A Generic Monte Carlo Simulation Algorithm For The Availability Prediction Of The Devices With Cold Stand-By Units

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***Abstract*—Simulation is a strong alternative of analytical methods in the area of reliability science. Availability prediction of devices within a defined period by Monte Carlo simulation is an application of the corresponding area. Devices that are connected parallel with their stand-by units are of concern as well. This study gives an outline of a method for generating a generic algorithm that enables the simulation of 'n' parallel devices. The new method is called LSLB (refers to the two main parameters used in the algorithm) method and the originality may be highlighted in twofold: firstly, it enables the engineer easily generate many scenarios for the stand-by device selection strategy when the operating device breaks down and secondly; it helps to generate a generic, short and comprehensible algorithm for the simulation of several devices. In the present paper, application of the method is exemplified to develop an algorithm for a parallel system in which no device has a priority as a main device and stand-alone operation of each device until a break down is considered as the case. Complete implementation in a MATLAB code is also achieved with 2 x 6 optional scenarios for device assignment strategy regarding to the potential difference in mechanical behavior of the devices.**

Keywords-stand-by; parallel; Monte Carlo simulation; generic; availability; LSLB method.

I. INTRODUCTION

Availability may be defined as measure of the ratio of operating time of the system to the sum of operating time of the system plus and down time [1]. There are analytical and Monte Carlo based simulation methods for prediction of availability. Each has some advantages but also shortcomings, some of which are common for both. There are also some suggestions to overcome those issues [1]. However, Monte Carlo simulation is reported to be more advantageous in complex systems availability analysis where some operational issues (different types of redundancy, different types of failure, preventive maintenance, start-up failure, switching, etc.) are taken account and where a flexible modeling algorithm is aimed [2-4]. It is also necessary to mention that the simulation results achieved by the Monte Carlo method are shown to be in accordance with the Markov Process calculations which may be considered as a more conventional method [2][3].

In simulation methods, the probabilistic prediction of the availability of a mechanic system is achieved by using random numbers generated from probabilistic distributions which are used to substitute operation time lengths (without any problem, i.e., full performance when operating) and repair time lengths. Probabilistic evaluation is needed since the failure time of a device is often random. When a limited time period is investigated in terms of a device's availability, device is expected to fail for some times and repaired for a new run. So, random numbers from an appropriate probability distribution are generated several times, until the limiting time is achieved.

There are some applications of the simulation method for availability prediction in the literature [2-4][6-7]. Cristina [2] simulated the operation of two parallel electro pumps that are simultaneously serving. Some availability and reliability indicators that are predicted is presented in the study. Held et al. [3] used a commercial software for simulating an optical network system in which 4 of the 5 units is working simultaneously. One of the most important aspects of that study is the sensitivity analysis held to understand the effect of variation in mean time to failure and repair time of each unit. Variations in the parameters of some units are reported to have significant effect on the overall reliability and availability while that of some units do not. It is also reported that sensitivity analysis would be valuable when there is limited data about the mechanic history of the simulated system [3]. Chowdhury et al. [4] simulated a back-up gas turbine system in which some of the turbines are simultaneously operating while some are waiting to supersede any failed turbine. Start-up probabilities of the units are taken into account and the objective of the study is reported as to determine the optimal number of gas turbines in order to satisfy the reliability criteria of the system.

 ISBN: 978-1-61208-234-9

Availability indicators are also presented in that study. Miao et al. [5] investigated a ring-standby structure in order to assess the corresponding reliability. Ring-standby structure is reported to be an important form of redundancy in which operating parallel units are linked to separate stand-by units, i.e., some units can supersede only some units [5]. Availability assessment is not included in that study.

When the devices (or a collection of devices, i.e., systems) have some stand-by units that are connected in parallel, using Monte Carlo simulation is not an easy process especially for the parallel systems that have more than two units. The more unit the more cumbersome is to think about 'if' and 'else' commands in programming. On the other hand, the computer codes such as MATLAB or FORTRAN do not work with real time. In programming art, time may be defined as time steps by the user but for a probabilistic simulation, in which the random times are generated iteratively if only the devices are operated, it is not so easy to think about the state of the devices. There is no means to put a clock on each device when programming with MATLAB (etc.). So; determining which device / or devices is under repair and which device / or devices is at stand-by state usually becomes a difficult task in parallel system's simulation. In addition, when an algorithm is generated for a defined number of devices, it is often hard to use the same algorithm for a different parallel system. A creative method seems to be necessary to think simple and simulate the parallel system in a comprehensible, controllable and short way. Any ability to develop a decision making structure for selecting the next device, when one another breaks down, would be a great chance. This paper will introduce the engineers such an algorithmic structure through the use of the LSLB method.

II. ABOUT THE MODEL

A. *Scope of the Simulation*

In the simulation of parallel systems that are built by parallel connection of stand-by units, there may be two main operational strategy in terms of a decision that whether any device will dominate the operation. Regarding to the economic and / or mechanical considerations, one of the devices may be assigned as a main device and all of other stand-by units are operated just to hold the system on when the main device is under repair. As soon as the main device is ready for operation, stand-by device does not wait until a breakdown and leave the task to the main device. In the second type of operational strategy, neither of the devices has a priority and all may operate as a stand-by unit. Additionally, every operating device runs until breakdown occurs. In both types of strategy, the operating device may do the task alone or with some stand-by units operating simultaneously. If the operation of the system is achieved by one device while the stand-by units are waiting in switch-off condition, that is defined as cold redundancy [3]. Alternatively, the stand-by units may support the system by simultaneously operating with the main device. That is defined as hot redundancy [3]. One more arrangement may be the warm redundancy, i.e. stand-by unit(s) are partly loaded and deteriorate so [3].

In the present study, the suggested method is outlined for the second type of strategy with cold redundancy. A parallel system in which only one device operates with no priority is simulated. It is important to mention that the algorithmic structure would be considerably different for the first type.

Preventive maintenance, logistics, fatigue, capital cost of the renewal and similar mechanic & economic considerations that would effect an availability work are not included in the study. Their inclusion would be definitely important for a strong availability assessment tool but the objective of this study is not to effectively simulate a mechanic system or make the optimum economical decision. Introducing the engineer with the generic use of LSLB (Length Short Length Big) method and its use for configuration of a decision making structure is aimed. However, it is expected by the authors that the integration may be easily welcomed by use of the LSLB algorithm.

B. *Main Assumptions*

Some assumptions and exclusions that would affect the algorithmic structure are given in this section. They are not only for simplification, but also for the definition of the system. Some of the following assumptions are common in the literature for similar studies [2-5] and it is reported that many of them are in accordance with the practical considerations [3].

- Failures are considered to occur randomly.
- Only one device runs the parallel system.
- Any fail of any component inside the units lead to breakdown of the unit. So 'breakdown' word refers to the fail of units in the parallel system.
- Units are independent and none of the failures effect or agitate the other.
- Devices start to operate with no delay when assigned. It is assumed that there would be a perfect switching.
- Failures are considered not to change the mechanical behavior of the device. In other words, history has not an influence on the mechanical behavior. That is one of the stand-points to the use of exponential distribution for random number generation.
- For all devices; a repair period starts instantaneously after the breakdown of the device.
- The simulation does not deal with any system having interaction between the simulated system and by so continuous operation of the simulated system is considered.
- Decision making procedures for stand-by device assignment are managed by the user of the code and decisions are not optimization based in terms of cost minimization.

It is necessary to add that the above assumptions should be revised if some additional mechanic data are desired to be included in the simulation, when the system is considered to be shut down periodically (or randomly) for a preventive

 ISBN: 978-1-61208-234-9

maintenance, imperfect switching has a possibility, start-up failure of the unit has a possibility, a repaired unit is not as good as new, fail word does not mean complete breakdown of the unit, any fail of one unit (or a system connected in series with the parallel system) significantly effects the failure characteristics of others, repair of the failed unit can't be achieved without interrupting the system's operation, etc...

On the other hand, some mechanical considerations may be easily taken into account by adjusting the utilized distribution functions. There would be no need for algorithmic modifications; for example, if the preventive maintenance is done without interrupting the system, the fair effect of preventive maintenance may be taken into account in the distribution function of mean time to failure. However, the mean value would be increased if the preventive maintenance is added to the simulation. Any reasons for delay in repair procedures may be handled in a similar manner.

C. Methodology

The availability prediction is achieved by simulating the trouble-free operation time (MTTF-mean time to failure) and repair time. Since the corresponding time periods show a random behavior, appropriate probability distribution functions are utilized to represent the probabilistic behavior of operation and repair. That approach refers to the 'event simulation' by Monte Carlo method. MATLAB programming is used for complete implementation of the method in a user-friendly computer code.

In the study, it is assumed that the probabilistic distribution of the trouble-free operation and repair times are fairly matched with exponential distribution under some assumptions. That is also in accordance with the literature [2][4][8]. Exponential distribution is adjusted by the mean time data supplied by the site engineer and random numbers generated from that distribution stand for the corresponding times. Each device has it's own characteristic exponential distribution. It is possible to use a inverse-transform method for generating random numbers from the exponential distribution [2][9]. However, considering the ease of use, MATLAB function 'exprnd' is utilized in the study. In addition, it is necessary to mention that the algorithm is not distribution dependent. The user of the method can easily utilize another kind of a distribution, if necessary.

Generating one random number means that the device has operated once until a breakdown. Then, the device assignment algorithm assigns an appropriate stand-by device according to the strategy made at the beginning of the simulation. Concurrently, a random number is generated as well to represent the repair time of the failed device.

This sequential procedure is carried out until the limiting time for the simulation period is lasted. Then the availability is calculated. However, it is necessary to repeat the procedure *'m'* times to obtain the mean value in terms of availability. The resulting average is regarded as the predicted availability.

D. Essence of the LSLB Method

The essence of the LSLB method lies in the creation of the following parameters ;

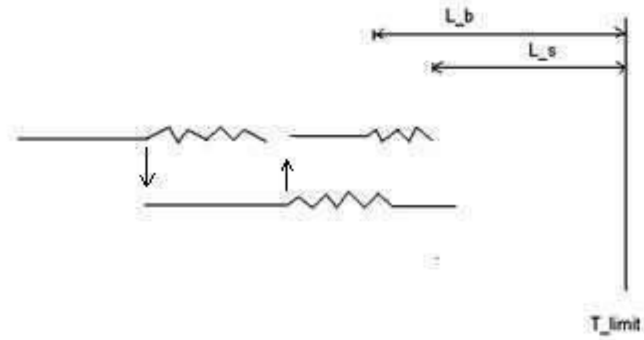

Figure 1. The main parameters used in the LSLB method

Figure 1 is schemed for any time period within the simulation time. The solid lines refer to the operation of a device while the zig-zags for repair. The direction of the rows shows the newly assigned stand-by device. As mentioned before, only one device is running the parallel system. *t_limit* is the overall time period in which the availability prediction is of concern. *L_b* refers to the big length and *L_s* refers to the small length. Sampling for each operation and repair period assigns a new *L_s* and *L_b* value to the corresponding device.

Nature of the method necessitates the iterative definition of the values for *L_s* and *L_b*. If the operating device fails, the decision making structure (see Section II.F) looks for an appropriate device to continue the run and when a device is assigned; *L_s* and *L_b* of that device is updated. The key point is to relate *L_b* and *L_s* of the assigned device with the parameters of the previously operated device; *L_s* of the newly assigned device is defined by using the *L_b* of the lastly operated device. Then by means of the *'q'* index, *L_b* of the operating device is defined.

The index *'i'* refers to the assigned operating device while the index *'q'* is used both for the previously operated device and the newly assigned device such that; just before the new assignment, *'q'* refers to the last operation which is ended by the fail of the device. If a new *'i'* is assigned, that means a stand-by device which have the i^{th} position on the assembly platform is switched-on. Subsequently, *L_s (i)* is defined by using the *L_b (q)*. Then, *q* is increased by one ($q=q+1$) and the *L_b* of the operating device is defined. *L_b* is always indexed as *L_b (q)* and never linked with the index *'i'*. *L_b* is a continuosly growing vector by the sequential increase of the *'q'*. As a result, the last *'q'* value reached at the end of the simulation shows; how many times the stand-by device assignment has been done. In addition, since the assignments are done when a fail occurs, *L_b(q)* is used for the determination of the fail time and fail period, if the fail occurs as a parallel system fail. On the other hand, it is necessary to emphasize that *L_s* parameter of any device is not associated with the previous *L_s* of that device. *L_b (q)* is used for the calculation of the new *L_s (i)* so; *L_s* history of a device is meaningless. However the last values of the *L_s* parameters of each device is used to make 'system_fail' or 'system_on' decision. MATLAB saves the current *L_s* values in a vector (with *n* -total number of devices-elements). New value of the *L_s (i)* changes the i^{th} element of the *L_s* vector inherently. By means of the *'i'* index, vector *'D'* (1xn) is updated too. This vector contains the data of how many times each device is assigned. That data may be valuable when the wearing of the devices is important or when the repair costs are different for the devices.

In the method, 'fail' or 'on' decision is structured on the following basis;

System_fail decision: if the *L_b* of the operating device is larger than all of the other's *L_s*, then the parallel system fails.

System_on decision: if there is any *L_s* bigger than the operating device's *L_b*, then it means that there is a device which is not under repair and ready for operation. The algorithm assigns that device for operation.

E. Structure of the Algorithm

The structure of the simulation algorithm may be summarized in five main categories ;

- Determination of the system, strategy making for the stand-by device assignment and the data input for the average mechanic behavior of the devices
- Generation of the random times (repair time etc.)
- Assessment structure for the 'sytem_fail' or 'sytem_on' decision.
- Repetition of the simulation for *'m'* times
- Processing of the simulation outputs

The whole algorithmic structure is explicitly schemed in the Figure 2.

F. Decision Making Modes for Device Assignment

In both cases (system_fail or not) the decision making structure has some different modes to make the assignment. They are generated by the authors of the present paper. It has been considered that their inclusion would be valuable when the mechanistic research in terms of stand-by device selection is being interested.

The (2 x 6) operating modes that are allowed for user choice in the algorithm :

Modes for system_fail;

1 When the system fails, the rule is to assign the appropriate device that will run the system as soon as possible but; if the number of the closest device is bigger than one, then the least assigned device (least weared) so far is selected. If that number is also not unique, any device among the corresponding ones is assigned randomly.

2 If the number of the closest device is bigger than one, any device among them is assigned randomly.

Modes for system_on;

1 The device that has the max value of actual *L_k* vector is assigned to continue the run of the system. If there is more than one device that has the *max (L_k)*, then the device that has the minimum index number is assigned (MATLAB default function for 'max' evaluation selects the first element in a vector if there is more than one maximum).

There is no mechanical meaning of this mode. It is only for the simplification of the algorithmic structure. However, after a sensitivity analysis, if it is seen that the other modes do not significantly favor the availability, it is unnecessary to punish the computer. Case-based further discussion may be necessary to decide about a decision making strategy for a parallel system's control loop in terms of simplification.

2 Among the selectable devices; assignment is done in a sequence following the index numbers (position on the assembly platform) of the devices. For instance; if the failed device is the second device, the assignment algorithm looks for the availability of the third device and then the fourth device if the third is not available. The sequence proceeds as a cycle of the index numbers.

3 Among the selectable devices; the one that has the maximum mean operating time (trouble-free) is assigned. If there is more than one device that has the same mean, any of them is assigned randomly. Random number generator of the MATLAB from a discrete uniform distribution is used for random assignment throughout the study.

That mode is considered to be more meaningful when there is a periodic maintenance procedure included in the study.

4 Among the selectable devices; the one that has the minimum mean repair time is assigned. If there is more than one device that has the same mean, any of them is assigned randomly

5 Among the selectable devices; the least assigned device is selected for operation. If there is more than one device that served in equal number of times, any one among them is assigned randomly.

In the algorithm, the least assignment refers to the counted assignment number thus far, not associated with the total operation time of that device.

6 Among the selectable devices; any of them is assigned randomly.

That mode is generated just for a comparison with the others. The results of that kind of randomness may be interesting for any researcher.

III. ABOUT THE COMPUTER CODE

All of the work in this study has been held by complete implementation of the algorithm to a MATLAB script. Considering the use of the code by the beginners of reliability science, the interface of the code was tried to be constructed user-friendly. The inputs of the code only necessitates the determination of the simulation period, number of the stand-by devices and their average mechanic data that are expected to be supplied by the site engineer. Since the investigation of device assignment strategy may be the most advantageous utilization area of the suggested

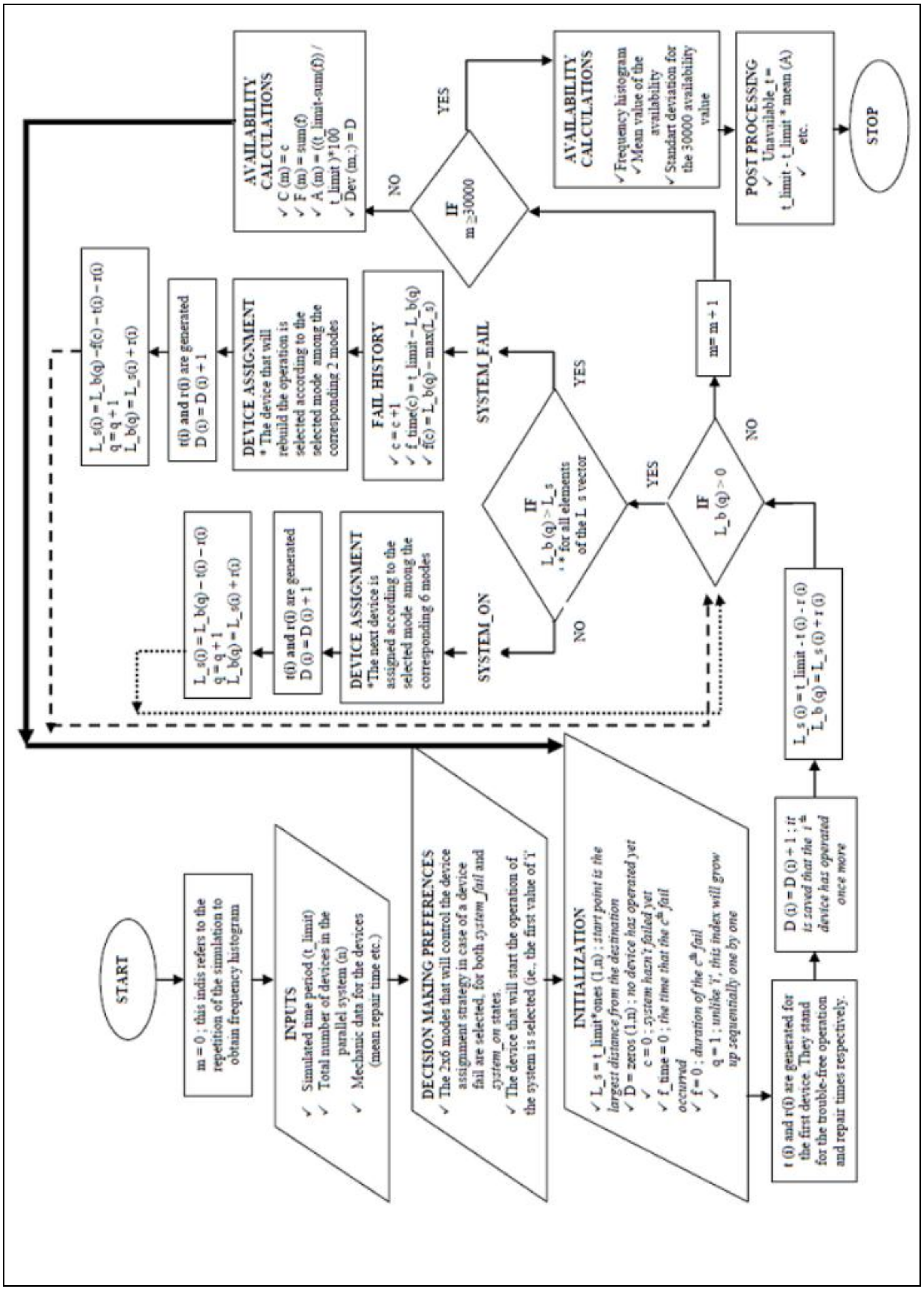

Figure 2. Flowchart of the LSLB based algorithm

algorithm, a decision menu is constructed as a button–type menu inside the code. For each simulation, at the beginning, the user can easily select any strategy for device assignment. Additionally, the code saves all the history within a simulation period. All the operational information (simulated) of a device and the system may be called by the user. For example, at each iteration (m), the system_fail times and their lengths, total time of the system_fails, how many times each device is assigned and the availability calculated are saved. That ability of the code is expected to be helpful when a modification for a further study is necessary.

IV. VERIFICATION OF THE MODEL

The consistency of the algorithm is verified through the simulation of a non-identical two-device cold redundant parallel system. However, prior to the discussion of the verification procedure it is important to highlight some key points about the model;

- In MATLAB, the default random number generator from exponential distribution requires the mean value of the distribution. That parameter is entered as hour based data in the model. That is in accordance with the simulation period which is entered as year data and converted to hour data by the code. One year is considered to be 8766 hours.
- The computer code calls for the mean and generates a distribution function. Then any number from that distribution is introduced as a random number to the simulation. So, mean time for trouble-free operation and mean time for repair are entered to the code to adjust the exponential distribution functions.
- The default uniform number generator of the MATLAB has been compared to the 'twister' algorithm which is also already implemented in MATLAB. A noticeable difference has not been observed.

Mechanic behavior of the devices are considered to not change within the present verification procedure as well as the presented base algorithm in this study. That is no wearing and the resulting variations in probability distribution functions or obsolescence of the device is considered during the simulation. So, selection of the first mode (i.e. if the number of the closest device is bigger than one, least assigned device is selected) in case of a system fail would not have a meaningful result in terms of a mechanistic investigation. If there are more than two stand-by devices, the first mode would randomly result in different availability values according to the device assigned. That is because the characteristics of the devices may be different. However, this randomness corresponds to the second mode as well. In other words, the first and the second mode of the 'system_fail' decision making algorithm become same when wearing effect is not considered in mechanistic investigation.

The six modes for the 'system_on' state would also show no difference in the results in a two-device cold redundant parallel system simulation. That is because; when there are two devices (and if the system is on) the algorithm looks for the available device which is always the other.

Consequently, 1x6 modes are held for the verification procedure which are expected to give the same results for two-device parallel system. No unexpected results have been arised. Same availability is achieved in all of the 6 modes. The two devices of the system are not necessarily identical. This result reveals that the algorithmic structure has no bugs and the model behaves as expected.

Simulation is traditionally repeated *'m'* times to obtain frequency histogram and mean value of the investigated parameter (s). The number that the simulation do not give significantly different outputs is considered to be the appropriate value of *'m'*, i.e. 30000 in this study. This number is not only determined for the two-device system but also for some other cold redundant parallel configurations with more devices. In the literature, some similar *'m'* values may be seen ; 10000 [2], 100000 [3], 30000[4], 10000 [5].

The execution of *'m'* iteration in the developed algorithm lasts only in a few minutes. That may be regarded as an advantageous property in complex system simulation.

V. CONCLUSION

An availability prediction tool for parallel systems is outlined through the use of new LSLB method in the paper. Introducing the engineers with the abilities of this new method is aimed. The suggested method enables the engineer simulate the systems with *'n'* stand-by units operating in cold redundancy state. Although the present simulation has been held under some assumptions, the decision making algorithm for device assignment is constructed in a generic manner and considers many scenerios as if more mechanistic investigation is of concern. The suggested algorithm may be a framework for future mechanistic / economic studies and some modifications on the algorithm may be easily done in LSLB method. As mentioned in the previous sections, the assumptions that simplify the simulation are not restrictive for a potential modification since the logic of the simulation does not rely on specific kinds of probability distribution functions or some functional interactions between the units. All the decisions are stemmed from a kind of geometric parameterization. Decision making algorithm which is consist of 2x6 modes is compatible with any further modifications in order to include more mechanic knowledge to the simulation. However, the presented version of the algorithmic structure is already appropriate for many practical cases.

The ability that is not only saving the operational history of the device but also of the system is one of the main advantages of the method for future mechanistic research. Short simulation times are advantageous in complex system simulation. Additionally, understanding the random behavior of the parallel systems (that may be considered as a common advantage of the simulation based prediction tools) and the ease of investigating device assignment strategy in automatical control loops may be valuable for the researchers.

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