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NEW APPROACH FOR THE JOINT OPTIMIZATION OF THE DESIGN AND MAINTENANCE OF MULTI-COMPONENT SYSTEMS BY INTEGRATION OF LIFE CYCLE COSTS

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ABSTRACT

This work presents a methodology for simultaneous design and maintenance optimization which objective's the minimization of the life cycle cost. This methodology helps designers to optimize the design of complex industrial systems (multi-component systems) based on the minimization of the life cycle cost (LCC). The research contribution comes from integrating two optimization tasks which traditionally are carried out in separate ways. In fact, during the design phase, the system architecture is usually optimized by neglecting maintenance expenses. While during the operational phase the system architecture is already finalized and maintenance optimization approaches allow only determining a minimum maintenance cost. In this work, design optimization refers to the optimization of reliability and maintainability characteristics. There are two approaches for optimizing reliability. The first one considers component reliability as a decision variable, and its cost is considered as a predetermined increasing function of component reliability. The second approach aspires to determine the type and number of redundant components of each subsystem. On top of that, there are two approaches for maintainability. The first one considers component accessibility as a decision variable, and its cost is considered as a predetermined increasing function of component accessibility. While, the second approach focuses more on the monitoring architecture. In addition, the maintenance optimization is able to optimally and automatically select what maintenance actions are applied, when they are applied, and to which structural components they are applied, so that the system can perform these missions with the required confidence level.

Keywords: reliability, maintainability, maintenance, early design phase, life cycle cost (LCC), complex industrial systems (multi-component systems).

INTRODUCTION

Nowadays, the new industrial systems present in the market are becoming increasingly complex. This complexity is due to the diversity of technologies used in the components, which once assembled constitute the final product (Menye, 2009). At the end, we will have high-tech products, which will require reliability and/or availability, security and performance. Obtaining a reliable system operating during its life cycle is an important subject that has aroused the interest of many authors. Two general approaches can be followed to ensure the system correct operation during its life cycle (Imam, 2015). The first approach is to improve these characteristics of reliability and maintainability. In this case, the system requires little maintenance over its entire lifetime. At the end, the development costs must be very important and the maintenance costs will eventually be optimized. However, the second approach prioritizing saving on design costs. In sum, the maintenance costs are not going to be optimized.

Nowadays, customers are not only affected by the intrinsic performance of a system, but they are also increasingly concerned by its sustainability and its associated services (Lesobre, 2013). To meet these expectations and customer's needs, companies that manufacture these systems, are moving from mass product to product/services sales (Rawat, 2016) (Keller, 2003). In this context, they not only propose to their customers to pay for the system itself but also for its use. Hence it is the companies' responsibilities to ensure that the system they are producing its functions for a contractual period (de Almeida, 2012). To implement these new services offers, a paradigm shift is needed during the design stages. In fact, it is no longer about minimization of manufacturing costs but the whole costs throughout the life cycle of the system must be considered (Dhillon, 2006). This involves rethinking the positioning of maintenance issues from the design stage. In this context, design for maintenance seems an opportunity to realize profits for manufacturers and customers, in order to create a win-win situation for both (Markeset, 2003a).

In this context, a new methodology for simultaneous design and maintenance optimization which objective's the minimization of the life cycle cost is proposed. This methodology aims to provide a decision support tool to help the designer in the design process to find the best configuration that has the minimum LCC. In this work, design optimization refers to the optimization of reliability and maintainability characteristics. There are two approaches for optimizing reliability. The first one considers component reliability as a decision variable, and its cost is considered as a predetermined increasing function of component reliability. The second approach aspires to determine the type and number of redundant components of each subsystem. On top of that, there are two approaches for maintainability. The first one considers component accessibility as a decision variable, and its cost is considered as a predetermined increasing function of component accessibility. While, the second approach focuses more on the monitoring architecture. In addition, the maintenance optimization is able to optimally and automatically select what maintenance actions are applied, when they are applied, and to which structural components they are applied, so that the system can perform these missions with the required confidence level.

The rest of the article is structured as follows. In the second section, a review of the literature on optimizing maintenance methods and design methods for maintenance are presented, as well as, the originality and distinction of this work. The third section specifies the proposed methodology. This methodology is based on three main steps. In the first and second ones an algorithm is developed under MATLAB, to build a maintenance plan under reliability constraints for a given mission duration. While, in the third step, a Monte Carlo simulation is used to model the behavior of the operating system in terms of failure. The fourth section presents a numerical example illustrating the methodology on a given multi-component system. The results obtained in the fifth section will allow us to evaluate the consistency of the methodology. Finally, the last section is devoted to the conclusions and suggestions for future researches.

LITERATURE REVIEW

Although research on maintenance issues has seen significant advances in recent decades, maintenance still has a negative image. It is often associated only with failures encountered by the system. If we now consider the role of maintenance from a perspective of managing the system during its life cycle, this image changes radically (Takata, 2004). The development of efficient maintenance allows the company that offers the service to make profits and its customers to benefit a quality service (Rawat, 2016) (Markeset, 2003a) (Markeset, 2003b) (Markeset, 2005). We pass from an activity that is perceived as a cost center to a profitable activity.

Traditionally, the field of maintenance is limited to the operational phase. This phase includes planning, diagnosis and implementation of maintenance operations (Chang, 2013) (Imam, 2012). In order to determine optimal inspection dates (Zhao, 2012), the dates of preventive replacements (Zhang, 2002), which are policies that reduce maintenance and production costs and increase reliability, others studies are carried out to determine the optimum ages of components at replacement time, optimal replacement times (Shafiee, 2013), intervals between replacements, determination of the preventive maintenance actions to be performed during an intervention. This means that in most cases systems are already involved in the operational phase of their life cycle. Failures may have already occurred or should occur (Dhillon, 2006). Nevertheless, in order to consider a significant reduction in the operating cost of the system, the optimization of the maintenance policy alone is not enough. It is in fact essential to carry out a wider reflection associating the system and its maintenance from the design stage (Markeset, 2005).

On the basis of available literature reviews, there are several publications in which design methods for maintenance are discussed, some are interested in the reliability/availability characteristics of the system: (Long, 2009), (Moghaddam, 2011), (Certa, 2011), (de Castro, 2003), (Juang, 2008), (Atashgar, 2016), while, others focuses more on the maintainability characteristic (Wani, 1999) (Chen, 2003) (Nishijima, 2009). The goal is to maximize or minimize certain objectives under certain constraints such as, costs, reliability, availability, maintenance time, weight, etc.. According to A.T. de Almeida and all, 68.3% of the work under this research thematic aims to minimize the cost, 37.6 to maximize reliability, 17.2 to maximize availability, 11.8 to minimize maintenance time and 15.7 for the others objectives (de Almeida, 2015).

Two general approaches can be followed to increase the system reliability through increasing the component reliability or by adding redundant components (Zoulfaghari, 2014). The first approach is called reliability optimization. It considers component reliability as a decision variable; and its cost, weight and other characteristics are considered as predetermined increasing functions of component reliability (Zeinal Hamadani, 2013). The aim of this first approach is to find the appropriate values of these variables (Beaurepaire, 2012). The second approach is variously called redundancy optimization, redundancy allocation or reliability redundancy allocation problem (Ebrahimipour, 2011). In this second approach, it is assumed that the characteristics of each component such as reliability, weight, cost, etc. are predetermined and the goal is to determine the type and number of components that should be applied in each subsystem. In most cases, the goal of optimizing redundancy is to maximize reliability (Nourelfath, 2007), (Okasha, 2009), (Torres-Echeverría, 2012).

In addition, analyzes to improve maintainability characteristics have received increasing attention in recent years reliability (Z Tian, 2011), (Olde Keizer, 2016), (Mulder, 2013). This analyzes tries to determine the optimal time to perform maintenance, as well as, improve accessibility to failed components. The purpose of these analyzes is to optimize the time to restore the system functioning. Improving accessibility means determining the system optimal dimensions and these components to make certain components more accessible (Chen, 2003), (Luo, 2014). An accessibility gain reduces the replacement time of the part in question and thus reduces the downtime of the system. In return, the various design efforts to make a component more accessible lead to increase the component cost.

Thus, with the development of advanced sensors and information technology, many studies show the added value of using these systems to determine the optimal moment to perform maintenance (Lesobre, 2014). These systems make it possible to optimize the decision process by monitoring the system state health and these components. Nevertheless, the evaluation of the benefits obtained between, the maintenance effort, and the design expenditures for the implementation of these systems for access to surveillance information, is not sufficiently taken into consideration in maintenance optimization studies.

It is clear from the literature review above that all of the design solutions proposed above must be validated by a cost analysis over the system life cycle. All the difficulty lies in finding a best compromise between improving system reliability and maintainability characteristics and gains in life cycle costs. To our knowledge, no research has been performed no general method, which takes into account the simultaneous design and maintenance optimization through the integration of life cycle cost. Design optimization refers to the reliability (reliability and redundancy) and maintainability (monitoring information and accessibility) optimization. In the following section we propose a design method for maintenance that allows to overcoming this limit.

METHOD

The developed methodology is based on an iterative process to optimize the design of a multi-component system at each iteration. The goal of these iterations is to reduce overall life cycle costs. The feedback loop makes it possible to modify the design parameters in order to find the balance to be sought. Figure1 illustrates the different steps of the proposed methodology. The first step allows the system reliability modeling, thus the components reliability laws, the links between these components and their properties are introduced. In the second step, a maintenance strategy optimal to be applied to the system is developed. The third step, using Monte Carlo simulation and by adding randomly generated faults, the system life cycle cost is evaluated.

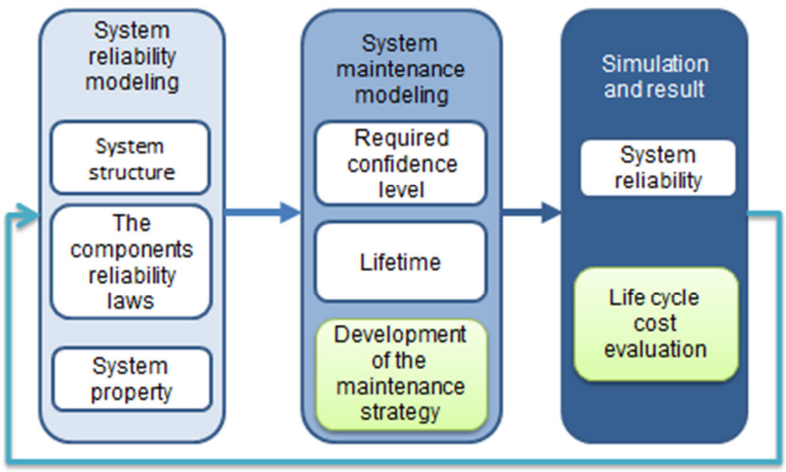

Fig.1 - New approach to design optimization

A. System Reliability Modeling

In practice, the dates of preventive maintenance for industrial systems are well-planned, because high operational availability is required and the breakdown of the system generates high immobilization costs. And, the user of these systems requires the autonomy of their systems over given periods of operations. The period between maintenance shutdowns is called mission, or MFOP (Maintenance Free Operating Period) (Lesobre, 2014). The system reliability assessment during its mission means the compilation of conditional reliability that the system survives for the duration of the MFOP of length t_{MFOP} units of time, knowing that it was in an operating state at the beginning of period t. This conditional probability called Maintenance Free Operating Period Survivability (MFOPS) is given by (Kumar, 1999):

$$MFOPS(t)_{sys}=\frac{R(t+tMFOP)_{sys}}{R(t)_{sys}}$$

Where $R(t)_{sys}$ is the system reliability at time t.

The equation of component reliability is given by equation (1), and the equation (2) represents the whole system reliability according to its structure (series, parallel, series- Parallel, parallel-series ...).

$$\mathrm{Ri(t)} = \int_0^t \exp(\lambda i(\tau))\, d\tau) \qquad (1)$$

$$R(t)_{sys}=1-\prod_{k=1}^{k}(1-\prod_{Ek=1}^{Ek}[1-Ri(t)]) \text{ Système en série-parallèle} \qquad (2)$$

λi (t): Failure rate.

$R_i(t)$: Reliability of component i.

$R(t)_{sys}$: Reliability of the system.

t: time.

k: number of subsystems in series.

Ek: the number of parallel components in the kth subsystem in series.

B. System Maintenance Modeling

To maintain the system and these components in operational condition, a maintenance strategy must be developed. The maintenance strategy contains the human and material resources to implement to achieve the required performance in the requirements specification (the required confidence levels, the operating time, the MFOP, etc.) (Guo, 2016).

In this work, basing ourselves on the work of Lesobre (2015), a maintenance policy based on the MFOP concept is introduced. This policy aims to ensure the proper functioning of a multi-component system over a given period, within a specified level of confidence. To do this, it evaluates, at the end of each operational period, the need to maintain the system. If the maintenance intervention is deemed indispensable, the policy selects the operations to be performed. As well, this policy is dynamic. This means that the maintenance decision is adapted according to the monitoring information available online.

To achieve requirements specification with the optimal maintenance cost, the maintenance policy needs to be optimized. The optimization of the maintenance policy consists in identifying the components to be replaced so that the system can perform their missions with the required confidence level. In fact, at each failure or if MFFPS is estimated below the specified confidence level, a maintenance operation must be performed on one or more components of the system. In this case, the problem can be formulated mathematically as follows:

$$\text{MIN } \sum_{i=1}^{n} X_i \quad C_i \qquad \text{S.t} \qquad \text{MFOPS (t)} > \text{NC} \tag{3}$$

Where n is the number of system components, X_i is a binary variable which indicates the maintenance operation on the component i, C_i is the operation cost (labour + spare part cost) of component i and NC is the specified confidence level.

To solve the previously mentioned problem, we have developed an algorithm under MATLAB. This algorithm determines the actions to be performed, based on three parameters (the MFOP, the confidence level and the state of the components). The sequence of these maintenance actions is established in a way that provides the best compromise (Reliability/Costs). The order of the actions in the list is important to ensure better confidence level and to ensure mission (MFOP).

C. Simulation

According to Roda (2014), maintenance costs, is neither static nor easily quantifiable (in contrast to the costs for acquisition or installation) but rather highly dynamic and depend on the actual failure behavior of a system and its components. Against this background, dynamic tools for an ex-ante estimation are a promising way to predict LCC under the given circumstances (Thiede, 2012).

Based on the properties of the system and the maintenance model, defined in the previous subparts, Numerical simulations based on the Monte Carlo method are implemented to evaluate the total costs. These simulations are performed by considering a required confidence level by the system during its operation, with its structure and the reliability properties of these components.

A Monte Carlo simulation provides an overall idea about system behavior at the number of the possible failures during their useful life (Imam, 2015). In addition, the Monte Carlo simulation method can also help in assessing the uncertainty in the data and the statistical sensitivity in the model (Fleischer, 2007). The longer simulation the more the results look likes the real life of the system (Imam, 2015).

Let us now look at the life cycle cost estimate $LCC(t)_{sys}$. The life cycle cost is detailed as follows:

$$LCC(t)_{sys} = C_I + C_{TM}(t) \tag{4}$$

Where C_I is the initial cost of the system and $C_{TM}(t)$ the total maintenance cost of the system over the mission duration [0, t]. The $C_{TM}(t)$ is expressed as:

$$C_{TM}(t) = C_{prv}(t) + C_{cor}(t) + C_{acor}(t) \tag{5}$$

Where $C_{prv}(t)$ is the preventive replacement cost of system components on [0, t], $C_{cor}(t)$ is the corrective replacement cost of failed components on [0, t], and $C_{acor}(t)$ is the additional cost related to the loss of production when the system is down (corrective replacement) on [0, t]. Let us now detail the expression of each of these costs.

The $C_{prv}(t)$ can be defined as:

$$C_{prv}(t) = \sum_{i=1}^{n} (C_i + D_i * \tau_I) * N_{i,prv} + C_{log,prv} * NMS_{prv} \tag{6}$$

Where n is the number of system components, C_i is the spare part cost of component i, D_i is the replacement duration of component in hour, τ_l is the hourly rate of labor, $N_{i,prv}$ is the number of replacements of component i during a system preventive stop on [0, t], $C_{log,prv}$ is the logistics cost and NMS_{prv} is the total number of the system's preventive maintenance stop.

Then the $C_{cor}(t)$ is given by:

$$C_{cor}(t)= \sum_{i=1}^{n}(C_i + D_i * \tau_l) * N_{i,cor} + (C_{log,cor} + C_{udig} * NINA) * NMS_{cor} \quad (7)$$

Where $N_{i,cor}$ is the number of replacements of component i during a system corrective stop on [0, t], C_{udig} is the unitary diagnosis cost for component, NINA is the number of components in the system whose monitoring information is not available, $C_{log,cor}$ is the logistics cost and NMS_{cor} is the total number of the system's corrective maintenance stop on [0, t].

When a corrective replacement occurs on the operating system, additional costs related to the immobilization of the system will be added to the maintenance cost. These are taken into account through the $C_{acor}(t)$, is expressed as:

$$C_{acor}(t)= \sum_{i=1}^{n} D_i * N_{i,cor} * \tau_{immob} + (D_{log,cor} + D_{udig} * NSIS) * AM_{cor} * \tau_{immob} \quad (8)$$

Where τ_{immob} is the hourly rate for a system immobilization, D_{udig} is the unitary diagnosis duration for component and $D_{log,cor}$ is the logistics duration of the system's corrective maintenance stop.

The system initial cost is given by:

$$C_I=\sum_{i=1}^{n} C_i + C_{NI,i} \quad (9)$$

Where $C_{NI,i}$ is the cost related to the information available level on component i (cost of a sensor).

D. Feedback Loop

The design of the system is validated based on the obtained life cycle costs value. In case these costs are unsatisfactory for the designer, it will be to identify the weak points of the system. The weak points here are the components that have the greatest impact on life cycle costs. After, it will be for the designer to modify the design parameters, in order to find the system configuration that corresponds to the LCC minimum.

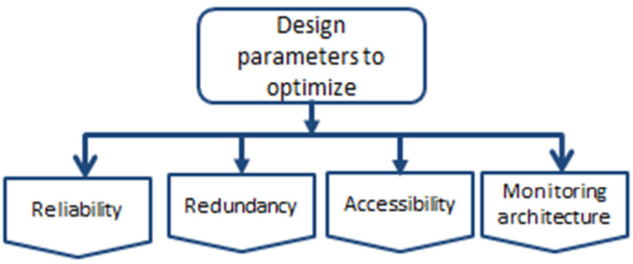

Fig. 2 - Design parameters to optimize

The various modifications to the design parameters discussed in this article are listed in Figure 2. The choice between these modifications is potentially the most complex part for the designer. The first challenge is to evaluate the technical viability of these different modification proposals depending on the component concerned. For example, it may be not possible to install redundancy on a given component or make it more accessible in the system. Depending on the results of this technical analysis, the number of proposals available to the designer may be reduced. If several solutions subsist, it will be a question of integrating these different proposals into the initial maintenance model to evaluate their impact on life cycle costs. The choice between these proposals is validated by evaluating the reduction in life-cycle costs. To illustrate the consistency of the methodology, an example of a multi-component system will be established in the next section.

NUMERICAL EXAMPLE

In this illustration, we tested our model on a multi-component system coming from a commercial heavy vehicle. This system is composed of six (06) components connected in series (see Figure 3). The model, which is applied in this section, tends to be close to the real system model (Lesobre, 2015).

Fig. 3 - System Structure Definition

The reliability properties, costs and replacement durations for the system components are defined in Table 1.

Let us now turn to the different properties of this system. The operation time is fixed at 5 years (represents the nominal contract duration). The MFOP fixed at six (06) months. The confidence level fixed at 80 %. The hourly labor rate is fixed at τ_l = 90 €, the hourly rate for a system immobilization is fixed at τ_{immob}=100€. The unitary diagnosis cost and duration are respectively fixed at C_{udig}=20€ D_{udig}=5min. The logistics cost of the system's preventive maintenance stop is fixed at $C_{log,prv}$=100€ and finally. The logistics cost and duration of the system's corrective maintenance stop are respectively fixed at $C_{log,cor}$=200€ and $D_{log,cor}$=1h. It is also assumed that the system components maintenance operations are independent of one another.

Table 1 - System parameters (W=Weibull distribution, G=Gamma process and L=degradation Limit) (Lesobre, 2015).

	A1	**A2**	**A3**	**A4**	**A5**	**A6**
Reliability model	**W(3.5e5,2)**	**W(3.5e5,7)**	**W(4e5,3)**	**W(4.5e5,7)**	**G(1.1e-4,1.5) L=20**	**G(8e-5,1.5) L=20**
C_i(en €)	500	500	500	500	500	500
$C_{NI,i}$(en €)	1	0	0	0	0	0
D_i(en €)	1	1	1	1	1	1

RESULTS AND DISCUSSION

According to the methodology developed, simulations based on the Monte Carlo method are carried out. For each simulation the LCC of the system over a 5 year is evaluated. To ensure the convergence of LCC estimation, 1000 stories are simulated. Figure 4 shows the result of the LCC of system and these components.

After estimating the LCC of given system and these components, the next step is to identify the most impacting components. According to Figure 4, design optimization should focus on component A1 as a priority.

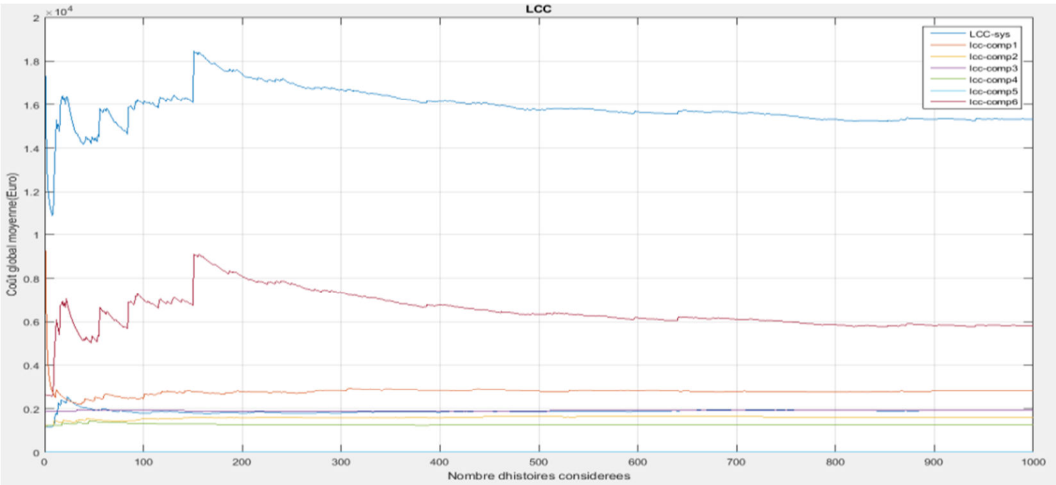

Fig. 4 - The life-cycle cost as a function of the number of stories

Table 2 illustrates the system life cycle costs for the various design optimizations (changes) made on component A1. The following modifications were made:

Case 1: Reliability optimization; Change component A1 by a more reliable component, however the cost of the new component is greater than component A1.

Case 2: Redundancy optimization; Installing redundancy by placing a component similar to component A1 in parallel works at the same time.

Case 3: Accessibility optimization; Making component A1 more accessible, this modification minimizes replacement duration, but the cost of the item can be increased.

Case 4: Monitoring architecture; Install a sensor to monitor the health of component A1. In fact, the cost of acquisition is increased.

Table 2 - The system life cycle costs for the various design changes made on component A1

	Initial Case	**Case 1**	**Case 2**	**Case 3**	**Case 4**
LCC (euro)	14081	12684	12028	13888	13286

According to Table 3, for each proposed design optimizations, life cycle costs are optimized. In the first case the LCC is decreased by 9.92 **%**, in the second case it is 14.56 %, in the third case 1.37 % and finally the last case is 5.56 %. Among the different design optimizations proposals, the best result is achieved by redundancy optimizing (case 2).

CONCLUSION AND FUTURE RESEARCHES

To optimize the life cycle cost of the complex industrial system, maintenance policy optimization alone is not enough. Indeed, it is essential to carry out a wider reflection associating the system and its maintenance from the design stage. To guide this reflection, design methodology for maintenance has been proposed. The developed methodology provides the designer with a decision support tool to find the system configuration that corresponds to the minimum LCC. The added value of this methodology lies in the design and maintenance optimization simultaneous. The design optimization refers here to the reliability and maintainability optimization. The reliability optimization is the components choice and the redundancies implementation. The maintainability optimization is the improve accessibility and the monitoring architecture installation. This methodology also allows providing an optimal opportunistic maintenance policy based on the MFOP concept. This maintenance policy ensures that the multi-component system operates over a given lifetime with a confidence specified level.

The research offers the following subjects for further researches: (a) applying the proposed model and procedure for multi-state systems; (b); Applying the four optimization methods together, and on all system components; (c) Use a meta-heuristic methods for maintenance optimization and comparing their results with those; (d) considering other objectives in addition to LCC, such as reliability, availability, time; (e) integrate other design parameters, such as availability, security, supportability, etc.

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