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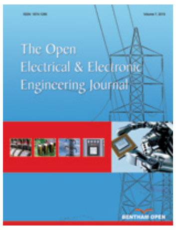

RESEARCH ARTICLE

Innovative Maintenance Model: Methodology of Decision Making and Global Economic Cost – Based Choice Using Fuzzy Logic Concepts

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Abstract:

Background:

In this paper, we propose the Development of a knowledge-based expert system applied to Electricity distribution Network maintenance.

Method:

The expert system utilizes the Matlab® platform, using its proprietary Fuzzy Logic Toolbox. The inputs to the expert system are the different situations related to cost variables to and the implementation of one of the maintenance optimizing solutions pertaining to the Live Work-Redundancy-Simultaneity-Security model as defined by the maintenance unit during a the global life cycle of the equipment. The output of the system indicates the economic feasibility and benefit of the solution to be adopted of for our Maintenance model. Application of the expert system methodology is shown as a simulation.

Conclusion:

The expert system may be of valuable assistance to utility engineers or asset managers in making strategic maintenance decisions such as “Economic solution”.

Keywords: Availability, Live work, Maintenance cost, Fuzzy logic, Decision aid, Deffuzzification.

1. INTRODUCTION

In a very tense electricity market, characterized by strong daily constraints to permanently meet the needs of increasingly demanding customers, it has become difficult to predict the conditions of operating and maintenance of electrical network facilities in a deterministic and flexible way [1]. Among the tools elaborated in order to control these constraints, the manager of the Moroccan National Electricity network has decided to develop a new maintenance methodology, which makes it possible to achieve maximum levels in terms of facility availability and service continuity.

In fact, and given that maintenance is a cost-generating function, managers often sought to reduce costs rather than improve functioning mechanisms. However, the great network evolution and intensified growth in demand have resulted in remarkable changes [2] which, for their part, have affected, inter alia, the maintenance function and made its role a central one. It has, thus, become a strategic function which guarantees the safety of the functioning of the network and the performance of its facilities.

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In fact, this research work is about maintenance optimization according to the maintenance approach called **L**ive Work – **R**edundancy – **S**imultaneous work – **S**ecurity (**LRSS**) [3].

We, thus, underline the specific characteristics with regard to the cost of the implementation of aspects of LRSS maintenance, which makes it possible to elaborate of an overall frame of reference for a successful implementation of a new maintenance approach within our company.

2. DESCRIPTION OF THE SYSTEM AND STUDIED PROBLEMS

2.1. Studied System

The present study concerns the facilities of the national electricity distribution network in Morocco.

Fig. (1). Components of the national distribution network.

The current policy of maintenance of these facilities takes into account the optimal configuration of the HV network and guarantees good functioning of the national electricity distribution network in order to ensure safe and economical electricity distribution and provide high quality services. It also makes it possible to standardize maintenance methods and keep its efficient practices [4]. By the end of 2015, the studied network is spread out over 230 transformer stations Fig. (**1**) and 23300 km of HV lines.

Given the increasing demand in electrical energy, it appears that improving the availability of facilities and reducing maintenance cut offs have become a strategic and inevitable requirement, which directly affects the quality of services and the brand image of the company.

2.2. Problem

Currently, the tendency is to exploit the electricity distribution network as fully as possible. This is particularly because it is economically and technically difficult to install new facilities and because of the increasingly growing demand compared to the relatively limited capacity of the existing facilities.

In this increasingly restrictive and constraining context, the operator of the network should ensure the continuity of services, hence the necessity to control the efficiency of maintenance methods. Continuous improvement of the availability of facilities is, therefore, a permanent activity of the operator of the network. The stakes identified are related essentially to scheduling and cost of maintenance operations of the network. Such operations should be carried out while minimizing the duration of cut-offs and possibly eliminate them.

Besides, and despite the network being fitted out with a set of regulation controllers and devices, which make it possible to optimize its operating [5], the implementation of different maintenance schedules makes its behavior more complicated. It results in a successive disruptions due to frequent and extended stops of facilities. Thus, in order to address this issue, we have developed an appropriate methodology, called LRSS.

The present work is essentially a comparison of the costs of the implementation of the three solutions of this methodology (cf. logical flow chart below), based on the results of expert system and the principles of fuzzy logic (discussed in details below). In fact, the parameters impacting the costs of the said solutions can be summarized as follows:

- Cost of solution "C_ sol" related to relevant maintenance operation mode, which can be calculated as follows:
    - Live Work: Cost of acquisition, maintenance and replacement of tooling and facilities required for live work intervention plus training cost [6].
    - Redundancy: Cost of designing, acquisition, installation and maintenance of additional facilities to ensure functional redundancy.
    - **S**imultaneous work: cost of accelerated depreciation of facilities due to delaying scheduled preventive maintenance stops (systematic or functional)
- Cost of non distributed energy C_ End related to commercial shortfall (slump in sales) ou or technical shortfall (network development, recourse to costly means of production) to be avoided upon the implementation of the solution.

Thus, consider the following value: C= C_Sol/C_End

If we take:

- L = Facility's service life
- P is the periodicity of the implementation of the generated operation mode

The economic feasibility and benefit of the solution to be adopted as one of the LRSS model solutions depends on the following conditions:

$$\boxed{P * C < L}$$

The methodology we have adopted is schematized in Fig. (**2**), taking into consideration the following definitions:

- Ci: Component i
- Op(i,k): Operational mode no. of preventive maintenance of the facility Ci
- Top(i,k): Operational mode time Op(i,k)

- A(i,k): Availability value equivalent to stop during operational Top(i,k)

2.3. Adopted Methodology

The method includes the 4 phases described hereafter, of which the sequence is summarized in (Fig. **3**).

Phase 1. Generation of Functions

The purpose of this phase is to design a set of plausible situations by enhancing cost variables related to the implementation of one of the maintenance optimizing solutions pertaining to the LRSS model. The choice of these variables is, therefore, determined by the purpose of the study and the scope of expected results and calls for engineering expertise and know-how [7].

Thus, any technical or economic variable pertaining to the modeling of our system can be potentially sampled, such as:

- Frequency and duration of scheduled unavailability of electrical facilities: the user/operator can determine the maximum number of facilities put out of service and make such unavailability dependent on the condition of putting into service of other facilities so that the complex reality of maintenance programs can be reasonably represented.
- The economic and commercial impacts of stops, essentially known as short falls correlated to the energy not distributed to customers and, ultimately, to non- invoiced services.

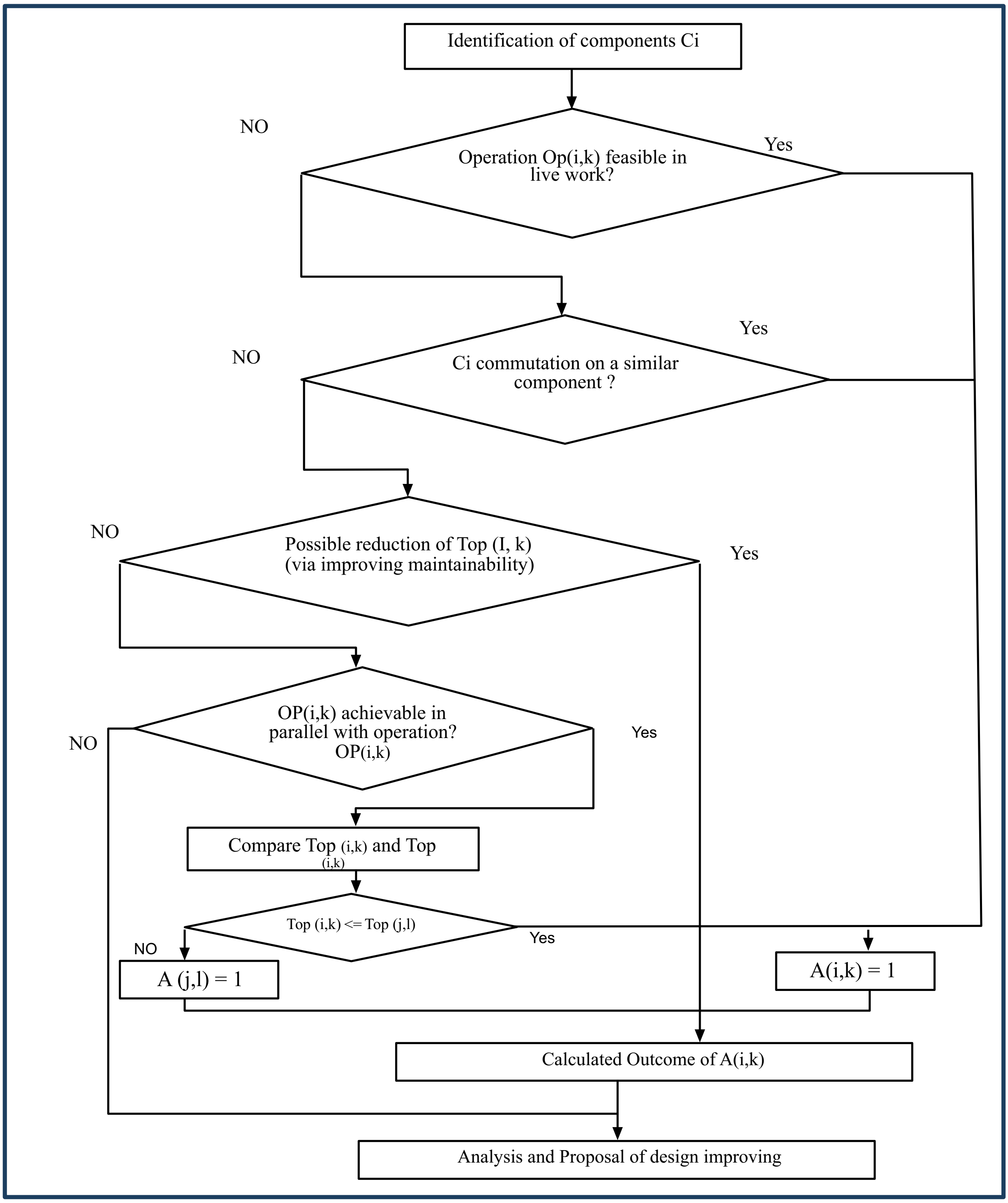


Fig. (2). Logical flow chart of LRSS model.

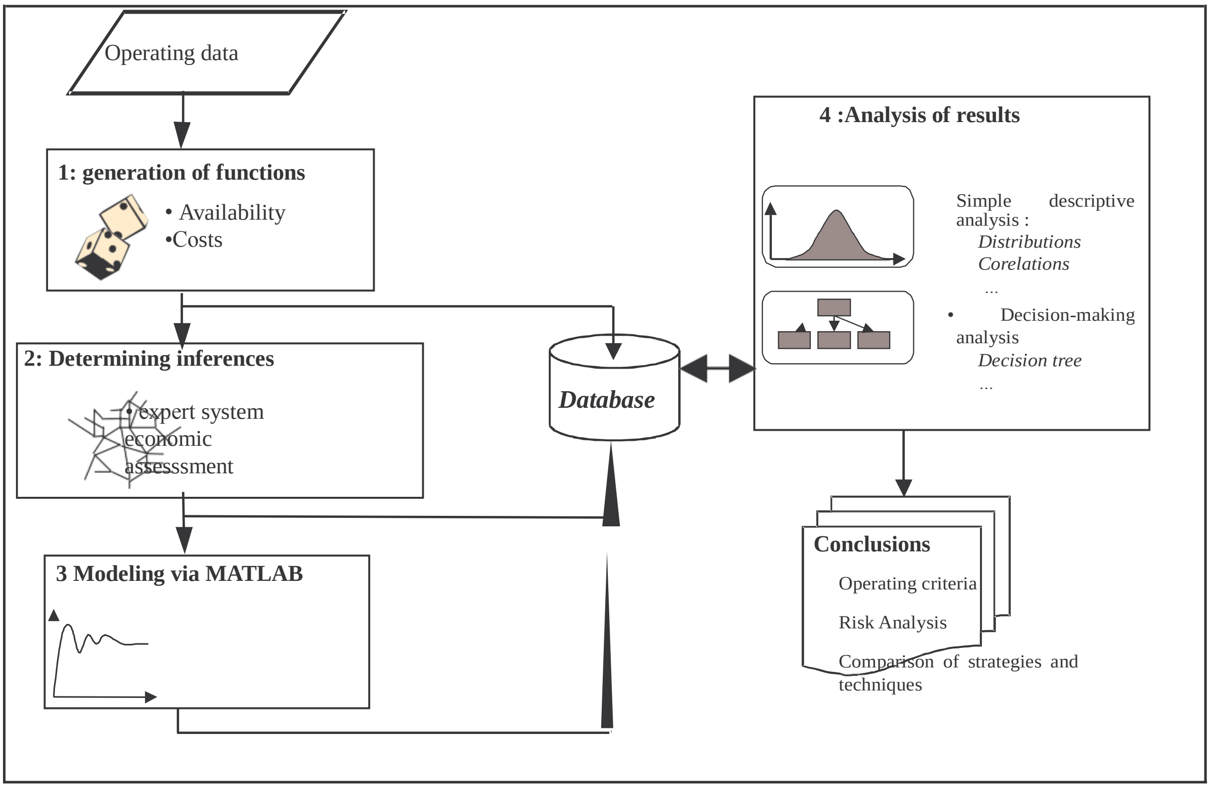


Fig. (3). Main phases of the method.

Phase 2. Determining Inferences

Each selected solution should be able to represent a preservation of an operating state that is sufficiently realistic and achievable, close to a typical state of continuous upkeep of facility operating. This requires finding out the facilities and operation modes concerned.

Moreover, for every selected solution:

- scheduling of maintenance stops should be reasonably compatible with constraints and operating rules and regulations;
- Operating rules and regulations should be constantly respected: ability or inability to tolerate loss of one element of the network (N-1), impact on the availability of the facility, maintainability constraints.

It should be stressed that the availability of such a robust and efficient tool that has permitted the operational implementation of the approach should be elaborated.

If all scenarios have a realistic implementation point, operators of the electrical system will have at their disposal a primary database likely to result in a distinction between acceptable and unacceptable situations (See phase 4). For this purpose, they have numerous results, such as, among others, adjusted maintenance programs, flexibility of electricity distribution means, estimation of costs of optimization solutions (redundancy…).

Phase 3. Modeling via MATLAB "IT Tool"

The aim of this phase is to have a graphic profile of the examined cost parameters. The characteristics of the resulting curves and graphs vary depending on the input elements (input) of the expert system.

Concerning the IT modeling tool, we have opted for the use of the MATLAB software program [8], which proves to be perfectly compatible with the concepts of fuzzy logic as well as with the fuzzification methodology detailed below [9].

Phase 4. Analysis of Results

Depending on the objectives of this study, decision-makers/ network [10] operators should define precisely the optimal solution that they have selected to maximize the availability of facilities, through optimizing the overall cost of their maintenance. In fact, only by relying on a combination of these factors can make decision-makers and network operators decide an efficient asset policy [11].

3. FUZZY LOGIC APPROACH AND FUZZIFICATION MODEL

Representing and using knowledge are central to any relatively new scientific discipline - artificial intelligence [12]. Until fairly recently, this discipline has had limited impact on industrial applications, for it has laid emphasis exclusively on the symbolic processing of knowledge as opposed to digital modeling traditionally used in engineering sciences.

In fact, Fuzzy logic [13] is a problem-solving control system methodology that lends itself to the implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. Fuzzy logic requires some numerical parameters in order to operate such as what is considered a significant error and significant rate-of-change-of-error, but exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them.

Fuzzy systems are part of knowledge-based systems or expert systems and their main objective is to implement a human know-how or linguistic rules through an IT program. Fuzzy logic [14] provides mathematical formalism for uncertain linguistic concepts.

3.1. Notions of Fuzzy Logic

The concept of fuzzy logic comes from the observation that the Boolean variable [15], which considers only two values (true or false), is inadequate and ill-adapted to the representation of most current phenomena.

Whereas, classical logic considers that a proposition is either true or false, fuzzy logic distinguishes infinity of truth values (between 0 and 1). It is then a generalization of binary logic to a multi-valued logic.

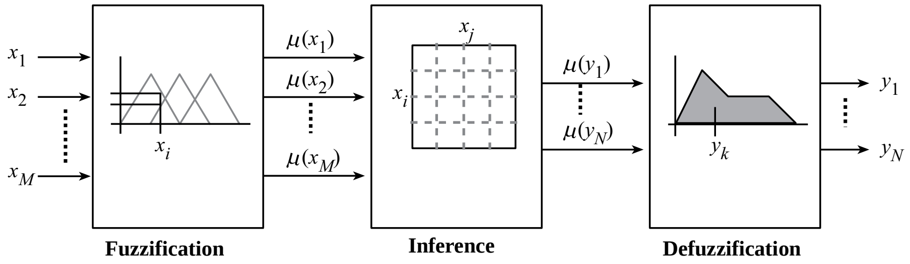


Fig. (4). Principle of fuzzy logic-based reasoning.

3.1.1. The Process of Decision-Making Through Fuzzy Logic

Fuzzy logic –based reasoning can be schematically represented as follows (Fig. **4**):

This method is based on the principle of degrees of membership from 0 to 1.

A function: 0 means not a member to a function, 1 means a member of the function and anything in between denotes partial memberships.

Membership functions can be defined using linguistic properties related to an human reasoning fast, high, and low…

The methods presented above have their own merits and each would have its applications suitable for specific reasons. Fuzzy logic is used in the expert system application presented in this paper due to:

a. its ability to represent and process data based on linguistic information.
b. its usability in a rule-based system.

3.1.2. Fuzzification

The indicator modelling is mad by fuzzification. The fuzzification is the Numerical/Linguistic conversion of different variables characterizing the different indicators. The different indicators are presented by the same membership functions $\mu(x)$.

In this step, we proceed as follows:

- Definition of membership functions of all variables [16]
- Translation from physical parameters to linguistic variables.

3.1.3. Inference

This block indicates the relation between input variables (expressed as linguistic variables) and output variables (also expressed as linguistic variables) by means of intermediary rules.

The fuzzy inference allows us to develop a decision by using the decision rules. The decision rules are described by linguistic terms. For example:

- If the availability indicator is medium and the performance indicator is important and quality indicator is medium then the global efficiency indicator is medium.
- If the availability indicator is important and the performance indicator is medium and quality indicator is medium then the global efficiency indicator is medium.
- If the availability indicator is medium and the performance indicator is medium and quality indicator is medium then the global efficiency indicator is medium.

3.1.4. Linguistic Variables

In general, the description of a given situation, phenomenon or a process includes fuzzy terms, such as:

- A little, a lot, enormously
- rarely, frequently, often
- cold, warm, hot
- small, medium, large
- etc.....

3.1.5. Membership Functions

Instead of belonging to the set « True » or the set « false » of classical binary logic, fuzzy logic admits degrees of membership to a given set. The degree of membership to a fuzzy set is realized by a number between 0 and 1. A precise value of the membership function related to a variable value is referred to as μ and called « membership factor ».

In theory, membership functions can take any form. However, they are often defined by segments and are referred to as « piecewise linear », (widely used, for they are simple and include areas where the notion is true and areas where it is true, a fact which facilitates the collection of expertise).

3.2. Rules

Several values of linguistic variables are interrelated by rules that make it possible to draw conclusions.

Rules can be expressed in a general form:

- If condition 1, then action 1 or
- If condition 2, then action 2 or
- If .....
- If condition n, then action n.

Conditions can depend on various variables interrelated by operators OR or AND.

A simplified description of inferences can be obtained by means of a tabular representation, called inference matrix.

3.3. Defuzzification

The fuzzification is the Linguistic/Numerical conversion of different variables characterising the global efficiency.

The method which is used here is the method of the centre of gravity. This method takes into account all available information.

In fact, Inference methods provide a membership function resulting from the output variable.

It is then fuzzy information. This fuzzy information should be transformed into a given value to be applied to the process control interface. Such transformation is called *defuzzification*.

The most frequently and widely used method of defuzzification is that of determining the gravity centre. Results of preceding calculation should be adapted to the control interface that is implemented.

4. PRESENTATION OF FUNCTIONS RELATED TO THE STUDIED SYSTEM

For the purposes of our study, we have identified three parameters in order to summarize the status of performance of the studied system [17].

We, thus, suggest that, for each parameter, the following modeling Fig. (**5**) should be adopted:

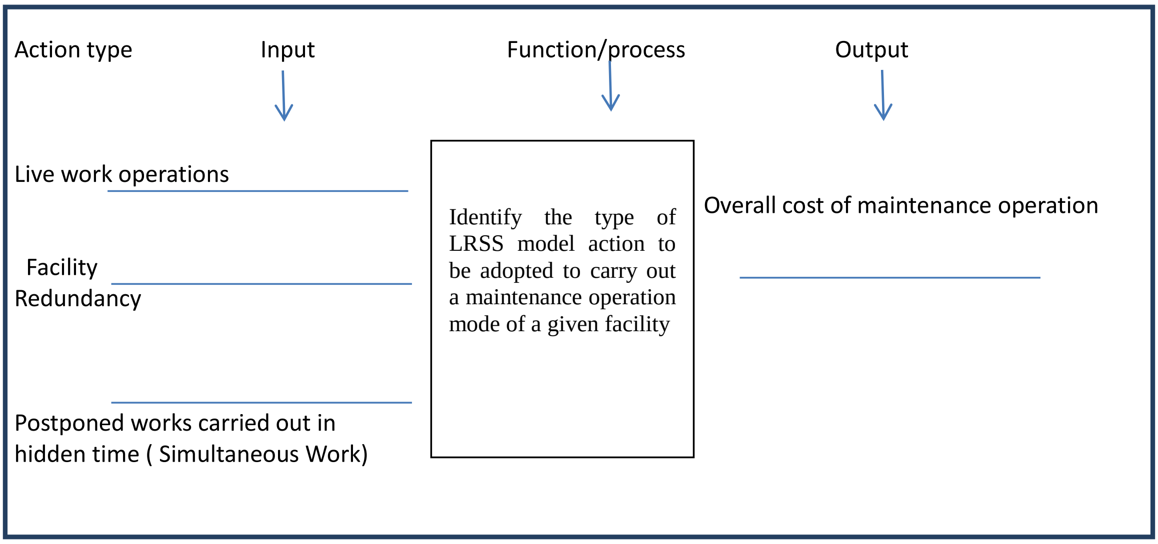


Fig. (5). Modeling functions.

4.1. Input Functions

4.1.1. Live Work (F1 – Fig. 6)

Cost of acquisition cost, maintenance and replacement of tooling and facilities makes it possible to carry out works in accordance with the concept of live work maintenance, in an interrupted way, and particularly live line work [6].

Cost of training (basic, updating, retraining courses) during the useful life of the facility.

4.1.2. Redundancy Facility (F2 – Fig. 7)

In order to increase the overall availability of the facility, one of the LRSS model solutions involves implementing a redundant facility, which ensures the total takeover of the function of a unit scheduled to be stopped for maintenance.

This solution is possible provided the following conditions be obtained:

-Technical and design feasibility of the implementation of a redundant facility: size and volume of the facility, junction, tilting devices)

  - ○ Economic benefit justified by amortization of additional budget within a reasonable period of time separate from the useful life of the facility.

This cost includes the main items below:

- cost of design engineering.
- Cost of works and supplies for the implementation of the new facilities.
- Cost of maintenance and upkeep of additional facilities.

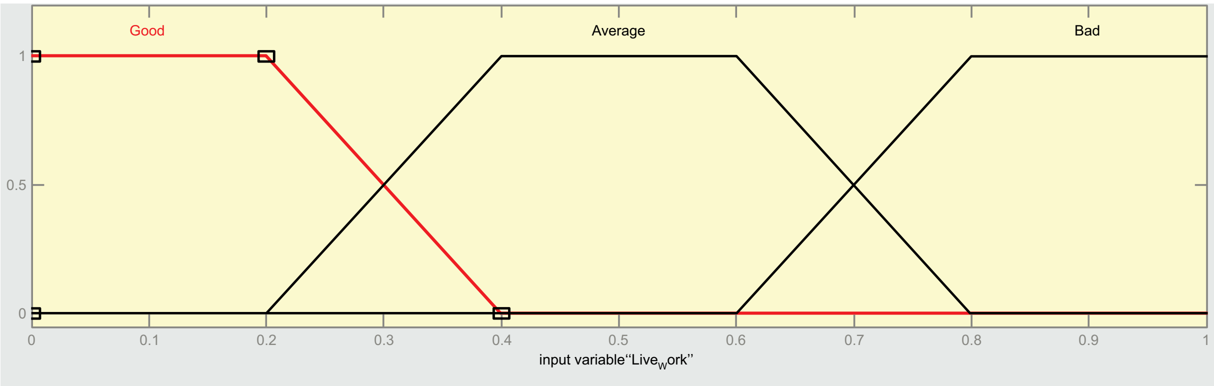


Fig. (6). Live Work function.

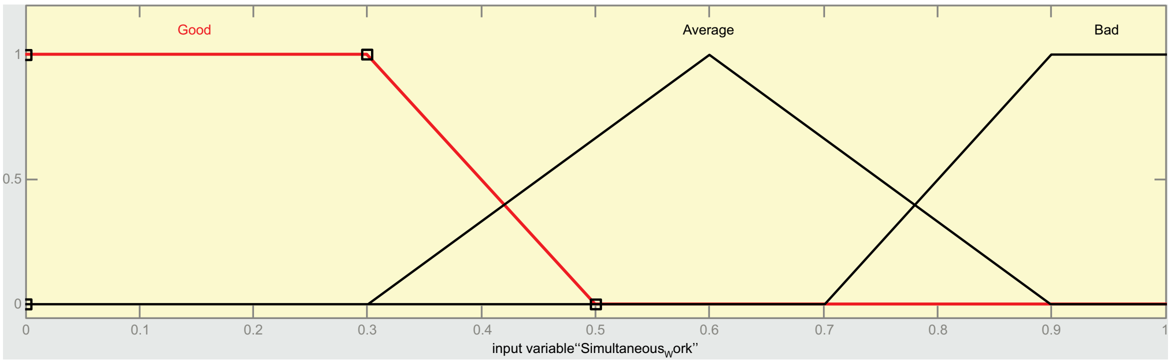


Fig. (7). Simultaneous work function.

4.1.3. Simultaneous Works (F3 - Fig. 8)

Given that works comprise various facilities, each with its own scheduled stops for maintenance, this situation results in frequent and repetitive stops, which leads to important disruptions in terms of provided services as well as unavailability during periods of peak electrical energy consumption.

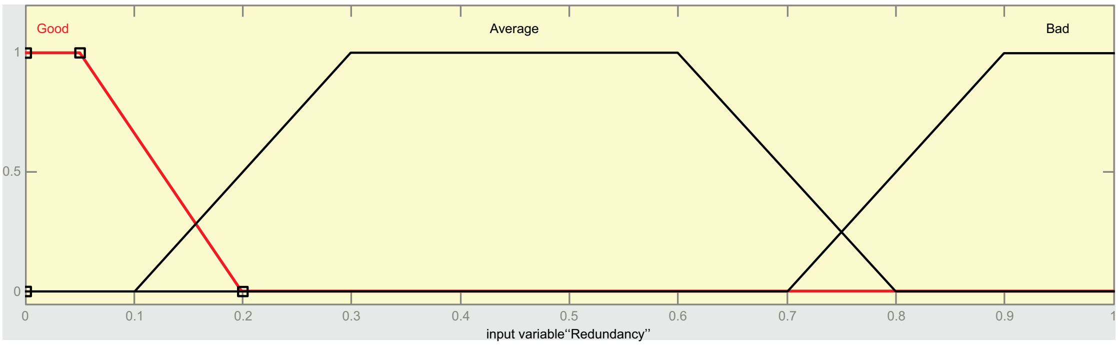


Fig. (8). Redundancy function.

In fact, in order to minimize the impact of the implementation and operation of two facilities on the overall availability of the system, LRSS model provides for a fusion of operation modes of the two facilities following specific rules.

The resulting costs are mainly those pertaining to accelerated depreciation of the performance and efficiency of facilities due to the delay in the execution of the operation modes recommended by manufacturers.

4.2. Output Function- (Fig. 9)

This function represents the analysis and decision making parameter, which will enable decision makers to decide on the technical and economic feasibility of the planned solution.

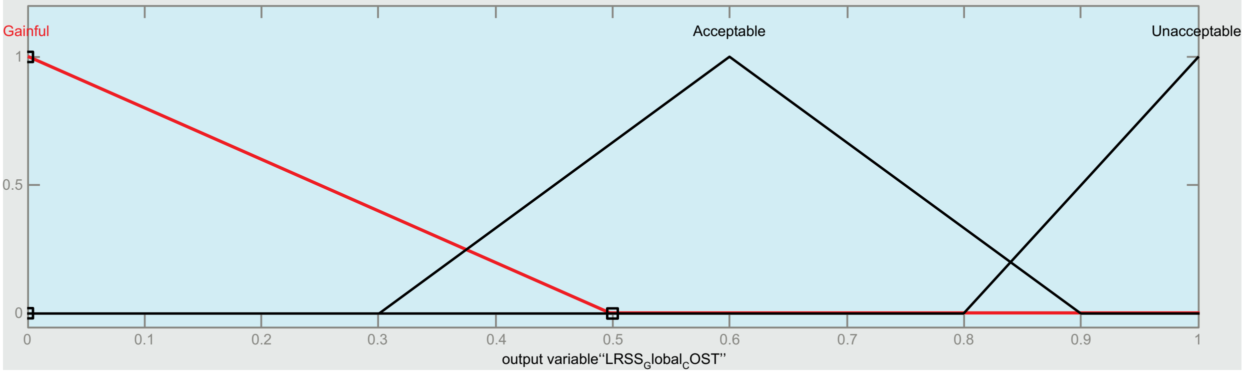
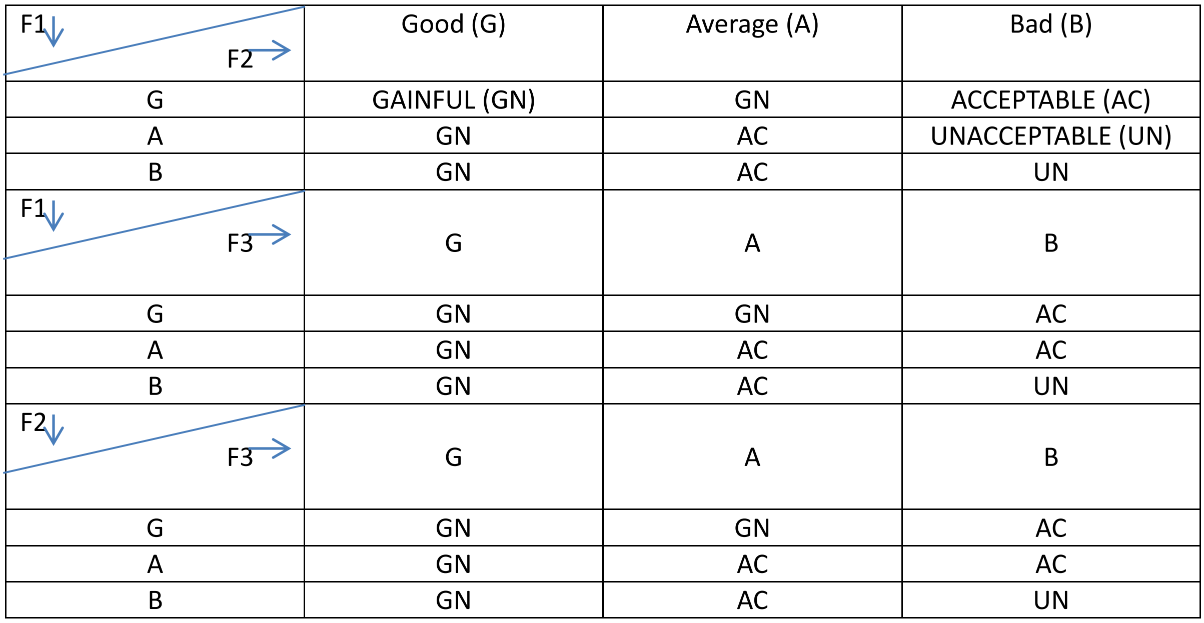


Fig. (9). LRSS Global cost function.

Further on in the present article, we will examine the mechanisms of assessing the risk of overall cost, which constitutes a strategic lever in our approach.

Below is the correlation table Fig. (**10**) of the rules assigned to the fuzzy subsets:

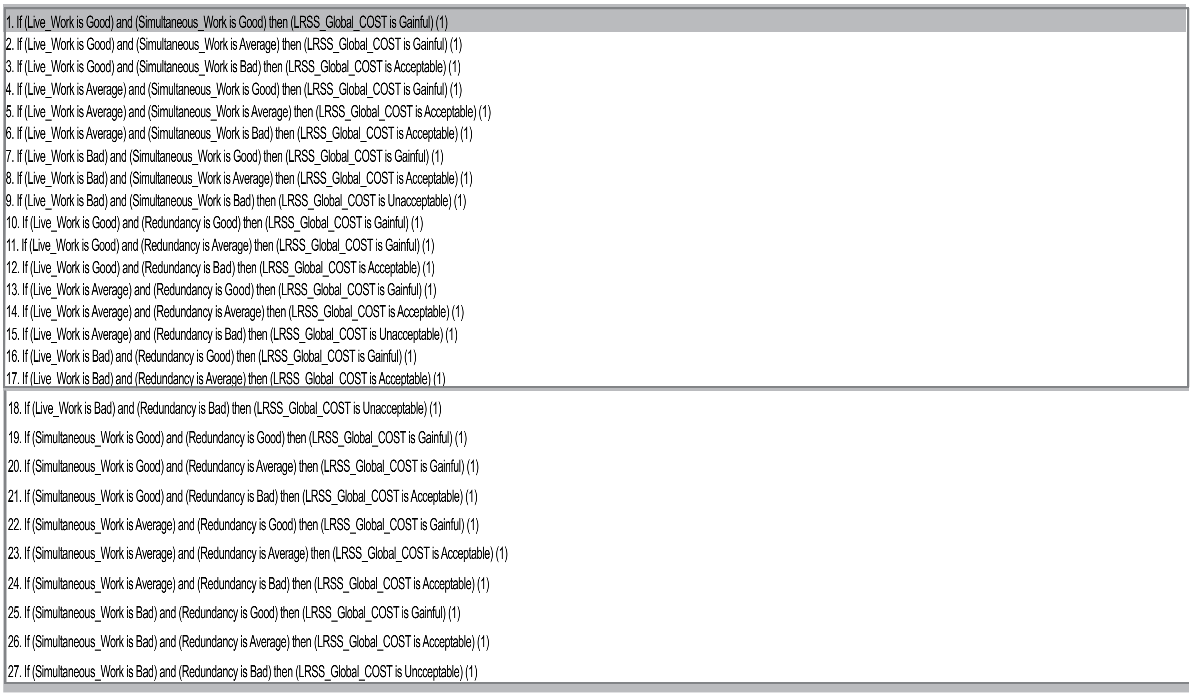


F1↓ F2→	Good (G)	Average (A)	Bad (B)
G	GAINFUL (GN)	GN	ACCEPTABLE (AC)
A	GN	AC	UNACCEPTABLE (UN)
B	GN	AC	UN
F1↓ F3→	G	A	B
G	GN	GN	AC
A	GN	AC	AC
B	GN	AC	UN
F2↓ F3→	G	A	B
G	GN	GN	AC
A	GN	AC	AC
B	GN	AC	UN

Fig. (10). Inference rules assigned to retained functions.

4.3. Membership Function

Inference rules derived from MATLAB IT software [8] package can be presented as follows (Fig. **11**):



1. If (Live_Work is Good) and (Simultaneous_Work is Good) then (LRSS_Global_COST is Gainful) (1)
2. If (Live_Work is Good) and (Simultaneous_Work is Average) then (LRSS_Global_COST is Gainful) (1)
3. If (Live_Work is Good) and (Simultaneous_Work is Bad) then (LRSS_Global_COST is Acceptable) (1)
4. If (Live_Work is Average) and (Simultaneous_Work is Good) then (LRSS_Global_COST is Gainful) (1)
5. If (Live_Work is Average) and (Simultaneous_Work is Average) then (LRSS_Global_COST is Acceptable) (1)
6. If (Live_Work is Average) and (Simultaneous_Work is Bad) then (LRSS_Global_COST is Acceptable) (1)
7. If (Live_Work is Bad) and (Simultaneous_Work is Good) then (LRSS_Global_COST is Gainful) (1)
8. If (Live_Work is Bad) and (Simultaneous_Work is Average) then (LRSS_Global_COST is Acceptable) (1)
9. If (Live_Work is Bad) and (Simultaneous_Work is Bad) then (LRSS_Global_COST is Unacceptable) (1)
10. If (Live_Work is Good) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
11. If (Live_Work is Good) and (Redundancy is Average) then (LRSS_Global_COST is Gainful) (1)
12. If (Live_Work is Good) and (Redundancy is Bad) then (LRSS_Global_COST is Acceptable) (1)
13. If (Live_Work is Average) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
14. If (Live_Work is Average) and (Redundancy is Average) then (LRSS_Global_COST is Acceptable) (1)
15. If (Live_Work is Average) and (Redundancy is Bad) then (LRSS_Global_COST is Unacceptable) (1)
16. If (Live_Work is Bad) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
17. If (Live_Work is Bad) and (Redundancy is Average) then (LRSS_Global_COST is Acceptable) (1)
18. If (Live_Work is Bad) and (Redundancy is Bad) then (LRSS_Global_COST is Unacceptable) (1)
19. If (Simultaneous_Work is Good) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
20. If (Simultaneous_Work is Good) and (Redundancy is Average) then (LRSS_Global_COST is Gainful) (1)
21. If (Simultaneous_Work is Good) and (Redundancy is Bad) then (LRSS_Global_COST is Acceptable) (1)
22. If (Simultaneous_Work is Average) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
23. If (Simultaneous_Work is Average) and (Redundancy is Average) then (LRSS_Global_COST is Acceptable) (1)
24. If (Simultaneous_Work is Average) and (Redundancy is Bad) then (LRSS_Global_COST is Acceptable) (1)
25. If (Simultaneous_Work is Bad) and (Redundancy is Good) then (LRSS_Global_COST is Gainful) (1)
26. If (Simultaneous_Work is Bad) and (Redundancy is Average) then (LRSS_Global_COST is Acceptable) (1)
27. If (Simultaneous_Work is Bad) and (Redundancy is Bad) then (LRSS_Global_COST is Unceptable) (1)

Fig. (11). List of rules by MATLAB.

5. RESULTS OF THE SIMULATION OF THE STUDIED SYSTEM

Following the modeling of the different functions and parameters in accordance with the principles of fuzzy logic and with the provisions of the software application employed, we have come up with the graphs of the studied variables correlation as well as their impact on the resulting parameter, namely LRSS's GLOBAL COST.

The graphs, which highlight this strong dependence and interaction between the three levers chosen at the beginning can be presented as follows (Fig. **12**).

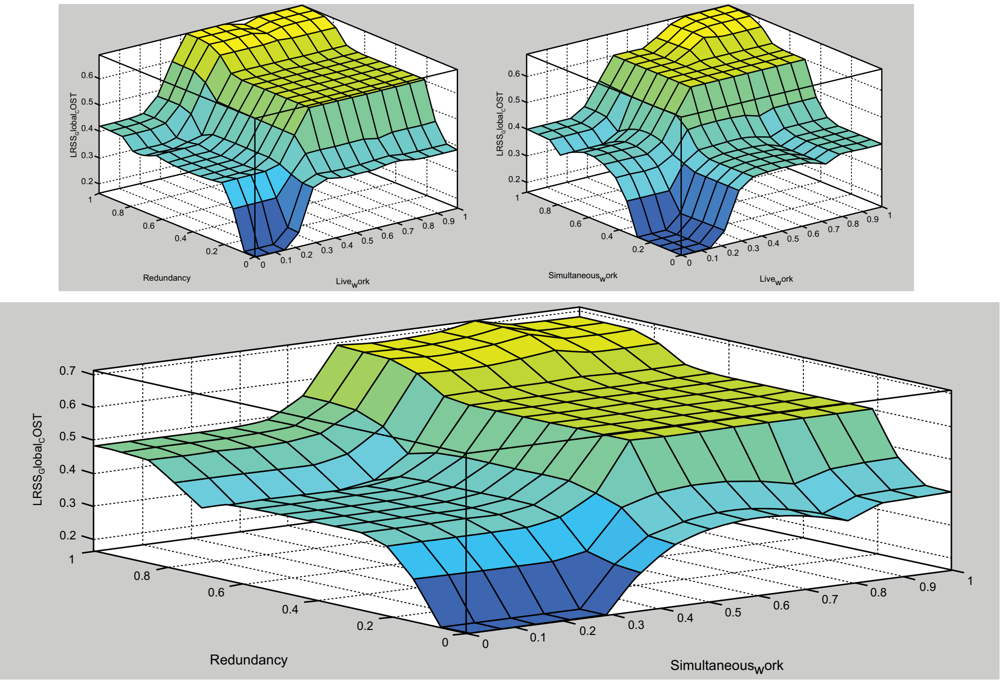


Fig. (12). Surface viewers.

It appears that this modeling constitutes a real tool box, including decision making support levers. In the diagram above, we notice that controlling the impact of the overall cost of the solutions implemented via LRSS model with regard to improving the system availability, at a value inferior to 50% (Fig. (**13**) hereafter), starts by observing maximum rates of input functions as follows:

- Live Work level: 30%
- Simultaneous Work: 77%
- Redundancy: 80%

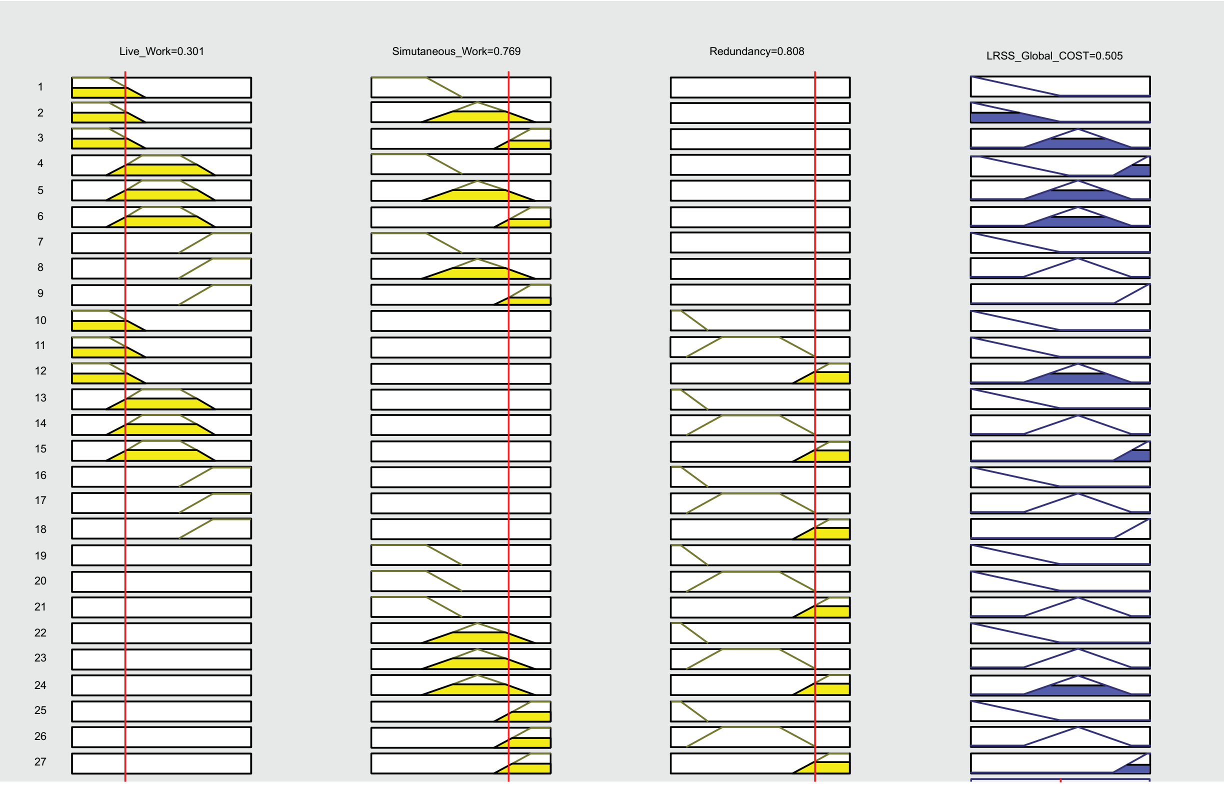


Fig. (13). Rules viewers (MATLAB).

Henceforth, these variables constitute input elements, of which the limit values should be in tune with the impact levels set by the management.

The main results of the simulations carried out, using this modelling via Matlab, can be summarized as follows:

Live Work Cost Impact	Simultaneous woks Cost Impact	Redundancy fonction Cost Impact	LRSS Global Cost Impact
0	0	0	0,16
1	0	0	0,16
0	0,5	0,5	0,38
0,5	0,5	0	0,38
1	1	0	0,38
0,5	0	0,5	0,4
0	1	0	0,4
0	0	1	0,4
1	0	1	0,48
0,5	0,5	0,5	0,6
0	1	1	0,68
1	1	1	0,94

It appears that the officer in charge of defining the new maintenance policy, based on the principle of our model, should consider the following results:

- maintenance operations, which exhibit weak cost stakes out of the three methods, can be undertaken using one or the other of these methods, without any particular preference. This should be done, at his request and based on available tools and resources.
- The impact of introducing these operational methods based on functional redundancy is very important in terms of overall cost irrespective of the cost of the merger of the operational modes (Simultaneity of operational modes).
- In case the three methods show a significant cost impact, the LRSS solution is not practical and is unjustified.

CONCLUSION

Face to the more and more constraining, uncertain and sometimes « surprising » operating conditions, which arise due to the higher demand for electricity and the increase in users' requirements, operators of the electricity distribution network seek to regularly use more advanced and up-to-date techniques, methods and procedures able to face these hazards and continue to run the facilities of the network safely and provide high quality service. In fact, application of part of the expert system concerning the evaluation of maintenance cost is shown in this paper as an example. The output of the expert system can be utilized as a basis for utility asset managers to make maintenance decisions, thus improving maintenance quality and overall availability. A fuzzy logic based technique has been presented for the identification and classification of cost impact of innovative maintenance method. The proposed technique requires considering the condition to choose or not to apply one of methods defined in LRSS Maintenance Model. The concept is applied in a knowledge-based expert system that converts maintenance cost into a more objective and useful representation of overall Cost. Resorting to concepts of fuzzy logic has made it possible to establish decision making criteria with regard to the choice of investment based on an exhaustive assessment of potential solutions.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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