Simultaneous Optimization of Design and Maintenance through a Hybrid Process Using Genetic Algorithms

O. Adjoul, A. Feugier, K. Benfriha, A. Aoussat

***Abstract*—**In general, issues related to design and maintenance are considered in an independent manner. However, the decisions made in these two sets influence each other. The design for maintenance is considered an opportunity to optimize the life cycle cost of a product, particularly in the nuclear or aeronautical field, where maintenance expenses represent more than 60% of life cycle costs. The design of large-scale systems starts with product architecture, a choice of components in terms of cost, reliability, weight and other attributes, corresponding to the specifications. On the other hand, the design must take into account maintenance by improving, in particular, real-time monitoring of equipment through the integration of new technologies such as connected sensors and intelligent actuators. We noticed that different approaches used in the Design For Maintenance (DFM) methods are limited to the simultaneous characterization of the reliability and maintainability of a multi-component system. This article proposes a method of DFM that assists designers to propose dynamic maintenance for multi-component industrial systems. The term "dynamic" refers to the ability to integrate available monitoring data to adapt the maintenance decision in real time. The goal is to maximize the availability of the system at a given life cycle cost. This paper presents an approach for simultaneous optimization of the design and maintenance of multi-component systems. Here the design is characterized by four decision variables for each component (reliability level, maintainability level, redundancy level, and level of monitoring data). The maintenance is characterized by two decision variables (the dates of the maintenance stops and the maintenance operations to be performed on the system during these stops). The DFM model helps the designers choose technical solutions for the large-scale industrial products. Large-scale refers to the complex multi-component industrial systems and long life-cycle, such as trains, aircraft, etc. The method is based on a two-level hybrid algorithm for simultaneous optimization of design and maintenance, using genetic algorithms. The first level is to select a design solution for a given system that considers the life cycle cost and the reliability. The second level consists of determining a dynamic and optimal maintenance plan to be deployed for a design solution. This level is based on the Maintenance Free Operating Period (MFOP) concept, which takes into account the decision criteria such as, total reliability, maintenance cost and maintenance time. Depending on the life cycle duration, the desired availability, and the desired business model (sales or rental), this tool provides visibility of overall costs and optimal product architecture.

***Keywords*—**Availability, design for maintenance, DFM, dynamic maintenance, life cycle cost, LCC, maintenance free operating period, MFOP, simultaneous optimization.

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I. Introduction

A. Context and Motivation

TODAY, large-scale new industrial systems, such as industrial vehicles and wind turbines, are becoming increasingly complex. This complexity is linked to the diversity of the technologies used in the components (electronic, mechanical, etc.), which once assembled form the final product [1]. These systems are characterized by very high maintenance costs of up to 60% of the life cycle cost in many cases [2], [3]. Moreover, their failures result in huge non-production losses due to downtime [4].

B. Problematic

The characteristic observed by [2], [3] is mainly due to the fact that maintenance is too low when designing the product and when deploying in the field. Maintenance when considered from the design stage usually incorporates two factors. The first is linked to the reliability of the system, and therefore to the reliability of its components and structure [5]. The second factor relates to maintainability, including accessibility and improvement of the monitoring architecture of the various components of the equipment [6].

The design of the reliability and maintainability of an industrial system is a complex problem, since it encompasses many sub-problems which often require specific studies dedicated to each of them [7]. These sub-problems include the allocation of reliability (the principle is to choose among several components with different performance/cost characteristics, components that can be included in the composition of the system), the allocation of redundancy (to find the optimal architecture), the allocation of maintainability that is characterized by the MTTR, and finally the allocation of diagnostic, characterized by the implementation of surveillance systems. Genetic algorithms can be used to model the sub-problems and converge towards a design configuration that, for example, would optimize the best availability at the lowest cost [8], [9].

Once the reliability and maintainability characteristics are set in the design phase, we know the theoretical availability of the system. Operational readiness can be brought closer to theoretical availability with a high maintenance policy. Optimizing maintenance policy is the identification of operations to be performed during a maintenance operation that balances reliability benefits with maintenance costs.

Defining an optimal maintenance policy is a task that has attracted many researchers in recent years. As a result, several avenues of reflection are being explored today, in particular those related to the improvement of the surveillance architecture through the development of information technology.

Generally, these two sets of decisions are dealt with sequentially or independently. First the design determines the system and then a maintenance plan is associated [10]. The decisions taken in these two sets are influenced by each other; therefore, to achieve high operational readiness of systems it is important to have the following key elements [11]:

- Optimal reliability and maintainability characteristics of industrial systems in the design phase.
- The optimal dynamic maintenance policy to be implemented in the operational phase.
- Appropriate linkage variables to quantify the interactions between the design and maintenance models in an optimization framework.

C. Contribution and Article Organization

From this perspective, our paper presents a tool for simultaneous optimization of the design and maintenance of multi-component industrial systems, integrating maintenance issues from the conception. This tool is designed to help designers to define the best technical solutions in the best product architecture. It also provides a definition of the maintenance policy to be deployed in the operating phase for a given system. The proposed tool maximizes the total operational reliability of the system studied over its entire lifespan while reducing its life cycle costs.

The rest of the article is organized as follows: After the introduction (Section I), Section II describes the problem of joint design and maintenance modeling and optimization and develops the mathematical models used to estimate the cost of the life cycle and the total operational reliability of the system. Section III presents the combinatorial resolution method based on genetic algorithms. An example from the literature and the results are presented in Sections IV and V respectively. Section VI concludes the paper and provides possible directions for future research.

II. Simultaneous Modeling of Design and Maintenance

From the same specification, designers can propose several technological solutions that differ in the choice of components, product architecture, assembly processes, etc. They result in similar design solutions (Sl_1, Sl_2,…, Sl_N) in operation, but different in reliability and cost. In order to ensure that all the proposed solutions function correctly during the operating phase, designers can propose several maintenance ($\mathrm{MP}_1, \mathrm{MP}_2, \ldots, \mathrm{MP}_M$). These maintenance plans are differentiated by the total operational reliability they provide to the system, their cost, etc. In the end, designers obtain several design solutions and maintenance plans for a given system.

Traditionally, maintenance decision-making process and design decision-making process are carried out sequentially. In this work, we consider a simultaneous decision-making framework. In order to maximize the system's total operational reliability over its entire operating life tm, we select at the same time the Sl_x system solution and its MP_{xy} maintenance plan which reduces the $\mathrm{LCC}_{\mathrm{Max}}$life cycle cost and $\mathrm{MRP}_{\mathrm{Max}}$ maintenance time. From a mathematical point of view, this can be stated as:

- Solution generation with associated maintenance plans

$$\mathrm{Sl}_1 = \begin{cases} \mathrm{MP}_{11} & \mathrm{LCC}_{11} & R_{sys}^{11}/\mathrm{tm} \\ \mathrm{MP}_{21} & \mathrm{LCC}_{21} & R_{sys}^{21}/\mathrm{tm} \\ & \vdots & \\ \mathrm{MP}_{M1} & \mathrm{LCC}_{M1} & R_{sys}^{M1}/\mathrm{tm} \end{cases}$$
$$\vdots$$
$$\mathrm{Sl}_N = \begin{cases} \mathrm{MP}_{1N} & \mathrm{LCC}_{1N} & R_{sys}^{1N}/\mathrm{tm} \\ \mathrm{MP}_{2N} & \mathrm{LCC}_{2N} & R_{sys}^{2N}/\mathrm{tm} \\ & \vdots & \\ \mathrm{MP}_{MN} & \mathrm{LCC}_{MN} & R_{sys}^{MN}/\mathrm{tm} \end{cases}$$

- Choice of solution and maintenance plan that minimize identified constraints

$$(\mathrm{Sl}_x, \mathrm{MP}_{xy}) = \begin{cases} \text{Maximize } (\mathrm{R}_{\mathrm{sys}}/\mathrm{tm}) \\ S.t\ \mathrm{LCC}_{\mathrm{sys}} \le \mathrm{LCC}_{\mathrm{Max}} \\ and\ \ \mathrm{MRP}_{\mathrm{sys}} \le \mathrm{MRP}_{max} \end{cases} \tag{1}$$

where *N* is the number of possible solutions, M is the number of possible maintenance plans, R_sys is the total operational reliability of the solution on t_m.

Design and maintenance modelling is formalized in detail in the following subsections.

A. Design Modeling

In the design phase, the designers define all components and their characteristics to ensure the fulfilment of the functions described by the functional architecture. In this step, our algorithm generates all possible design solutions (Sl_1,…, Sl_N) by adjusting the design parameters for the maintenance of each i component and evaluating their initial costs. The term "possible" means that it respects the constraints of limited design resources defined in the specification. Although the method is still valid regardless of the number of variables considered, we consider only four parameters to determine the choice of equipment i of a multi-component system. These parameters are: reliability level (R_i), the possibility of setting up a (S_i), sensor, the level of redundancy of a component (P_i) and its accessibility level (MTTR_i).

Sometimes, it may be impossible to install a sensor on a given component or make it more accessible in the system. The designer must first assess the technical viability of these four parameters for each component. Then, based on the results of this technical analysis, the number of design parameters for each component is defined. In the end, it gets several solutions from the system Sl_1, Sl_2,…, Sl_N), which vary according to their design parameters (R_i, P_i, MTTR_i et S_i). We define a possible Sl_P design solution as a particular choice of design parameters.

After generating all possible design solutions, let us now focus on evaluating their initial costs. The initial costs of a design solution are:

$$C_I = \sum_{i=1}^{n} C_i + C_{NI,i} \quad (2)$$

where n is the number of components in the system, C_i the cost of component i and $C_{NI,i}$) is the cost of the information available on component i (example: cost of a sensor).

B. Maintenance Modeling

We model maintenance by generating for each possible solution (Sl_p) all possible dynamic maintenance policies characterized by Maintenance (MP_{P1}, MP_{P2},.., MP_{PM}). Then we select the one that maximizes the total operational reliability of the system. The maintenance policies proposed here are based on the MFOP maintenance-free operating period concept developed by [12]. Each MFOP (or MFOP cycle) is usually followed by a Maintenance Recovery Period (MRP). MRP is defined as the period during which appropriate maintenance is performed on the system to enable it to successfully complete the next MFOP [13], [14]; it depends on the extent of the maintenance work to be performed [15].

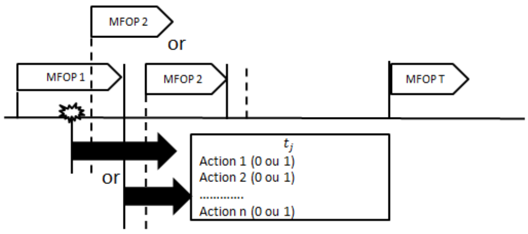

Fig. 1 MFOP Dynamic Maintenance Policy

Fig. 1 illustrates the decision process for developing an MP_{Py}, dynamic maintenance policy, based on the MFOP concept, for a possible design solution Sl_P. It consists of two stages:

The first step is to define the dates of maintenance stops t_j, the length t_{MFOPj} of each $MFOP_j$ and the number of N_{AM} maintenance stops. Note that the $t_j$date of a maintenance shutdown represents the end of an MFOP or the occurrence of a system-level failure.

The second step is to select the X_{ij} maintenance actions to be performed at each t_j on each i component. X_{ij} can take two values:

- X_{ij}=1 if component i is replaced at the beginning of the period $MFOP_j$,
- $X_{ij} = 0$ otherwise

In this article we seek to maximize for each period $MFOP_j$ (lenght t_{MFOP_j} units of time), the probability of survival called MFOP Survivability ($MFOPS_{j_{sys}}$) under constraints of total cost resources and maintenance downtime. We can define this period mathematically:

$$MFOPS_{j_{sys}} = \frac{R_{sys}(t_j + t_{MFOP_j} / H_{i,t_{j(i=1\,à\,n)}})}{R_{sys}(t_j / H_{i,t_{j(i=1\,à\,n)}})} \quad (3)$$

with t_j the start date of the period $MFOP_j$, $R_{sys}(t_j)$ the total operational reliability of the system at the time t_j, n the number of system components and $H_{i,tj}$ the monitoring information available online for each i component at the time t_j.

In this article we limit surveillance information to two levels, level 1: no information, level 2: information on operating status Walk or Fail [16]. So we can formulate our problem as:

$$(t_j, X_{ij}) = \begin{cases} \text{Maximize} \quad MFOPS_{j_{sys}} \\ S.t \quad C_{TM}(t_m) \le C_{TM_{max}} \\ and \quad \sum_{i=1}^{n} MTTR_i \, X_{ij} \le MRP_{max} \end{cases} \quad (4)$$

with j=1,…, l where l is the number of times the system has performed on [0 ; t_m], MRP_{max} is the maximum maintenance time allowed to perform {X} operations during a maintenance operation and $C_{TM_{max}}$ the maximum total maintenance cost on [0 ; t_m].

The total cost of maintenance $C_{TM}(t_m)$, of a possible system Sl_P design solution over a finite time horizon is given by [16]:

$$C_{TM}(t_m) = C_P(t_m) + C_C(t_m) + C_D(t_m) \quad (5)$$

where $C_P\,(t_m)$ is the preventive replacement cost of system components on [0 ; t_m], $C_C(t_m)$ the patch replacement cost of failed components on [0 ; t_m] and $C_D(t_m)$ the extra cost of the diagnosis when the system is in corrective maintenance.

Preventive maintenance cost $C_p(t_m)$ is:

$$C_p(t_m) = \sum_{i=1}^{n} (C_i + MTTR_i * \tau_0) * N_{i,p} + C_{log,p} * AM_p \quad (6)$$

where $N_{i,p}$ the number of preventive replacements of component i on [0, t_m], $C_{log,p}$ the logistics cost of preventive maintenance stops and AM_p the number of preventive system maintenance stops on [0, t_m].

The corrective maintenance cost $C_C(t_m)$ is:

$$C_c(t_m) = \sum_{i=1}^{n} ((C_i + MTTR_i * \tau_0) + (MTTR_i * \tau_{immob})) * N_{i,c} + (C_{log,c} + (D_{log,c} * \tau_{immob})) * AM_c \quad (7)$$

where $N_{i,c}$ is the number of component patch replacements i on [0, t_m], τ_{immob} is the cost of operating loss per system immobilization time, $D_{log,c}$ the logistic time associated with the corrective maintenance stop $C_{log,c}$ the logistic cost associated with the corrective maintenance stop on [0, t_m] and AM_c the logistic cost associated with the corrective maintenance stop on [0, t_m].

During a corrective shutdown, system diagnosis is fundamental to identifying the component(s) responsible for the failure and thus to directing the maintenance actions to be performed. For some components, the available monitoring information provides information on their operation. In this case, no additional diagnostic costs will be recognized. On the other hand, for components that are not known to operate, a test will have to be carried out with additional costs. These costs will be taken into account in the expression $C_D(t_m)$ given by:

$$C_D(t_m) = (C_{UD} + (D_{UD} * \tau_{immob})) * NSIS * AM_c \quad (8)$$

where C_{UD} the unit cost of diagnosis for a component D_{UD} the unit time of diagnosis for a component, and finally NSIS the number of components in the system whose monitoring information is not available.

In order to estimate the total cost of maintenance $C_{TM}(t_m)$, and the total reliability for pre-determined strategies, a Monte-Carlo simulation-based maintenance model was developed. This is based on the proposed maintenance policy, the structure of the system, the modeling of the reliability of its components and the available monitoring information. When the number of stories is large enough to guarantee convergence, this simulation allows assessing the average total maintenance cost and the average total operational reliability for the policy under consideration with the associated parameters. This average cost and average reliability can be used to compare and optimize maintenance policy.

C. Simultaneous Assessment and Selection

To select an optimal pair (a design solution and its maintenance policies combine optimal), an evaluation objective must be defined. Our goal is to maximize total operational reliability. In this article, the total operational reliability of a system means the reliability of the entire multi-component system and its lifetime. Evaluating this objective usually requires numerical assessment methods, such as the Carlo Mounting Method. As mentioned earlier, the system is performing a succession of periods $MFOP_j$ of t_{MFOP_j} duration. Evaluating the total operational reliability of the system R_{sys} over its lifetime t_m is equivalent to estimating the average $MFOPS_{j_{sys}}$, over all periods l. In addition, the $MFOPS_{j_{sys}}$ over each period j is closed to the calculated average $R_{sys}(t_m)$. In other words, the variance of $R_{sys}(t_m)$ must be low.

Total system operational reliability is provided by:

$$R_{sys}(t_m) = \frac{\sum_{j=1}^{l} MFOPS_{j_{sys}}}{l} \quad \text{with j=1,…,l} \quad (9)$$

Now let us have a look at the evaluation of $MFOPS_{j_{sys}}$. It is defined in the previous part as the reliability of the system at the end of the period j $R_{sys}(t_j + t_{MFOPj})$ on the reliability of the system at the beginning of that period j $R_{sys}(t_j)$, taking into account the information available at t_j.

In order to assess the reliability of a multi-component system $R_{sys}(t)$ at a given point in time t, the reliability of each component at that point t must be assessed. The application of the reliability calculation expressions of these two basic subsystems allows the reliability of the complete system to be assessed at the moment t.

The following relationships provide the reliability of a serial and parallel structure.

Parallel system:

$$R_{sys}(t) = 1 - \prod_{i=1}^{n}(1 - R_{A_i}(t)) \quad (10)$$

Serial system:

$$R_{sys}(t) = \prod_{i=1}^{n} R_{A_i}(t) \quad (11)$$

where n is the number of components of the structure, Ri(t) the reliability of each component i.

III. Global Resolution Method

We have chosen the genetic algorithm (GA) as the resolution method. AGs are able to solve optimization problems with several objectives and constraints; and efficiently handle all types of variables [17].

We propose a hybrid design and maintenance optimization tool based on genetic algorithms (HODMAGs) (Fig. 2). This tool combines two dependent algorithms: a principal and a secondary. The main algorithm ensures optimization of the design in terms of reliability R_i, redundancy P_i, monitoring architecture S_i and accessibility characterized by $MTTR_i$. The secondary algorithm focuses on the determination of a dynamic maintenance plan based on the MFOP. This second algorithm allows having a MP_{Px} maintenance plan that maximizes the total operational reliability of the system by limiting the resources of cost and maintenance time.

The HODMAGs process was implemented as follows: The main algorithm starts by generating all possible design solutions $(Sl_1,\ldots, Sl_N)$ by adjusting the parameters R_i, P_i, $MTTR_i$ and S_i of each i component (Section II *A*) and integrating their initial costs. Then, for each possible solution (Sl_p), the secondary algorithm is run to obtain an optimal dynamic maintenance plan MP_x that maximizes the average total operational reliability of the system under constraints of limited cost resources and maintenance time (Section II *B*). In the end, the main algorithm classifies the different solutions according to their average total operational reliability, in order to select the one that maximizes system reliability (Sl_x) over its entire operating time t_m.

IV. Numerical Example

In this section, an illustration of an example from literature is proposed. The objective is to demonstrate the relevance of the proposed methodology and to test the HODMAGs tool. The structure of the multi-component system considered for this illustration is described in Fig. 3. The reference multi-component system consists of four series components, the data of which are a combination of those applied in [16], [18]. We choose to take a serial system with 4 components to easily illustrate and justify the results obtained by the proposed tool.

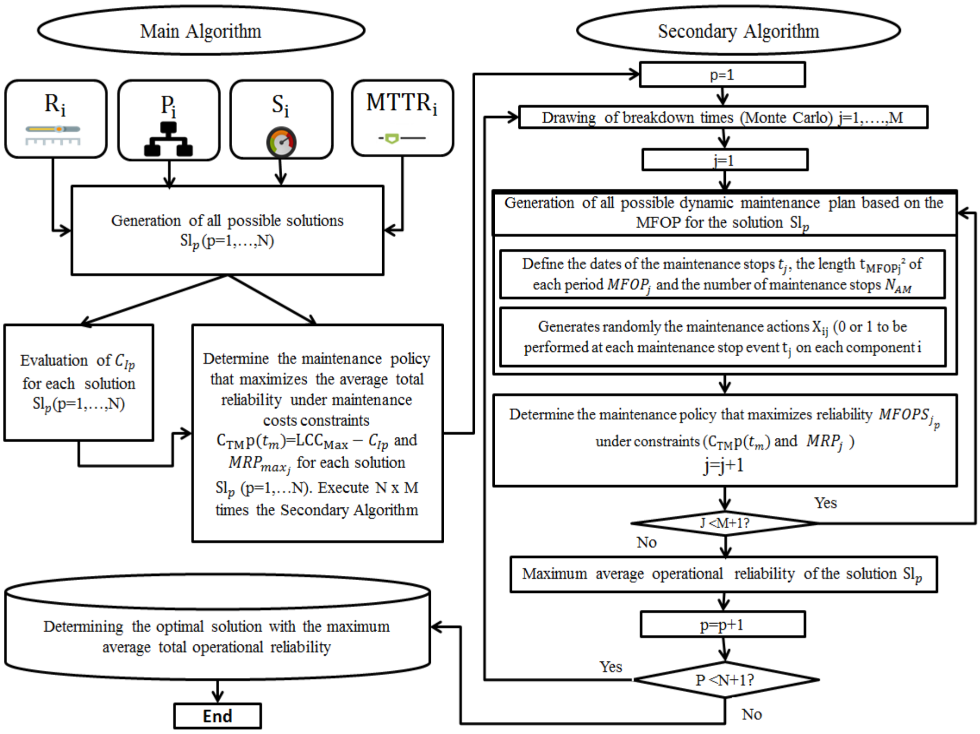

Fig. 2 HODMAGs

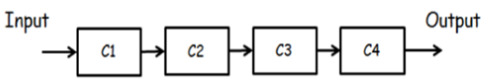

Fig. 3 Structure of the multi-component reference system

For this reference system [16], [18], we assume that the cost and the unit duration of diagnosis are respectively C_{udig}= 20€ and D_{udig} = 5 min, the hourly rate of labor is τ_{MO} = 90€ and the cost of the loss of holding by fixed-capital hour τ_{immob} = 100€. Then for towing, the cost and duration considered are respectively $CRemor$ = 1500€ and $DRemor$ = 5h. The logistic cost of the preventive and corrective maintenance stop is $C_{log,prv}$ = 100€ and $C_{log,cor}$ = 200€ for a fixed duration of $D_{log,cor}$= 1h. Table I summarizes the design parameters $(R_i, P_i, MTTR_i, S_i)$ for different components of the reference system considered in this example.

TABLE I
REFERENCE SYSTEM DESIGN SETTINGS (W= WEIBULL LAW) [16], [18].

	A1	A2	A3	A4
Reliability Model Ri	W(3.5e5,2)	W(3.5e5,7)	W(4e5,3)	W(4.5e5,7)
D_i(h) MTTRi	1	1	1	1
Si	0	0	0	0
Redundancy Pi	0	0	0	0
C_i(€)	311	458	407	500

We also introduce hypotheses in relation to the reference system to define the parameters necessary for the simulation:

- Implementation and adjustment of the four parameters $(R_i, P_i, MTTR_i, S_i)$ is possible for each component i.
- The R_i and $MTTR_i$ parameters are real and continuous with max and min values ranging from -50% to + 50% of the reference system values.
- The Pi and Si parameters are discrete integer parameters that can only be 0 or 1.
- The properties of A_i and A'_i its parallel component) are assumed to be identical.
- The installation of a sensor will cost $C_{NI,i}$ = 50€ [9].

Note that information on system operation/failure is assumed to be known. This assumption is realistic if we consider that the system failure systematically causes an immobilization.

V. RESULTS AND DISCUSSION

Based on the system properties and the design and maintenance tool defined in the previous sections, simulations are put in place to assess the average total operational reliability$R_{sys}^{moy}(tm)$. These simulations are carried out over a 5-year operating period. The annual mileage is set at 100,000 km. We also consider that the MFOP is set at six months, which is 50,000 km. We assume that the maximum lifecycle cost is LCC_{max} = 8000€ and the maximum maintenance recovery time MRP_{max} is set at 3 hours. To solve the combinatorial optimization problem defined in Section IV *B* (HMO), we programmed the algorithms proposed under

MATLAB. In both algorithms (primary and secondary), the passing rate and the mutation rate are 0.5 and 0.2, respectively. In addition, the population size is 200; the number of iterations is 600. Finally, it should be noted that the number of history of Monte Carlo is fixed at M=1000. The Monte-Carlo simulation can give a global idea of the entire life of the system. The two behaviors can be compared in the long term to the number of possible system failures during this extended period. The larger the number of history of the Carlo Monster simulation, the more the results look like the real life of the system.

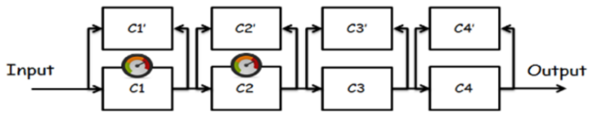

Fig. 4 New configuration obtained by the proposed tool

TABLE II
PROPERTIES OF THE COMPONENTS OF THE SOLUTION

	A1 and A1'	A2 and A2'	A3 and A3'	A4 and A4'
Ri (KM)	W(3.46e5, 3.2)	W(3.63e5, 8.1)	W(4.08e5, 3.5)	W(4.70e5, 6.9)
MTTRi(h)	1.1	1.2	1.2	1.2
Si	1	1	0	0
Pi	1	1	1	1

TABLE III
THE MAINTENANCE PLAN TO BE DEPLOYED IN OPERATION OF THE SOLUTION

Tj (*10000 Km)	5	10	15	20	25	30	35	40	45
A1	0	0	1	0	0	0	1	0	0
A2	0	0	0	1	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	1
A4	0	0	0	0	0	1	0	0	0
A1'	0	0	0	0	0	1	0	0	0
A2'	0	0	0	0	0	0	0	1	0
A3'	0	0	0	1	0	0	1	0	0
A4'	0	0	0	0	0	0	0	0	0

Fig. 4 and Table III illustrate the structure of the solution and its dynamic maintenance plan obtained by the proposed tool (HODMAGs), respectively. The design parameters $(R_i, P_i, MTTR_i, S_i)$ for each component of this new solution are presented in Table III.

Table IV presents the characteristics of the new solution and the reference solution. It is noted that the operational reliability of the new solution has increased by 26% compared to the original solution with the same constraints on life cycle cost and maintenance response time. The initial costs of the new solution are higher than those of the reference system, but there is a significant decrease in maintenance costs over the entire operating period. This is due to the fact that the changes to the reference system may cost a little more in terms of investment costs, but they do bring a significant improvement in the performance of the system in terms of maintenance costs, reliability, failure, etc.

TABLE IV
AVERAGE TOTAL OPERATIONAL RELIABILITY AND COSTS OF THE SOLUTION AND THE REFERENCE SYSTEM

	Reference System	Solution obtained by the proposed tool
Average Total Operational Reliability (%)	0.78	0.98
Average Global Costs LCC	7 912€	7 840.6€
Initial Costs C_I	1 676€	2 950.5€
Average Maintenance Costs C_{MT}	6 236€	4 890.1€

These results demonstrate the value of having a tool that allows designers to visualize the consequences of their design choice, in terms of lifecycle costs and performance; and in terms of total operational reliability. Thus, based on limited life cycle cost and MRP resources, the tool converges to a couple of solutions, consisting of a design solution and its dynamic maintenance plan for a given system which maximizes system performance in terms of total operational reliability.

VI. CONCLUSION AND PERSPECTIVES

In this article, we presented a tool for simultaneous optimization of the design and maintenance of large-scale multi-component industrial systems. It helps the designer to find technical solutions and a product architecture by integrating maintenance issues from the conception. The goal is to maximize the system's average total operational reliability performance based on limited lifecycle resources and maintenance recovery times over.

The tool was confronted with an example from the literature composed of four serial components. Using the proposed algorithm, a configuration (parallel series) consisting of 8 new components and two sensors was obtained. This solution has increased the reliability of the reference system by about 26%, under the same life cycle cost constraints imposed on the reference system.

In order to generalize and optimize the proposed tool, several research avenues can be undertaken, including: (a) Adapt the proposed tool and procedure to multi-state systems; (b) Use other meta-heuristic methods and compare them with those of AGS; (c) Test the proposed approach for K-out-of-N subsystems and (d) Test the robustness of this tool on new examples from the industrial world.

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