LCC concept, maintenance of equipment that has exceeded its effective life is avoided. Refurbishment or replacements are options to be evaluated for partial or total elimination of the causes of failure. The combination of TBM (*Time Based Maintenance*) and CBM (*Condition Based Maintenance*) is the main strategy for the maintenance activities that are carried out today. RCM (*Reliability Centered Maintenance*) is a method that establishes the optimal solution based on systematic estimates of the state of the equipment. It uses criteria such as: maintenance history, experience with similar equipment, real-time data, etc. Based on these, the type of maintenance to be performed is identified and helps to establish a maintenance schedule.

Both within the transmission companies and within the electricity distribution companies, there are a series of maintenance strategies to improve the reliability of the equipment (figure 2.2). Most companies use a combination of strategies that take into account the practical and economic aspects of maintenance planning and maximizing equipment availability. The goal is to find solutions both in the short term, to optimize maintenance and replacement of existing assets, and in the long term, to optimize the design of new assets to reduce future maintenance and replacement needs.

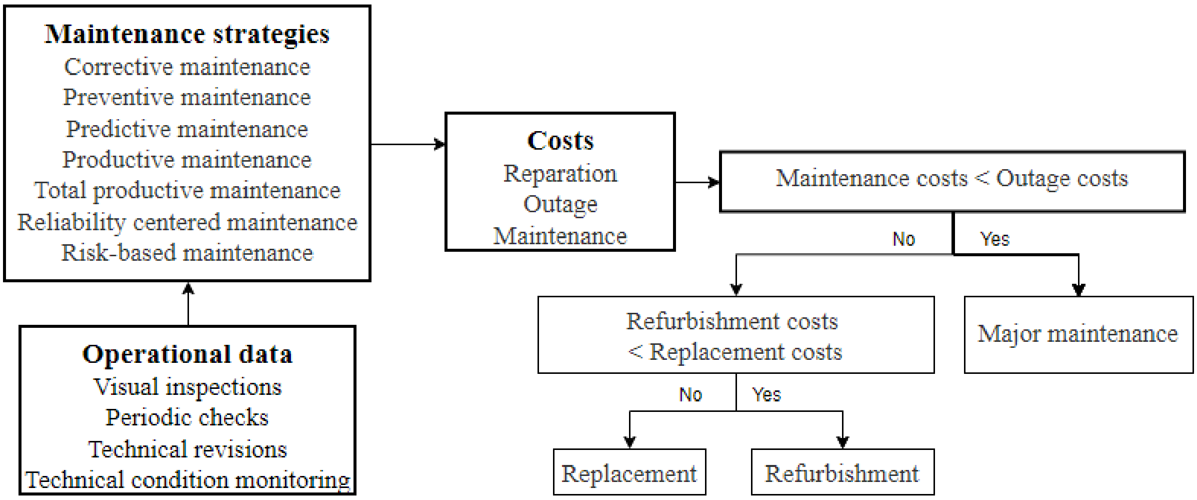

Fig. 2.2. Synthesis of maintenance strategies and associated activities

2.4. DECISION MODELS FOR LIFE CYCLE ASSESSMENT

Decision support strategies are established by identifying the activities required to maintain system reliability at an acceptable level, by performing optimal maintenance and/or replacing critical system components. Transmission and system companies use a combination of time-based, condition-based, reliability-based strategy based on various situations such as: type of equipment, position in the system, accessibility, availability of outages, reliability records, age of equipment, availability of parts, etc.

System operators are faced with making decisions to repair or replace a piece of equipment, and most of them are in favor of replacement. For this reason, it is necessary to carry out a full economic analysis to assess repair costs and replacement costs. An incorrect decision can have a significant impact on equipment performance, maintenance and operating costs.

2.5. RELATIONSHIP BETWEEN LCC AND THE INTEGRATION OF NEW TECHNOLOGIES

The need to implement Smart Grid is influenced by the aging of electrical equipment, thermal limitations, operational limitations and security of electricity supply. The implementation of the smart grid results in the optimization and reduction of insecurity caused by the occurrence of accidental events that occur during the operation of electricity transmission and distribution installations.

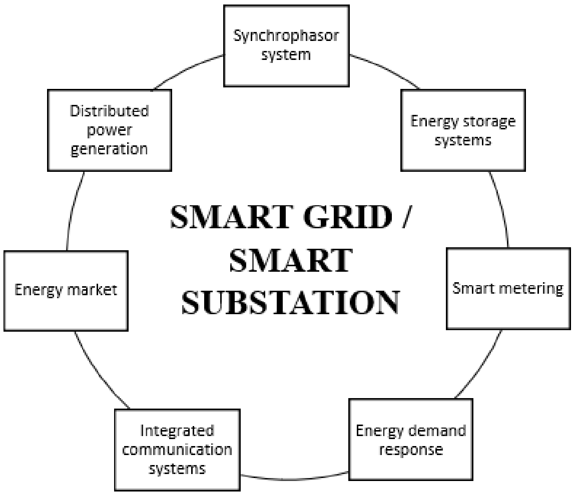

Fig. 2.3. Identifying the main characteristics of the smart grid / smart substation

The smart grid directly depends on a reliable, robust and secure communication system with high data rate capability. Future concerns will focus on the development of improved security-compatible algorithms for smart grid communication and protocols, as well as identifying methods to reduce and eliminate interference. In figure 2.3. the main characteristics of the smart grid that are required by the system operators to satisfy the consumers and to ensure the operational safety of the grid are presented.

LCC contributes to decision-making related to the choice of digital technologies applied in areas such as: life cycle management, electrical energy storage systems, electrical vehicles, environmental protection.

CHAPTER 3:

MATHEMATICAL MODELS FOR LIFE CYCLE ESTIMATION. VALIDATION IN THE FRAMEWORK OF POWER SUBSTATIONS

In this chapter, the focus was on the evolution of mathematical life cycle estimation models. At the beginning, the aim was to ensure the safe operation of the system by exploiting electrical equipment using reliability models, Markov techniques, etc. Later, it was tried to find solutions related to the evaluation of the technical condition of the equipment, environmental problems, mathematical models were developed through which the cost-benefit analyzes are carried out. After that, genetic algorithms were used to get a clearer view of life cycle costs.

Addressing various methods for increasing the life cycle of a power substation, from reducing SF6 emissions, the advantages of using GIS, to improving maintenance programs, introducing automation systems, introducing more advanced monitoring systems, uncertainty assessment methods, dynamic programming etc. have led to advantageous results on this subject.

Mathematical modeling optimization techniques for lifetime improvement must use stochastic and probabilistic methods to satisfy uncertainties related to system operational safety at the time of failure.

Environmental requirements put pressure on most transmission and distribution companies to meet environmental policies. That is why carbon emission reduction studies must be carried out right from the design process.

The 39 mathematical models analyzed offer diverse perspectives on how to evaluate the life cycle of power substations. With proper maintenance and asset management according to the requirements, results can be obtained to increase the life cycle of a power substation. Studies have highlighted the fact that in the analysis of the condition of electrical equipment, in addition to the technical evaluation, there is also the economic component that has an essential role in decisions regarding repairs or even replacements. That is why the economic side must also be taken into account when carrying out the planning project of the power substations.

3.1. MATHEMATICAL MODELING OF THE LIFE CYCLE

Mathematical modeling is used in all fields of activity, being useful to describe a phenomenon or to understand how a system works or to make predictions about the behavior of assets. To build a mathematical model of the life cycle of a power substation, it is important to consider all aspects that can influence the safe operation of the power substation.

Figure 3.1 shows the evolution over time of publications according to the field of analysis.

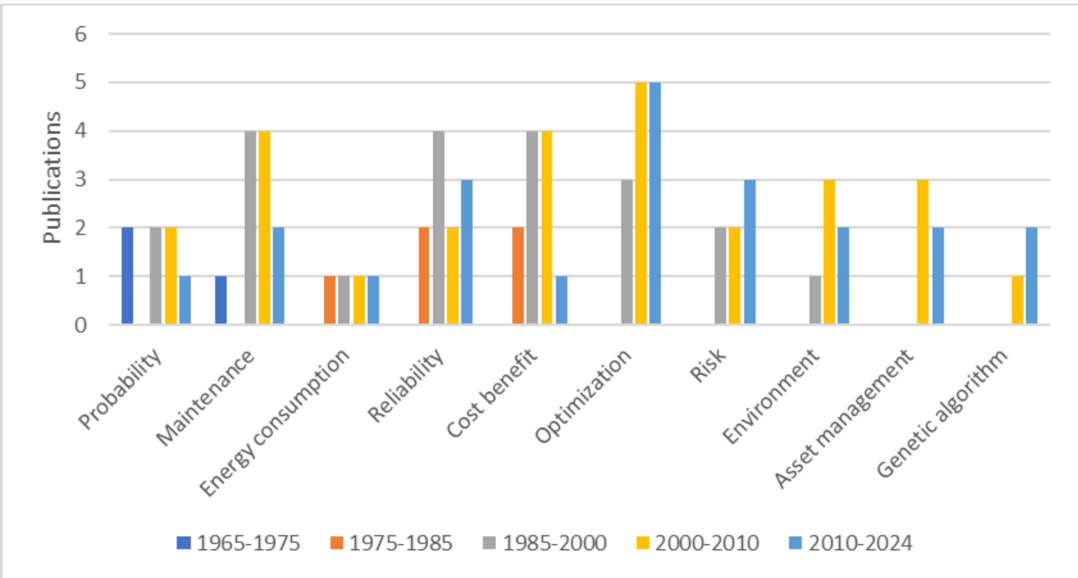

Fig. 3.1. The results of the documentation regarding the evolution of the publications according to the field of analysis

3.2. ANALYSIS OF MATHEMATICAL MODELS OF THE LIFE CYCLE

In order to classify the key publications, databases were explored, a number of 106 journal articles and papers presented at relevant conferences were identified and analyzed. With a focus on a better understanding of the most effective LCC modeling strategies, different concepts, advantages and barriers are investigated along with a qualitative analysis of the most common applications and areas of use.

Therefore, when building a mathematical life cycle estimation model, all stages involved in each electrical equipment are taken into account, including design, operation, maintenance, repair, support and decommissioning [2]. Since the 20th century, researchers have been concerned with estimating the remaining life of power substations. The main focus was on system reliability, system performance depending on equipment condition, better cost management throughout the life cycle of the studied element. Since 2000, the focus has been on the deterioration of electrical equipment in substations and the associated costs.

Extending the lifetime of power substations is influenced by the choice of long-term strategies [3]. It is mainly affected by maintenance costs, but also by environmental issues. Therefore, most studies use the life cycle cost as a mathematical model to increase the life cycle of power substations.

3.4. PROPOSAL FOR IMPROVING THE MATHEMATICAL MODEL OF LCC

In order to establish a mathematical model, it is important to do a comparative study between various mathematical models, to take into account the variables to be used, the availability of data and parameters. In addition to these aspects, researchers must also take into account the simulation stages of the model, to have a broader view of the current problems and needs.

Starting from the life cycle structure presented in [2] and taking into account [4], equation (3.1) can be considered as a mathematical model:

$$C_{LC} = C_A + \sum \frac{1}{(1+r)^{y_1}} C_O + \sum \frac{1}{(1+r)^{y_2}} C_M + \sum \frac{1}{(1+r)^{y_3}} C_R + \sum \frac{1}{(1+r)^{y_4}} C_F + \sum \frac{1}{(1+r)^{y_5}} C_E + \sum \frac{1}{(1+r)^{y_6}} C_{SSM} + \sum \frac{1}{(1+r)^{y_7}} C_D \quad (3.1)$$

unde :

C_{LC} – life cycle cost; C_A – acquisition cost; C_O – operation cost; C_M – maintenance cost; C_R – repair cost; C_F – additional cost in case of failure; C_E – cost of environmental protection; C_{SSM} – cost of ensuring the health and safety of the staff; C_D – decommissioning cost; r – discount rate; y1, y2, y3, y4, y5, y6, y7 – years in which the costs are included.

The life cycle cost model is used to make decisions about the investments required to build a power substation. The introduction of the discount rate is justified by the fact that some costs occur at different points in time. Therefore, it is necessary to develop a multi-algorithm optimization framework for finding an appropriate solution. Being a robust model with development possibilities, it offers the possibility to adapt to future requirements.

The case study focused on the economic benefits brought by the replacement of old electrical equipment and implicitly the integration of the power substation into the SCADA system, thus significantly reducing operating and maintenance time. Also, through this investment there is a conservatively estimated reduction in operating and maintenance expenses by 50%.

The net present value expressed by relation 3.2 was used as a mathematical model:

$$NPV = \sum_{t=1}^{D} \frac{V_t - (I_t + C_i)}{(1+i)^t} \quad (3.2)$$

unde : Vt – the annual benefit obtained following the realization of the investment; It – annual investment; Ct – annual operating expenses; D – duration of study; i – discounted rate.

For the cost-benefit analysis, a study duration of 15 years and a discount rate of 5% were considered. Also, 2 cases were considered: case 1 – the case where the modernization is not implemented and case 2 – the case where the modernization is implemented.

Expenditure on maintenance and repair activities accounted for over 27% of total expenditure. They are due to the age and the advanced degree of wear and tear of the existing equipment, as well as to keeping it in operation even if it is aging. When the equipment is replaced, a significant decrease in expenses by 50% is observed.

Analyzing the expenses before and after considering the investment and entering them into the formula (3.6), it turns out that NPV > 0, which means that the investment is profitable.

CHAPTER 4:
EXTENDING THE LIFE CYCLE THROUGH MAINTENANCE MANAGEMENT OF EQUIPMENT IN POWER SUBSTATIONS. GREEN LEAN SIX SIGMA APPROACH

4.1. MANAGEMENT CONCEPTS AND APPROACHES

4.1.1. LEAN and SIX SIGMA

The origins of *Lean* are related to the Toyota production system, where the main management objective was to reduce waste [5]. The concept is based on eliminating waste and improving flow in production [6]-[8]. The *Six Sigma* methodology was first implemented by Motorola (1987) and is based on the identification and elimination of defects in order to improve system performance [6], [9]. Motorola created a series of steps, which were later replaced by General Electric (GE) with four phases: measure, analyze, improve, and control. After that, the defining phase was added before the measuring phase to form the *DMAIC* (*Define, Measure, Analyze, Improve and Control*) process.

There are many areas where the two methodologies have common bases in terms of: the origin, principles, concepts, objectives and approach of project management. The differences between the two methodologies consist of: definition, complexity, how they are viewed, approached, scope, identification of gaps, the level of the problem, etc. Thus, the integration of the two methodologies is possible and beneficial.

4.1.2. LEAN SIX SIGMA (LSS)

The LSS model for the optimization of preventive maintenance [89] can help to carry out an analysis to establish operational objectives and plan maintenance activities. To achieve the objectives, the model must go through the following steps:

- adopting an organizational structure based on maintenance activities and not on strategies;
- the introduction of performance measures for each maintenance activity.

- identifying the factors that affect the improvement of maintenance activities.
- identification of all cost elements related to changes in factors that affect the improvement of maintenance activities.

4.1.3. GREEN LEAN SIX SIGMA (GLSS)

Due to the limitations of Lean and Six Sigma, companies need techniques to help make effective environmental decisions [10]-[14]. The most widely used approach is DMAIC [10], which is recognized as a continuous improvement cycle of problem solving (fig. 4.1).

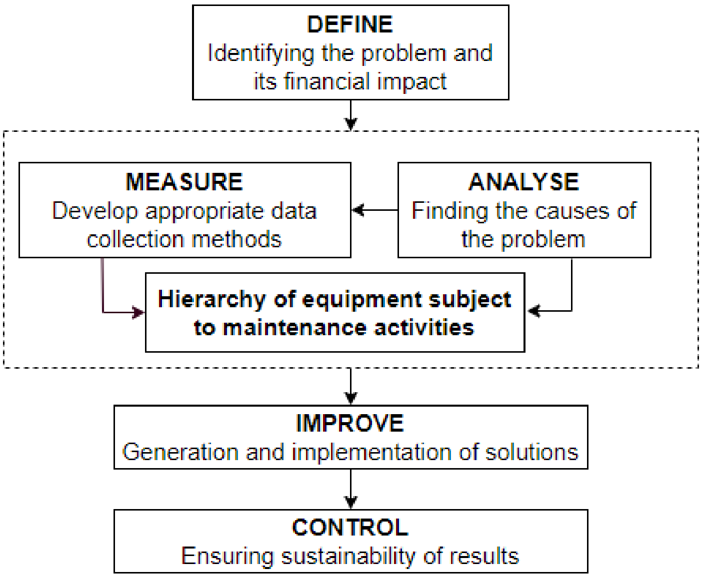

Fig. 4.1. GLSS phases

Green Lean Six Sigma (GLSS) is a strategy that can help energy companies mitigate environmental impacts such as pollution, carbon emissions, resource depletion, and energy consumption.

4.2. CASE STUDIES: APPLICATION OF GLSS CONCEPT FOR EQUIPMENT MAINTENANCE MANAGEMENT IN THREE HIGH VOLTAGE POWER SUBSTATIONS

4.2.1 GLSS PHASE 1: DEFINE

The *purpose* of this phase is to provide the maintenance manager with an alternative work method to be used to increase the life cycle of a power substation by considering all stages of the life cycle.

Objectives: reliable electricity supply service for end users; durability of the power substation; the possibility of replacing the insulation of compact substations with SF6 with free-SF6 gases; methods of self-diagnosis and self-healing of electrical equipment; mitigating the environmental impact on power substations; stimulating the evacuation of electricity produced without carbon emissions.

For the application of the GLSS concept, three power substations with different voltages and schemes, within the transmission network, are considered. All three substations belong to SEN and are located in the central area of the country.

Restrictions: Performance standards, in force, that electrical equipment must comply with.

Solutions: digitized substations; new substations, located right in the load consumption center to limit power and electricity losses; flexibility in transited electric power control systems.

4.2.2 GLSS PHASE 2: MEASURING THE TECHNICAL PERFORMANCE OF HIGH VOLTAGE EQUIPMENT

The measurement phase includes gathering information as well as analyzing existing data to establish a reliable method of measuring process parameters and performance. This phase includes some advanced measuring tools. Identification of potential design or commissioning failures is done using FMEA.

During this phase, tables were presented to identify the factors that affect the technical performance of high voltage equipment. These tables include: the type of equipment, the main components of the equipment, the factors affecting the technical performance of the equipment and the degradation processes of the equipment (major and minor failure modes).

The high voltage equipment considered are: circuit breakers, disconnectors, current and voltage measuring transformers and surge arresters.

The power substations considered in the case study are equipped with two types of circuit breakers (fig. 4.2):

- SF6 circuit breakers, manufactured by ABB, Areva, Siemens (59 circuit breakers, of which 1 GIS circuit breaker);
- oil circuit breaker, manufactured by EP Craiova (14 circuit breakers).

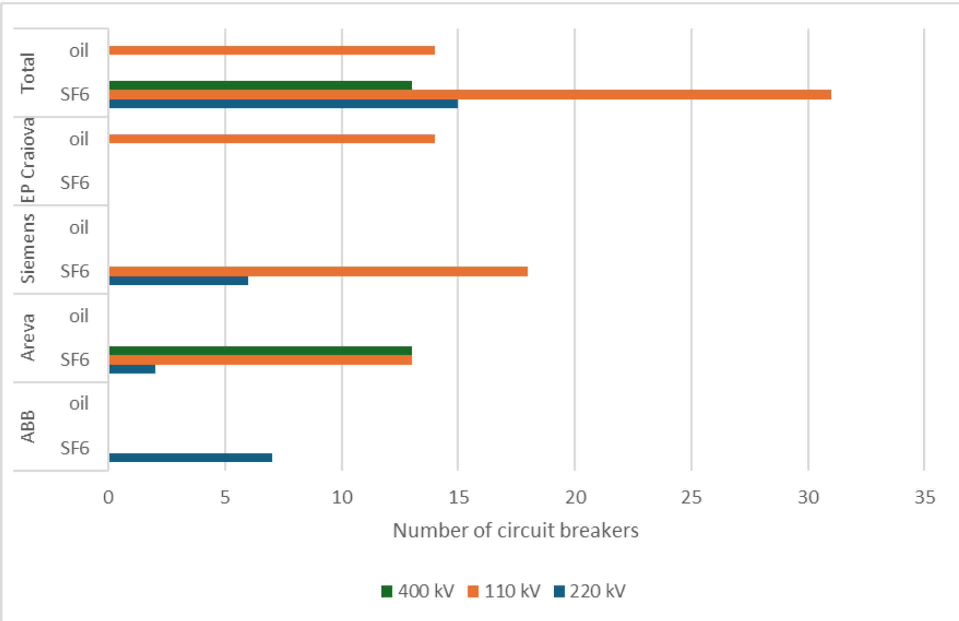

Fig. 4.2 Types of circuit breakers rated, classified according to voltage level and their manufacturing companies.

In this phase, an example is presented with the main measuring points and measuring devices used to evaluate the equipment based on technical condition, importance and health and safety indices.

4.2.3. GLSS PHASE 3: ANALYSIS OF THE IMPACT OF THE FAILURE OF HIGH VOLTAGE EQUIPMENT ON THE PERFORMANCE OF THE SUBSTATIONS

The phase verify whether the applied measures correspond to the expected results and whether the established requirements for improving the maintenance process are applicable or should be redefined and filtered. The phase also includes potential errors and their causes.

The equipment evaluation criteria are used to determine the indicators (technical condition, importance, environmental protection, health and safety) necessary to make a ranking of the equipment. Each type of equipment has a specific set of performance criteria.

There are criticality rates (scores) for indicators of technical condition and importance, from 1 to 5. Most assets assessed will be in groups 1 and 2. This means that the equipment does not require any specific remedial action at the time of assessment. Those in groups 3, 4 and 5 should have an individual action plan based on the identified failure mode, overall rate of progression and exposure to criticality.

(1). **Technical condition index**

The criteria used to evaluate the technical condition index can be: operational experience, visual inspections or the results of measurements and monitoring.

$$i_{st} = \prod_{n=1}^{5} Criterion\ n. \quad (4.1.)$$

(2). **Importance index**

Knowing only the technical condition of the equipment is not enough for planning maintenance activities, it is necessary to estimate the consequences of failure. The importance of equipment can depend on: technical aspects, social and legal aspects, financial aspects, impact on the environment, workplace safety, occupational health, etc. The importance index is a result of the risk assessment.

$$i_{imp} = \prod_{m=1}^{5} Criterion\ m \quad (4.2)$$

(3). **Environmental protection, health and safety index**

In this case, the evaluation of scores is done from 1 to 7 for the most likely consequences of some breakdowns, at the equipment level of an electrical substation, on occupational health, stuff operational safety and the environment.

$$I_{mss} = \prod_{s=1}^{7} Criterion\ s \quad (4.3)$$

Questionnaires have been proposed to assess technical status, importance and occupational health and safety. Based on the data obtained from the measurements, as well as those taken from the monitoring systems, each evaluation criterion can be assigned a score. For each piece of equipment within the 3 power substations under analysis, indices are calculated. The obtained results were represented graphically.

4.2.4. GLSS PHASE 4: ÎMBUNĂTĂȚIREA MANAGEMENTULUI MENTENANȚEI ECHIPAMENTELOR DE ÎNALTĂ TENSIUNE

The phase aims to identify, implement and monitor the solutions adopted during the analysis phase, to ensure that the chosen solution is the optimal one. This phase also includes the standardization of maintenance procedures, the creation of an information improvement application, procedures, the definition of the improvement strategy, the elimination of activities that are not necessary and the assessment of risks.

4.2.4.1. Proposing a global priority index of maintenance activities (i_g)

Based on the analysis of the technical condition of the equipment, its importance and the protection of the environment, health and safety of the operative staff, it is proposed to correlate the three indicators and calculate a **global priority index of maintenance activities** (i_g). The general expression is:

$$i_g = \sqrt{i_{st}^2 + i_{imp}^2 + i_{mss}^2} \tag{4.4}$$

With the help of the Matlab, a 3D graphic representation was made. The results can be represented in an x-y-z coordinate system as in Fig. 4.3. On the ox axis is the technical condition index of the equipment (i_{st}). On the oy axis is the importance index of the equipment in the electrical network (i_{imp}). On the oz axis is the environmental protection, health and safety index (i_{mss}).

For each coordinate point (i_{st}, i_{imp}, i_{mss}) a global index (i_g) will result.

4.2.4.2. Proposing a new methodology for ranking electrical equipment from the point of view of the priority of maintenance activities

Based on the i_g value, a classification is proposed, which will indicate a ranking of the electrical equipment from the point of view of the priority of the maintenance activities.

The distances from each point g(i_{st}, i_{imp}, i_{ms}) to the origin (0,0,0) will be denoted by d.

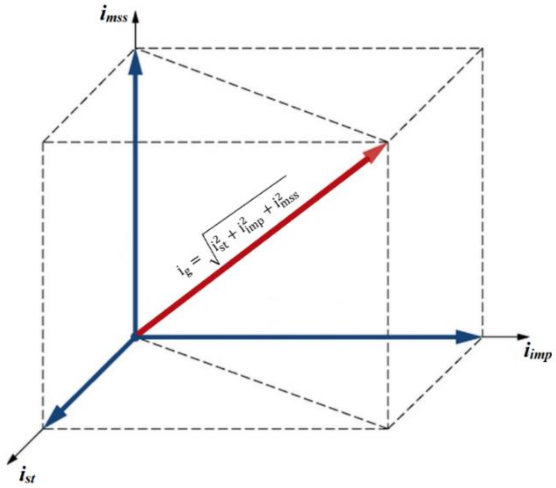

Fig. 4.3 The principle of determining the distance d in the priority diagram

Establishing the priority of maintenance actions will be done according to the distances d in the priority diagram. For each equipment, a distance d_k is calculated, with k = 1...n, where n = no. the equipment. The comparative analysis of the size of the distances d_k determines the order in which the equipment will be subjected to maintenance actions. Electrical equipment that has the largest d_k distances will have priority.

4.2.4.3. Graphical simulations in Matlab for the prioritization of maintenance activities for the three power substations, by equipment category

3D diagrams have been shown that highlight how maintenance activities are determined according to the magnitude of the **global priority index of maintenance activities**. In principle, the evaluation of the dependence between each two indices $i_{imp} = f(i_{st})$, $i_{mss} = f(i_{st})$, $i_{mss} = f(i_{imp})$ will be done by using two-dimensional graphic representations.

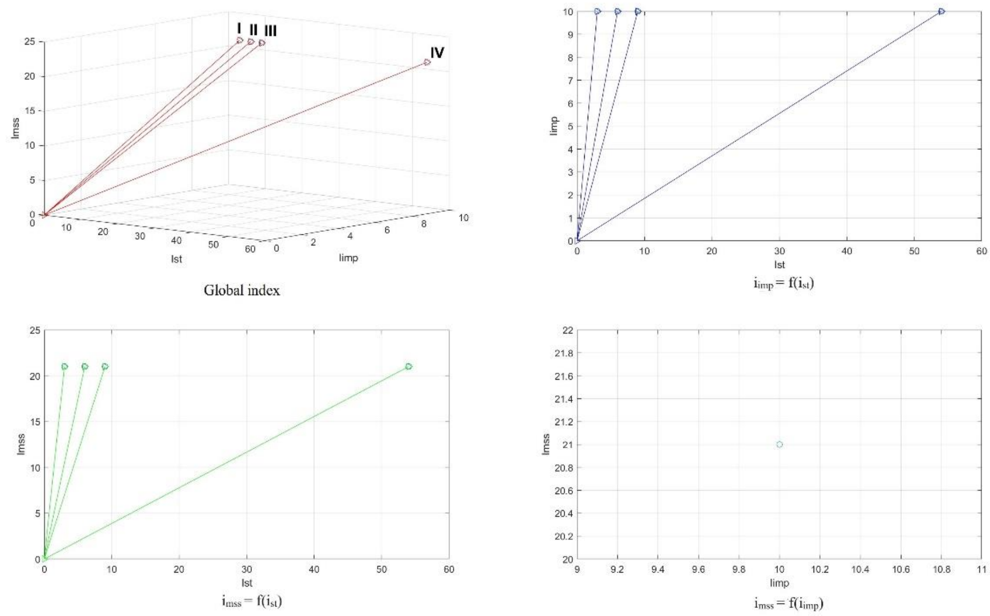

Fig. 4.4 Example of prioritization of maintenance activities for circuit breakers in substation A – 220 kV

The graphic analysis for the prioritization of maintenance activities was carried out for each of the three power substations, for each circuit breaker and disconnector.

For substation A, the analysis also extended to the voltage transformer and the current transformers.

4.2.5. GLSS PHASE 5: CONTROL OF THE RESULTS OF THE PREVIOUS PHASES FOR CONTINUOUS IMPROVEMENT

4.2.5.1. Control of the prioritization of maintenance activities by equipment category for the three power substations

First, the importance of the electrical equipment was controlled and analyzed according to its technical condition, in order to estimate the level of maintenance impact (low, medium, high) on reducing the risk of failure. The environmental impact of the equipment was then tracked based on its technical condition as well as its importance for the equipment to fulfill its role within the transmission grid while meeting the specification criteria, including environmental requirements.

The result of the ranking by category of electrical equipment, taken into account in the study, was presented, according to the value of the global priority index of maintenance activities.

By analyzing the results, forecasts and decisions can be made and maintenance actions can be planned. Depending on the value of the global index, a classification of the necessary maintenance activities is made, as follows:

- $i_g \in [0, 50)$ – normal operation;
- $i_g \in [50, 1000)$ – technical inspections;
- $i_g \in [1000, 5000)$ – minor maintenance;
- $i_g \in [5000, 10000)$ – major maintenance;
- $i_g \geq 10000$ – replacement of components/equipment.

Based on the above classification, the graphs in figures 4.5 and 4.6 were made in Matlab to highlight the circuit breakers within substation (220 kV, respectively 110 kV), which exceed the limits of safe operation, as well as the activities that will be applied depending on the value of the global index. The same principle applies to the other equipment in the power substations.

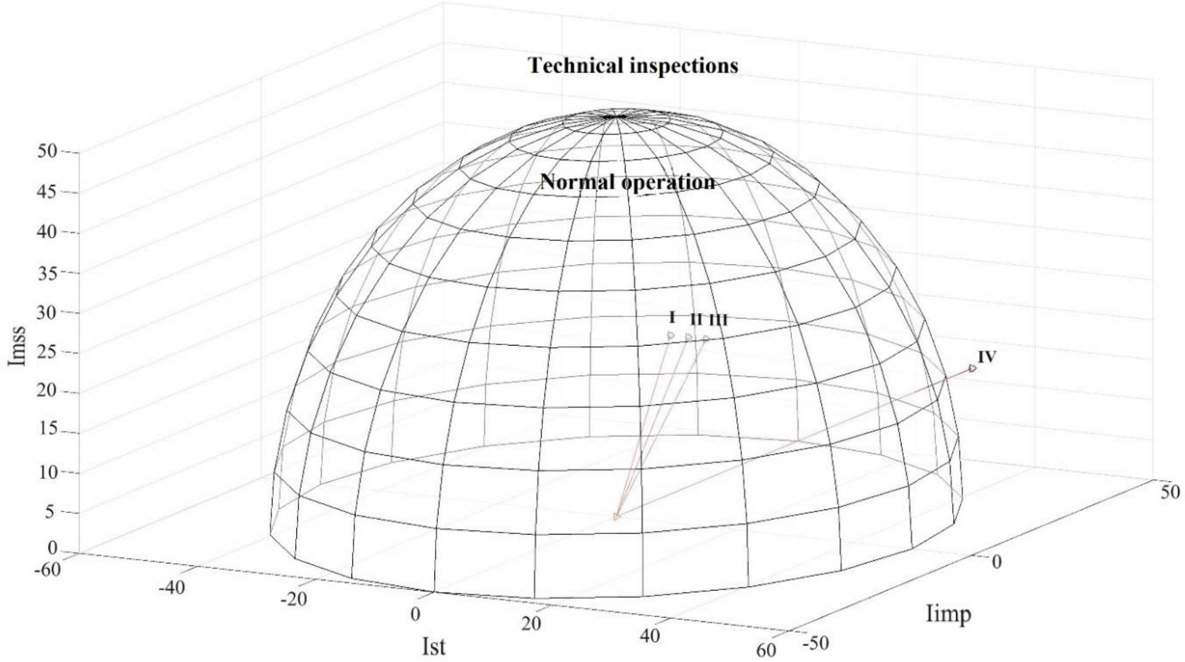

Fig. 4.5 Ranking of maintenance activities according to the value of the global index for circuit breakers in 220 kV substation

Analysing figure 4.5, most of the circuit breakers are inside the half-sphere that defines normal operation, and only one circuit breaker is outside it, which means it will need further inspection. Regarding 110 kV substation (figure 4.6), the values of the global index are much higher and for this reason 3 half-spheres were built: the first half-sphere covers the equipment that needs technical inspections (ig < 1000), the second half-sphere deals with the circuit breakers for which ig ∈ [1000, 5000) and which require minor maintenance activities, and the third half-sphere establishes the equipment that is prioritized from the point of view of the need for major maintenance activities. It is noted that category VIII of circuit breakers have a global index value greater than 10000, which leads to component replacements or even equipment replacement.

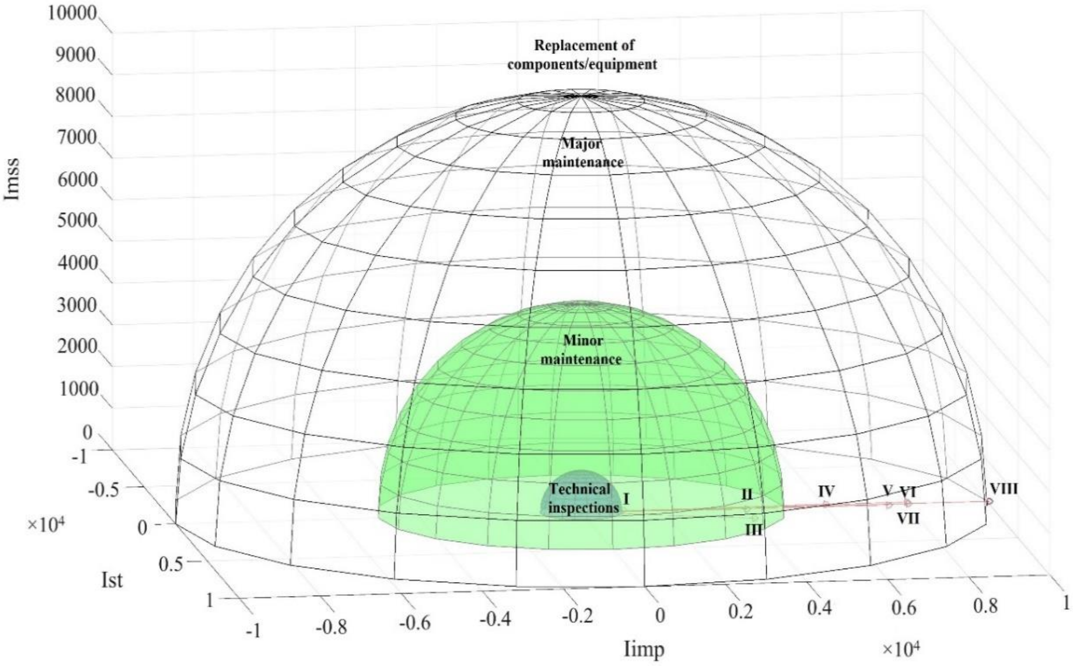

Fig. 4.6 Ranking of maintenance activities according to the value of the global index for circuit breakers in 110 kV substation

4.2.5.2. Proposing an algorithm of a decision process for continuous improvement

The decision-making process can be explained by presenting it as a decision flow diagram. It details an overview of the process on three different decision levels: equipment level, substation level and company level.

Decisions to replace equipment through different solutions depend not only on the increased failure rate, but also on the availability of spare parts or the current capacity of the equipment.

Combining the technical data/information of the solutions with relevant economic data will result in a quantification of costs and benefits for each solution. The technical information of the solutions should not be expressed exclusively in economic terms, but could also be expressed in other terms, such as reliability or expected lifetime. System performance (topology and network development, load curve change) influences asset decision-making. Possible consequences and impacts on the system are obtained from reliability calculations.

The costs and benefits of the solutions are combined with the risks involved in each solution. The goal is to obtain the optimal decision regarding external requirements (social information). Both safety and social risks must be considered to complete the decision-making process. A balancing of the risks will lead to the final decision.

4.3. CONCLUSIONS AND ORIGINAL CONTRIBUTIONS

This chapter proposes risk assessment and management and identifies a new methodology, Green Lean Six Sigma, which uses aspects of traditional Lean and Six Sigma methodologies, while providing the necessary tools to decide, implement and sustain improvements that have a positive impact on the environment.

The power substation asset maintenance process was examined and all operations and activities directly and indirectly associated with maintenance were analyzed for process improvement.

Original solutions were generated and implemented. Noteworthy:

- Creation of a questionnaire to assess the impact of electrical equipment failure on the health and safety of staff and the environment;
- Proposals for improving the questionnaires for assessing the impact of the failure on the technical condition and the importance, which will be able to be used to support maintenance programs focused on reliability;
- Proposing environmental protection, health and safety (i_{mss}), technical condition (i_{st}), importance (i_{imp}) indices, in order to analyze the performance of circuit breakers, disconnectors, current transformers, voltage transformers and surge arresters;
- Numerical simulations of the 3 indices, based on the data obtained from measurements/monitoring and the scores assigned according to the evaluation questionnaires, for each of equipment within the 3 power substations that were the subject of the case studies. The following were analyzed: 73 circuit breakers (insulated in oil, sulfur hexafluoride and GIS), 206 disconnectors, 77 current transformers, 81 voltage transformers, 54 surge arresters.
- The proposal of a solution to improve substation maintenance by generating a global priority index of maintenance activitites had as its objective the implementation and monitoring of the solutions adopted during the analysis phase.
- Determination by graphic simulations in Matlab, according to the global priority index of maintenance activitites, of the hierarchy for 491 equipment from the 3 analyzed substations.
- Control of the prioritization of maintenance activities by equipment category for the three power substations.
- Proposing an algorithm of a decision-making process for continuous improvement. The control phase is very important because it confirms the implemented improvements, facilitates the distribution of the budget and the planning of the works.

By following the five phases presented, applying robust analysis tools and a dedicated management system, maintenance cost savings are expected to be at least 20% higher than when applying reliability-centered maintenance.

CHAPTER 5
PROSPECTS FOR CONTINUING RESEARCH

The collection and organization of information based on a SWOT analysis of strengths and weaknesses, opportunities and threats allowed the identification of perspectives for the continuation of the research undertaken in this thesis and forecasting the evolution of a GLSS implementation project at the level of the power transmission company.

DISSEMINATION OF THE RESEARCH RESULTS CARRIED OUT WITHIN THE THESIS

I. 2 Articles published in WoS indexed journals with impact factor/1 as first author + 1 Article submitted to the UPB Bulletin, under review

- **Georgiana Ion**, Sorina Costinaş, Andrei Stan*, Analysis of the Evolution of Mathematical Models for Estimating Life Cycle of Power Substations*, TEM JOURNAL-TECHNOLOGY EDUCATION MANAGEMENT INFORMATICS, Ed. UIKTEN, Volume 13/2024, Issue 1, pp. 5-15, ISSN 2217-8309, DOI: 10.18421/TEM131-01, **IF=0.6, WOS:001179511200030**.
- Stan Andrei, Sorina Costinaş, **Georgiana Ion**, *Overview and Assessment of HVDC Current Applications and Future Trends*. Energies 2022, Vol. 15, Issue 3, Article Number 1193. https://doi.org/10.3390/en15031193, FEB 2022, eISSN1996-1073, **IF=3, WOS:000755376100001**.
- **Georgiana Ion**, Sorina Costinas, *Application of green lean six sigma for maintenance management of electrical equipment in transmission substations*, Scientific Bulletin, National University of Science and Technology POLITEHNICA of Bucharest, Serie C: Electrical Engineering (under review)

II. 3 scientific papers published in conference volumes indexed IEEExplore/ 2 as first author

- **Georgiana Ion**, Sorina Costinas, Andrei Stan, Florin Bălășiu, *Assessment of Life Cycle of Autotransformers*, Electrical, Computer and Energy Technologies (ICECET), 2022 International Conference on, IEEE, Prague, Czech Republic, 20-22 July, 2022. **DOI: 10.1109/ICECET55527.2022.9872982**
- **Georgiana Ion**, Sorina Costinas, Andrei Stan, Marius Eugen Tiboaca, *Trends to Increase the Life Cycle of a Substation in Context of Smart Grid*, 10th International Conference on Energy and Enironment (CIEM2021), oct. 2021, ISBN: 978-1-6654-4584-9/21, Publisher: IEEE, **DOI: 10.1109/CIEM52821.2021.9614762.**
- Marius Eugen Tiboaca-Ciupageanu, Sorina Costinas, **Georgiana Ion,** Andrei Stan, *Machine Learning Algorithms for Load Forecasting Based on Big Data*, 2023 11th International Conference on ENERGY and ENVIRONMENT (CIEM), Bucharest, Romania, 2023, pp. 1-5, **DOI: 10.1109/CIEM58573.2023.10349757**.

SELECTIVE BIBLIOGRAPHY

[1]*Kawauchi Yoshio, Marvin Rausand,* "Life Cycle Cost (LCC) analysis in oil and chemical process industries." Toyo Engineering Corp, Chiba (1999).
[2]*International Electrotechnical Commission,* "IEC 60300-3-3: 2017 Dependability management–Part 3-3: Application guide–Life cycle costing", Geneva, Elveția, 2017
[3]*Balzer G., Neumann C.,* "Asset simulation and life cycle assessment for gas insulated substation", RECIFE: Assessing and improving power system security, reliability and performance in light of changing energy sources, 2011, report 87
[4]*Sarma Kamal C., Hojjat Adeli,* "Life-cycle cost optimization of steel structures", International Journal for Numerical Methods in Engineering 55, no. 12 (2002), pp. 1451-1462, DOI:10.1002/0470867353.ch8

[5]*Ghane Kamran,* "A model and system for applying Lean Six sigma to agile software development using hybrid simulation", 2014 IEEE International Technology Management Conference (ITMC), Chicago, IL, USA, pp. 1–4, DOI:10.1109/itmc.2014.6918594

[6]*Siddh Man Mohan, Soni Gunjan, Gadekar Gaurav, Jain Rakesh,* "Integrating lean six sigma and supply chain approach for quality and business performance", 2014 2nd International Conference on Business and Information Management (ICBIM), Durgapur, India, pp. 53-57, DOI:10.1109/icbim.2014.6970949

[7]*Rabii Ouardaoui, Naoufal Sefiani, Omar Akouri,* "Model of a maintenance process improvement approach inclusioning Lean Six Sigma and Preventive Maintenance optimization", 2018 International Colloquium on Logistics and Supply Chain Management (LOGISTIQUA), Tangier, Morocco, pp. 19–24, DOI:10.1109/LOGISTIQUA.2018.8428285

[8]*Trubetskaya Anna, Olivia McDermott, Anthony Ryan,* "Application of Design for Lean Six Sigma to strategic space management" The TQM Journal 35, no. 9, 2023, pp. 42-58

[9]*Souraj Salah, Abdur Rahim, Juan A. Carretero,* "The integration of six sigma and lean management", International Journal of Lean Six Sigma, vol. 1 no 3, 2010, pp. 249-274, DOI: 10.1108/20401461011075035

[10]*Farrukh Amna, Sanjay Mathrani, Aymen Sajjad.* "A DMAIC approach to investigate the green lean six sigma tools for improving environmental performance" 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), Brisbane, Australia, 2021, pp. 1-6, DOI: 10.1109/CSDE53843.2021.9718462.

[11]*Nagadi Khalid,* "Implementation of green, lean and six sigma operations for sustainable manufacturing. A Review", International Journal of Production Management and Engineering, 2022, *10*(2), pp. 159-171.

[12]*Trubetskaya Anna, Olivia McDermott, Anthony Ryan,* "Application of Design for Lean Six Sigma to strategic space management" The TQM Journal 35, no. 9, 2023, pp. 42-58

[13]*Antony Jiju, Hoerl Roger, Snee Ron*, "An Overview of Lean Six Sigma", A practical guide for continuous improvement professionals in higher education, 2020,DOI:10.1108/978-1-78769-929-820201002.

[14]*Gholami Hamed, Norhazrina Jamil, Muhamad Zameri Mat Saman, Dalia Streimikiene, Safian Sharif, Norhayati Zakuan,* "The application of green lean six sigma", Business Strategy and the Environment 30, no. 4, 2021, pp:1913-1931, DOI:10.1002/bse.2724

[15]*Georgiana Ion, Sorina Costinaș, Andrei Stan, Marius Eugen Țiboacă*, "Trends to Increase the Life Cycle of a Substation in Context of Smart Grid", 10th International Conference on Energy and Environment (CIEM 2021), oct. 2021, ISBN: 978-1-6654-4584-9/21, DOI: 10.1109/CIEM52821.2021.9614762

[16]*Comănescu, Gh., Costinaş, Sorina, Iordache, M.*, "Partea electrică a centralelor şi staţiilor. Note de curs", Editura Proxima, Seria Cursuri Universitare, Bucureşti, 2005, 349p, ISBN 973-7636-08-2.