Design for maintenance: new algorithmic approach

Oussama Adjoul, Khaled Benfriha and Améziane Aoussat
Department of Product Design and Innovation Laboratory, Arts et Métiers Institute of Technology, HESAM University, Paris, France

Abstract

Purpose – This paper proposes a new simultaneous optimization model of the industrial systems design and maintenance. This model aims to help the designer in searching for technical solutions and the product architecture by integrating the maintenance issues from the design stage. The goal is to reduce the life-cycle cost (LCC) of the studied system.

Design/methodology/approach – Literature indicates that the different approaches used in the design for maintenance (DFM) methods are limited to the simultaneous characterization of the reliability and the maintainability of a multicomponent system as well as the modeling of the dynamic maintenance. This article proposes to go further in the optimization of the product, by simultaneously characterizing the design, in terms of reliability and maintainability, as well as the dynamic planning of the maintenance operations. This combinatorial characterization is performed by a two-level hybrid algorithm based on the genetic algorithms.

Findings – The proposed tool offers, depending on the life-cycle expectation, the desired availability, the desired business model (sales or rental), simulations in terms of the LCCs, and so an optimal product architecture.

Research limitations/implications – In this article, the term "design" is limited to reliability properties, possible redundancies, component accessibility (maintainability), and levels of monitoring information.

Originality/value – This work is distinguished by the use of a hybrid optimization algorithm (two-level computation) using genetic algorithms. The first level is to identify an optimal design configuration that takes into account the LCC criterion. The second level consists in proposing a dynamic and optimal maintenance plan based on the maintenance-free operating period (MFOP) concept that takes into account certain criteria, such as replacement costs or the reliability of the system.

Keywords Reliability, Maintainability, Simultaneous optimization, Dynamic maintenance, Design for maintenance (DFM), Life-cycle cost (LCC), hybrid optimization algorithm, Multicomponent industrial systems

Paper type Research paper

1. Introduction

1.1 Context

The effective maintenance planning is needed for any major industrial system, referred to large-scale systems, such as industrial vehicles, production systems, wind turbines, machine tools, aircraft, ships, and so on. And that's because the operating and maintenance costs of these systems can represent up to 60 percent of their overall life-cycle costs (LCCs) (Dhillon, 2006). In addition, their failures can lead to significant downtime (Markeset and Kumar, 2003). For example, the failure of a $ 5,000 wind turbine bearing could result in $ 250,000 in maintenance because the replacement requires specific repair equipment and a specialized maintenance team (Kusiak and Li, 2011). The users of these systems know this, and they are increasingly considering the overall LCC and availability before committing to acquiring this type of equipment (Rawat and Lad, 2016). To meet the customers' expectations, companies evolve and adopt the new economic model; thus, they pass from selling a manufactured system to the sale of global service, including the manufactured system (Lesobre, 2015; Markeset and Kumar, 2003). In this context, they propose to their customers to pay rent, including the provision of the industrial equipment, its maintenance, its evolution (update), and its withdrawal (recycling). As a result, the manufacturer is now responsible for the long-term availability of its equipment, which implies a deep issue related to the maintenance from the design stage.

1.2 Problematic

The design of such systems or equipment has to deal with the product architecture first and choosing the components/units with the cost, the reliability, the weight, and some other attributes, corresponding to the scope statement specifications (Zoulfaghari *et al.*, 2014). On the other hand, the design has to facilitate the maintenance process by particularly improving the real-time monitoring of the equipment through integrating new technologies such as connected sensors, Internet of Things (IoT) systems, and intelligent actuators (Karre *et al.*, 2017).

Once the design is done, maintenance contracts will be defined to maintain the required system availability during the operational phase. The definition of a maintenance contract is based on the system configuration and the conditions of use specified by the user. To specify these conditions, manufacturers and users evaluate variables related in particular to the operational environment (climatic conditions, operational conditions, etc.), to the use of the system (number of hours per day, number of km per day . . .) or the type of missions performed (Goel *et al.*, 2003). This information is then combined to select an optimal maintenance plan.

In terms of research, we find in the literature that issues related to design and maintenance are generally treated in a sequential or independent manner (Goel *et al.*, 2003; Rawat and Lad, 2016). However, the decisions made in these two sets influence each other. The design for maintenance is considered as an opportunity to optimize the costs that can be generated during the life of an industrial product (Markeset and Kumar, 2001), which can reach up to 60 percent of the LCCs, particularly in the nuclear or the aeronautical activities (Dhillon, 2010).

1.3 Objective

This article presents a new **design for maintenance** (DFM) model that assists the designers in the stage of choosing the technical solutions for the large-scale industrial products. Large scale refers to the complex and the long-run multicomponent industrial systems, such as trains, aircraft, and so on. The goal is to minimize the LCC of this type of system. The proposed model is based on a two-level hybrid algorithm for simultaneous optimization (design and maintenance), using genetic algorithms. The first level is to determine the optimal design for a given system. For this purpose, the designer can act on various aspects, such as the choice between components with different reliability characteristics, the choice to invest in a more complete monitoring architecture, the choice to consider adding a redundant component, or still the choice to work on the components accessibility (maintainability). The second level aims to optimize the cost of the maintenance policy according to the level of reliability required. The proposed maintenance policy is dynamic and integrates different solutions offered by new connected and intelligent technologies.

The contribution of this research is to create a decision support tool by providing designers with LCC projections. Depending on the life-cycle expectation, the desired availability, and the desired business model (sales or rental), the tool offers a simulation in terms of the LCCs and so an optimal product architecture along with an adapted maintenance plan.

The rest of the article is organized as follow. After the introduction (section 1), section 2 reviews the design literature for the maintenance. Section 3 describes the joint modeling and optimization problem of the design and the maintenance and develops the mathematical models used to estimate the LCC. Section 4 presents the method of combinatorial resolution based on genetic algorithms. The solution method and the results are presented in section 5. Section 6 concludes the paper and presents future research guidelines.

2. State of the art: design for maintenance (DFM)

In spite of the fact that the research on the maintenance problems has been advanced significantly during the last decades, the maintenance still suffers from a gloomy image. It is often limited to the operational phase, which includes the development of the inspection plans (Zhao and Nakagawa, 2012), the preventive planning (Zhang *et al.*, 2002), the execution of the diagnostic and/or the maintenance operations, and so on.

The literature shows that there are four approaches to design methods for maintenance (Figure 1). The first two approaches are concerned with the characteristics of the reliability and/or the availability of the industrial system (Certa *et al.*, 2011; Long *et al.*, 2009; Moghaddam and Usher, 2011). While the latter two are interested in the maintainability characteristics (Chen and Cai, 2003; Mulder *et al.*, 2013; Nishijima *et al.*, 2009; Wani and Gandhi, 1999). The goal is to maximize or minimize certain parameters such as costs, reliability, availability, maintenance time, weight, and so on. According to (de Almeida *et al.*, 2015), 68.3 percent of works under this theme aim to minimize the cost, 37.6 percent to maximize reliability, 17.2 percent to maximize availability, 11.8 percent to minimize maintenance time, and 15.7 percent to maximize remainder (weight, volume, . . .).

In order to increase the reliability of an industrial system, we can deal with the level of reliability of the components or the redundancy (Zoulfaghari *et al.*, 2014). The first approach considers the reliability of the components as a decision variable. It consists in finding the reliability values of each component of the system that best meet the required objectives and constraints (Beaurepaire *et al.*, 2012). The second approach, redundancy allocation, is to find the number of components to apply in each subsystem (Ebrahimipour and Sheikhalishahi, 2011). In the majority of cases, the goal of the redundancy is to maximize the reliability (Nourelfath and Ait-Kadi, 2007; Okasha and Frangopol, 2009; Torres-Echeverría *et al.*, 2012). These two approaches, used separately or combined, can be grouped into the category of DFM in favor of reliability (Amari and Pham, 2007).

The third approach focuses on improving the accessibility to the failing components in particular and the maintainability in general. Several tools exist to improve system maintainability characteristics in the design phase, including detailed design, logistical support, and ergonomics (Chen and Cai, 2003).

The last approach, the improvement of diagnosis and prognosis, is to change the monitoring architecture, in order to continuously measure the performance gaps as well as to determine the right moment to perform the maintenance (Lesobre *et al.*, 2013). This approach has received increasing attention in recent years, thanks to the development of connected sensors and information technology (Mulder *et al.*, 2013; Olde Keizer *et al.*, 2016; Tian *et al.*, 2011). These systems make it possible to optimize the decision process by monitoring the system and the components degradation state. Nevertheless, it is necessary to evaluate

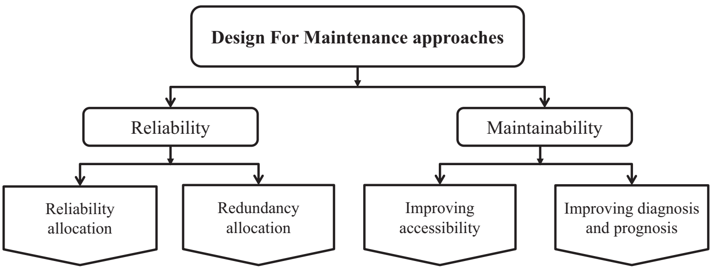

Figure 1.
Design for maintenance approaches

the potential gains in the maintenance compared to the investments in the design and the deployment of the connected monitoring systems.

In terms of numerical optimization methods, we found that the heuristic and the meta-heuristic methods such as genetic algorithm (GA), simulated annealing (SA), and particle swarm optimization (PSO) have been widely applied in this area. (Okasha and Frangopol, 2009) proposed a multiobjective model including redundancy, reliability, and LCC simultaneously as objective functions. (Wang *et al.*, 2009) examined the problem of multiple objective redundancy allocation in serial–parallel systems. The developed model uses the system reliability and the design cost as objective functions and the system weight as a constraint. (Suman, 2003) investigated three types of multiobjective optimization problems, including cost, reliability, and weight factors. They applied the simulated annealing method to solve these problems.

To conclude, the different approaches used in the DFM methods are limited to the simultaneous characterization of the reliability and the maintainability of a multicomponent system as well as the modeling of the dynamic maintenance. The term "dynamic" refers to a policy capable of integrating available monitoring information to adapt the maintenance decision in real time (Lesobre *et al.*, 2014a). This article proposes to go further in the optimization of the product, by simultaneously characterizing the design, in terms of reliability and maintainability, as well as the dynamic planning of the maintenance operations. This combinatorial characterization is performed by a two-level hybrid algorithm based on the GAs. The detailed problem is discussed in the next section.

3. Description and modeling

For the same specifications, designers can offer several technological solutions in terms of the choice of components, product architecture, assembly process, and so on. As a result, they lead to similar products from the operational point of view but can be differentiated in terms of reliability and design costs. In order to maintain the same level of operational performance for all the proposed solutions, the designers compensate for the unreliability of a strengthened maintenance plan, resulting in increased LCCs. In this work, we propose a new approach to optimize design and maintenance in the same time phase. The designer will then have a decision support tool that will allow him to find the configuration that best fits his business model because the tool offers a LCC profile for each configuration.

The modeling of the design and maintenance is formalized in detail in the following subsections, as well as their combination.

3.1 Design modeling

During the design phases, the designers define all the hardware devices (elementary component, subsystem, sensor, etc.) required for the realization of the functions described by the functional architecture (phase of the hardware architecture projection on the software architecture), as well as their characteristics. For example, a temperature probe may be suitable for a redundant approach, while a pump may be monitored for degradation (use of the prognosis) (Relf, 1999). In this work, four design parameters for maintenance are taken into consideration when defining a device i of a multicomponent system. Among these parameters, we can mention the choice of its reliability level (Ri), the choice to invest in a more efficient monitoring instrumentation by the implementation of a sensor (Si), the choice to consider putting a component with redundancy (Pi), or the choice of its level of accessibility ($MTTRi$).

However, it may be impossible, for example, to install a sensor on a given component or to make it more accessible in the system. Therefore, the designer must first evaluate the technical viability of these four parameters regarding each component. Then, based on the results of this technical analysis, the designer defines the number of design parameters available according to each component. In the end, he obtains several solutions of the system Sl1, Sl2, . . ., SlN, which vary according to their reliability or their LCC. The goal is to select the Slx system solution capable of performing missions at the lowest cost over its entire life cycle. We define a design solution as a particular choice of design parameters. The problem can be defined as follows:

$$\begin{array}{lll} \mathrm{Sl}_1 & \mathrm{LCC}_1 & R^1_{sys}/\mathrm{tm} \\ \mathrm{Sl}_2 & \mathrm{LCC}_2 & R^2_{sys}/\mathrm{tm} \\ & \cdots & \cdots \\ \mathrm{Sl}_\mathrm{N} & \mathrm{LCC}_\mathrm{N} & R^1_{sys}/\mathrm{tm} \end{array}$$

$$\text{Optimal solution} = \min(\mathrm{LCC_x})\ \text{et}\ R^x_{sys}/\mathrm{tm} >= \mathrm{NF} \tag{1}$$

where N represents the number of solutions, R^x_{sys} is the reliability of the solution, NF is the level of reliability required, tm is the duration of an operation.

The LCC of multicomponent industrial systems can be broken down into initial costs of the C_I system and C_{TM} maintenance costs (Hwang, 2005).

$$\mathrm{LCC(t)}_{sys} = \mathrm{C_I} + \mathrm{C_{TM}(t)} \tag{2}$$

3.1.1 Assessment of the initial costs of the system. The initial costs of the system correspond to:

$$\mathrm{C_I} = \sum_{i=1}^{n} \mathrm{C_i} + \mathrm{C_{NI,i}} \tag{3}$$

where n is the number of components in the system, C_i is the cost of component i, and $C_{NI,i}$ represents the cost related to the information available on component i (e.g. cost of a sensor). Indeed, to improve the information on given component i, a more sophisticated monitoring architecture can be proposed. This choice leads, for example, to add sensors to access its operating state or if possible to its level of degradation. Incremental costs associated with the implementation of enhanced monitoring of certain components will impact the initial costs of the system through the $C_{NI,i}$.

The cost of equipment depends on several parameters, such as the materials selected, the manufacturing processes, the efforts made in the design, the technologies adopted, the repair time. Indeed, in this present research, we have considered that the cost of component i depends on its reliability R_i and $\mathrm{MTTR_i}$ replacement time. (Kumar *et al.*, 2012) have proposed a relationship between the reliability R_i(MTBF) of a component and its manufacturing cost; this mathematical formula can be given by:

$$C_i = \alpha_i R_i^{\beta_i} + \delta_i \tag{4}$$

where α_i, β_i, and δ_i are constants, representing the physical property of component i. The relationship is graphically illustrated in Figure 2 (a).

Furthermore, we suggest a linear relationship between the MTTR of a component and its manufacturing cost, as proposed by (Kumar *et al.*, 2012) and which can be given by:

$$C_i = a_i - b_i \cdot MTTR_i \tag{5}$$

where a_i and b_i are constants. The relationship is graphically illustrated in Figure 2 (b).

The cost of each component i can be given mathematically by:

$$C_i = (\alpha_i R_i^{\beta_i} + \delta_i + a_i - b_i \cdot MTTR_i) \tag{6}$$

The evaluation of $C_{TM}(t)$ maintenance costs requires simulating the behavior of the operating system in order to model its most appropriate maintenance policy. The following section details the maintenance policy introduced as well as the maintenance cost assessment model.

3.2 Maintenance modeling

The modeling proposed here is based on the concept of the maintenance-free operation period (MFOP), developed by Hockley in 1998. Hockley defines the MFOP as a period of operation while the equipment must be able to carry out the assigned missions without maintenance action and without restricting the operator in any way due to the system failures or limitations (Hockley, 1998). Each MFOP (or MFOP cycle) is usually followed by a maintenance recovery period (MRP). MRP is defined as the period while the appropriate maintenance is performed on the system to enable it to successfully complete the next MFOP (Brown and Hockly, 2001; Dinesh Kumar *et al.*, 1999). The duration of the shutdown will depend on the extent of maintenance work to be performed (Al Shaalane and Vlok, 2013).

The benefits of using the MFOP concept are:

(1) Allow clear specification of the client needs (Mitchell, 2000).

(2) Allow autonomy of the systems over given periods of operations.

(3) Limit the corrective maintenance to the planned maintenance.

(4) Maximize the operational availability of the systems.

(5) Allow for reduced system repair costs (Hockley, 1998).

(6) Facilitate the management of the spare parts.

(7) Allow integrating and updating at a time t the components status information.

3.2.1 Dynamic maintenance plan. A dynamic maintenance plan integrates the information available online to adjust the decisions in terms of maintenance operations. For this purpose, (Lesobre *et al.*, 2014b) propose a decision-making process that is useful for our approach.

The first step of the decision process is to define at the time t the need for a maintenance intervention of the multicomponent system. Note that the time t represents the end of an MFOP or the system failure. To make this decision, we seek to assess the conditional

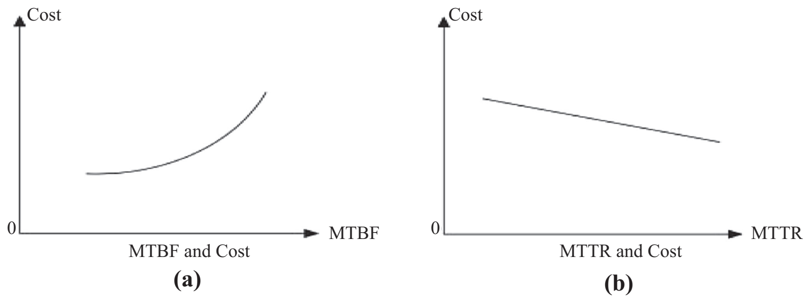

Figure 2.
Relationship between (a) R (MTBF) and component cost, (b) MTTR and component cost (Kumar *et al.*, 2012)

probability of the system operation until the end of the next MFOP, taking into account the information available at t. This conditional probability called maintenance-free operating period survivability (MFOPS) is given by:

$$\mathrm{MFOPS}(t) = R_{sys}\left(t + \frac{t_{MFOP}}{H_{i,t_{(i=1\ à\ n)}}}\right) \Big/ R_{sys}\left(\frac{t}{H_{i,t_{(i=1\ à\ n)}}}\right) \tag{7}$$

where $R(t)_{sys}$ is the reliability of the multicomponent system at time t. This reliability $R(t)_{sys}$ at time t depends on its structure (series, parallel, parallel–series, etc.), the reliability of these components, and the monitoring information available online $H_{i,t}$.

The second step of the decision process is to compare the system's $MFOPS(t)$ with a specified reliability level NF:

(1) If the $MFOPS(t) > NF$, the decision process considers that the maintenance intervention is not necessary. The multicomponent system can be then deployed on the next MFOP without going through the workshop.

(2) In the opposite case, if $MFOPS(t) < NF$, the maintenance intervention is considered essential.

When a maintenance intervention is required, a decision criterion makes it possible to select the actions to be performed on this occasion. In this paper, we introduce a maintenance decision rule based on maximizing the reliability/replacement cost ratio over the MFOP period. Mathematically, the problem can be formulated as follows:

$$\underset{\{X\}}{MAX} \sum_{i=1}^{n} X_i \frac{\Delta R_i}{(C_i + MTTR_i * \tau_{MO})}$$

$$\mathrm{S.t}\quad \mathrm{MFOPS}(X,\ t) > \mathrm{NF}\ \ \mathrm{et}\ \ \mathrm{MRP}(X,\ t) = \sum_{i=1}^{n} MTTR_i\, X_{ij} < \mathrm{MRP}_{max} \tag{8}$$

where n represents the number of components in the system, ΔR_i is the evolution of the MFOPS before and after the replacement of the component i, C_i the cost of component i, $MTTR_i$ the replacement time of component i, τ_{MO} the hourly rate of the labor, X_i is a binary variable that takes the value of 1 if the maintenance operation on component i is well performed, 0 otherwise, MRP_{max} the maximum maintenance time allowed to perform {X} operations, and NF is the level specified reliability.

3.2.2 Assessment of the total maintenance cost. According to (Roda and Garetti, 2014), the maintenance costs are neither static nor easily quantifiable (unlike the acquisition or the installation costs), but rather dynamic and dependent on the levels of solicitations and failures encountered. In this context, we will use the Monte Carlo model for an accurate estimation. This model is recommended for predicting the maintenance cost in given circumstances (Thiede *et al.*, 2012).

The total maintenance cost $C_{TM}(t_m)$ is given by:

$$C_{TM}(t_m) = C_{prv}(t_m) + C_{cor}(t_m) + C_{scor}(t_m) \tag{9}$$

where $C_{prv}(t_m)$ represents the cost of preventive replacement of the system components on [0, tm], $C_{cor}(t_m)$ the replacement cost of the components that failed on [0,t_m], $C_{scor}(t_m)$ the additional cost related to the production loss when the system is in the corrective maintenance.

Let us now detail the expression of each of these costs.

The cost of preventive maintenance $C_{prv}(t_m)$ corresponds to:

$$C_{prv}(t_m) = \sum_{i=1}^{n}(C_i + MTTR_i * \tau_{MO}) * N_{i,prv} + C_{log,prv} * AM_{prv} \quad (10)$$

where $N_{i,prv}$ is the number of preventive replacements of component i on $[0,tm]$, $C_{log,prv}$ is the logistics cost related to the preventive maintenance stops, and AM_{prv} is the number of preventive maintenance stops of the system on $[0,tm]$.

The corrective maintenance cost $C_{cor}(t_m)$ is given by:

$$C_{cor}(t_m) = \sum_{i=1}^{n}(C_i + MTTR_i * \tau_0) * N_{i,cor} + (C_{log,cor} + C_{udig} * NSIS) * AM_{cor} \quad (11)$$

where $N_{i,cor}$ represents the number of the corrective replacement of the component i on $[0,tm]$, $C_{log,cor}$ the logistics cost related to the corrective maintenance stop on $[0, tm]$, C_{udig} unit cost of a component diagnosis, NSIS the number of components in the system for which monitoring information is not available, and AM_{cor} the number of the system corrective maintenance downtime on $[0, tm]$.

When a replacement occurs on the system in operation, additional costs related to the immobilization of the system will be added to the replacement cost. These are taken into account via cost $C_{cor}(t_m)$, which given by:

$$C_{scor}(t_m) = \sum_{i=1}^{n} MTTR_i * N_{i,cor} * \tau_{immob} + (D_{log,cor} + D_{udig} * NSIS) * AM_{cor} * \tau_{immob} \quad (12)$$

where τ_{immob} represents the cost of the operating loss per system downtime, $D_{log,cor}$ is the logistic duration related to the corrective maintenance downtime, and D_{udig} the unit diagnostic duration for a component.

3.3 Simultaneous modeling of design and maintenance

In general, design and maintenance decisions are made sequentially. Often, manufacturers face significant maintenance costs due to the design choices and relatively low-reliability levels of certain components. As mentioned before, we propose an approach that considers design and maintenance simultaneously. In concrete terms, the goal is to enable designers to visualize the consequences of their design choices in terms of LCCs. Thus, depending on the business model of the company, designers can prioritize low-cost design and low maintenance cost design. For example, if the designed product is for rental then, designers may favor a low LCC design to maximize the margin in the operating phase. However, if the product is designed for sale, designers should focus on low-cost design to maximize the margin for sale.

3.3.1 Simultaneous design and maintenance problem. The problem of simultaneous design and maintenance decisions discussed earlier can be formulated as follows:

Objective:

$$\text{Minimise LCC} = \text{MIN}(C_I + C_{TM}(t)) \quad (13)$$

Constraint:

$$\text{System reliability level } NF\text{: MFOPS} > NF \quad (14)$$

$$\text{Cost } C_i \text{ of component i}: \; C_{mini} \leq C_i \leq C_{maxi} \quad (15)$$

$$\text{Maintenance Time MRP}: \; MRP < MRP_{max} \quad (16)$$

3.3.2 Assumption. The optimization problem dealt with here also requires some reasonable assumptions:

(1) The list of usable components is previously known

(2) The characteristics of the components (cost, failure rate) are known.

(3) Only the failure of known components is considered.

(4) The cost of the system, which is the sum of the costs of its components, is known.

(5) The state of each component is independent of other components.

4. Global resolution method (developed algorithm)

In the present research, we have chosen the GA as a method of resolution, which is able to solve optimization problems having several objectives and/or constraints and to effectively handle different variables (Deb and Jain, 2003).

We propose a hybrid optimization design and maintenance model based on GAs (MHAGs) (Figure 3). This model combines two dependent algorithms, the main algorithm and a secondary one. The main algorithm ensures the optimization of the design in terms of reliability (*Ri*), redundancy (*Pi*), monitoring architecture (*Si*), and finally accessibility characterized by the MTTRi (resolution of the problem described by the expression 1). The secondary algorithm focuses on the determination of a dynamic maintenance plan based on the MFOP (resolution of the problem described by expression 9). This second algorithm makes it possible to have a minimum C_{TM} maintenance cost under a reliability constraint.

The MHAGs process has been implemented as follows. In the beginning, the main algorithm starts, by generating all the possible design solutions ($Sl_1, \ldots, Sl_N$) by the adjustment of the parameters R_i, P_i, $MTTR_i$, and S_i of each component i (section 3.1), as well

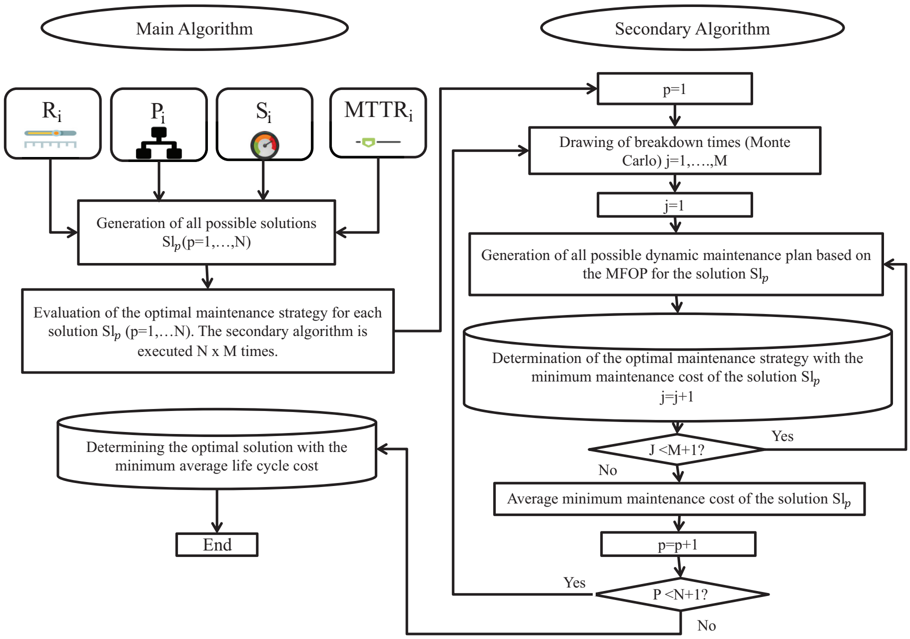

Figure 3.
The hybrid optimization process based on GAs

as evaluating their initial costs. Then, for each possible solution (Slp), the second algorithm is executed to obtain a dynamic maintenance plan while minimizing maintenance costs (section 3.2). In the end, the main algorithm classifies the different solutions according to their LCCs, in order to select the one that minimizes the LCC.

5. Numerical example

In order to demonstrate the relevance of the proposed model (MHAGs), we chose to apply the algorithm to an existing example from the literature (heavy vehicle industry). Using the same input data, we obtain consistent and very satisfactory results.

As shown in Figure 4, the multicomponent reference system consists of four (04) serial components, the data of which are a combination of those applied in (Lesobre *et al.*, 2014a, b; 2013). We choose here to take a series system with four components in order to easily illustrate and justify the results obtained by the proposed model (algorithm).

We also introduce assumptions about the reference system to define the parameters needed for the simulation:

(1) The implementation and the adjustment of the four parameters $(R_i, P_i, MTTR_i, S_i)$ are possible for each component i.

(2) The parameters R_i and $MTTR_i$ are real and continuous with max and min values varying between − 50 percent and + 50 percent of the reference system values.

(3) Parameters P_i and S_i are discrete integer parameters that can only take the value of 0 or 1.

(4) The installation of a sensor on a component Ai will add a cost *CNI*,i corresponding to 10 percent of the cost of component Ai.

(5) The cost of each component Ai must be between 100 and 1,000 euros.

Table I summarizes the design parameters $(R_i, P_i, MTTR_i, S_i)$ of each component of the reference system considered in this example, as well as their type, their maximum and minimum values.

Now, having a look at the different properties of this reference system (Lesobre *et al.*, 2014a,b; 2013), with five years' operating time, the MFOP is six (06) months, the MRP is 3h, and the NF is 0.8 (80 percent). It is also assumed that the maintenance operations are

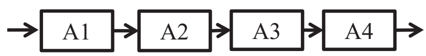

Figure 4.
Structure of the multicomponent reference system

Table I.
Simulation data (W = Weibull's Law) (Lesobre *et al.*, 2014a,b; 2013)

	A1	*A2*	*A3*	*A4*	Type	Min	Max
Reliability model R_i	*W*(3.5e5,2.0)	*W*(3.5e5,7.0)	*W*(4e5,3.0)	*W*(4.5e5,7.0)	Continuous	− 50% (MTBF)	+50% (MTBF)
$MTTR_i(h)$	1	1	1	1	Continuous	− 50%	+50%
Sensor	0	0	0	0	Discrete	0	1
Redundancy P_i	0	0	0	0	Discrete	0	1
$\mathbf{C}_i$(en €)	311	458	407	500	Continuous	100	1000

independent of each other. Thus, the hourly rate of labor is fixed at $\tau_{MO} = 90€$ and the cost of the exploitation loss per hour of immobilization stays for $\tau_{immob} = 100€$. The logistics cost associated with the preventive and corrective maintenance shutdown is respectively $C_{log,prv} = 100€$ and $C_{log,cor} = 200€$ for a duration set at $D_{log,cor} = 1h$. Finally, the cost and the unit duration of diagnosis are respectively $C_{udig} = 20€$ and $D_{udig} = 5$ min.

6. Results and discussion

To solve the simultaneous design and maintenance optimization problem, we have programmed the algorithms proposed in MATLAB programming language. In both algorithms (main and secondary), the crossover rate and the mutation rate are respectively 0.5 and 0.2. Moreover, population size and maximum generation are 200 and 600, respectively. Thus, the number of Monte Carlo history is fixed at $M = 1,000$.

Figure 5 illustrates the structure of the new solution obtained by the proposed model (MHAGs). The design parameters (R_i, P_i, $MTTR_i$, S_i) of each component of this new solution are presented in Table II. Figure 6 presents the estimation of the average overall cost of the

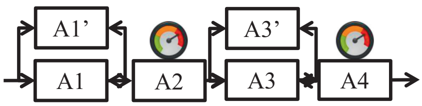

Figure 5.
The new configuration obtained by the proposed model

	*A*1 et *A*1'	*A*2	*A*3 et *A*3'	*A*4
R_i	*W*(3.4e5, 2.8)	*W*(3.6e5, 8,4)	*W*(3.6e5, 3.4)	*W*(4.0e5, 8.1)
$MTTR_i(h)$	0,71	1.14	0,98	0,51
S_i	0	1	0	1
P_i	1	0	1	0

Table II.
Properties of the components of the new solution

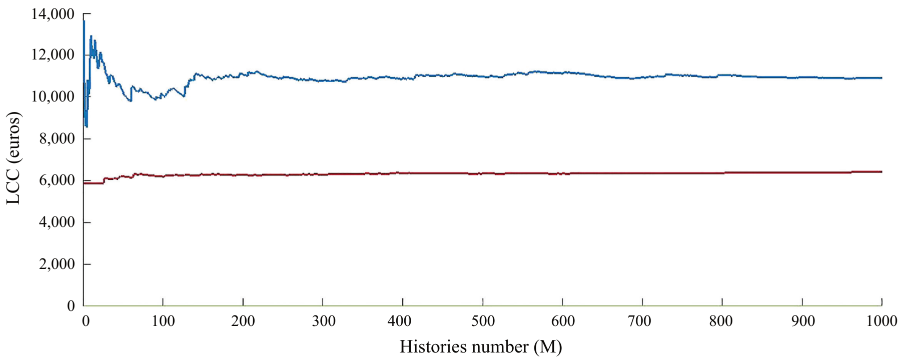

Figure 6.
The LCC of the reference system and the new solution according to the number of M histories

In euros	Initial costs C_I	Total maintenance cost C_{TM}	LCC
Reference system	1.703 e3	8.607 e3	10.310 e3
New solution	3.369 e3	3.848 e3	7.217 e3

Table III.
Overall costs of the new solution and the reference system

reference system (blue mark, LCC = 10.3104 e3) and of this new solution (red mark, LCC = 7.2173 e3). Note that, the new solution allows a decrease of 30 percent in the LCC compared to the reference system. However, the maintenance plan and the maintenance cost of the reference system are optimized, that is, the second algorithm is applied to the reference system.

Table III shows that the initial costs of the new solution are larger than the reference system, but there is a significant reduction in maintenance costs over the entire operating period. However, if we look at the costs of the entire life cycle, we note a drop of 30 percent in the reference system.

This is explained by the good choice of the design parameters that helps to reduce maintenance efforts and maintain the system as long as possible in good operating conditions. This shows the end of having a fun tool that provides a LCC projection in the design phase according to different configurations.

7. Conclusion and perspective

We have proposed and experimented a new algorithmic model of the simultaneous optimization for the design and maintenance of the large-scale multicomponent industrial systems.

Concerning the design, four decision variables are proposed for each component (its reliability, maintainability, redundancy, and monitoring information level). Regarding the maintenance, we proposed three decision variables (the NF, the MRP, and the reliability/replacement cost ratio) for each maintenance intervention (in case of failure or if MFOPS is estimated to be below the required level of reliability).

The proposed model is based on a two-level hybrid algorithm for simultaneous optimization (design and maintenance), using GAs. The first is to determine the optimal design for a given system based on the LCC. The second level aims to optimize the cost of the maintenance policy according to the level of reliability required. The proposed maintenance policy is dynamic and integrates different solutions offered by new connected and intelligent technologies.

The algorithm was confronted with an example from the literature consisting of four components in the series. The use of the proposed algorithm has resulted in a new (serial–parallel) configuration consisting of six new components and two sensors. This new solution has reduced the LCC about 30 percent compared to the reference system, under the same constraints imposed on the reference system.

This research has two major interests. The first is to find the optimal design under stress to minimize the LCC. The second interest is to allow designers to experiment with several possible architectures by adjusting design variables, objectives, and maintenance constraints.

In order to generalize and optimize the proposed model, several lines of research can be undertaken, in particular, to test the robustness of this model on new examples.

References

Al Shaalane, A. and Vlok, P.J. (2013), “Application of the aviation derived maintenance free operating period concept in the South African mining industry”, *South African Journal of Industrial Engineering*, Vol. 24, pp. 150-165.

Amari, S.V. and Pham, H. (2007), “A novel approach for optimal cost-effective design of complex repairable systems”, *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, Vol. 37, pp. 406-415, doi: 10.1109/TSMCA.2007.893454.

Beaurepaire, P., Valdebenito, M.A., Schuëller, G.I. and Jensen, H.A. (2012), “Reliability-based optimization of maintenance scheduling of mechanical components under fatigue”, *Computer*

Methods in Applied Mechanics and Engineering, Vols 221-222, pp. 24-40, doi: 10.1016/j.cma.2012.01.015.

Brown, M.A. and Hockly, C.J. (2001), "Cost of specifying maintenance/failure free operating periods for Royal Air Force aircraft", *Annual Reliability and Maintainability Symposium. 2001 Proceedings. International Symposium on Product Quality and Integrity (Cat. No.01CH37179). Presented at the Annual Reliability and Maintainability Symposium. 2001 Proceedings. International Symposium on Product Quality and Integrity (Cat. No.01CH37179)*, pp. 425-432, doi: 10.1109/RAMS.2001.902503.

Certa, A., Galante, G., Lupo, T. and Passannanti, G. (2011), "Determination of Pareto frontier in multi-objective maintenance optimization", *Reliability Engineering & System Safety*, Vol. 96, pp. 861-867, doi: 10.1016/j.ress.2010.12.019.

Chen, L. and Cai, J. (2003), "Using Vector Projection Method to evaluate maintainability of mechanical system in design review", *Reliability Engineering & System Safety*, Vol. 81, 147-154, doi: 10.1016/S0951-8320(03)00075-9.

de Almeida, A.T., Ferreira, R.J.P. and Cavalcante, C.A.V. (2015), "A review of the use of multicriteria and multi-objective models in maintenance and reliability", *IMA Journal of Management Mathematics*, Vol. 26, pp. 249-271, doi: 10.1093/imaman/dpv010.

Deb, K. and Jain, S. (2003), "Multi-speed gearbox design using multi-objective evolutionary algorithms", *Journal of Mechanical Design*, Vol. 125, P. 609, doi: 10.1115/1.1596242.

Dhillon, B.S. (2010), *Life Cycle Costing for Engineers*, Taylor & Francis, Boca Raton, FL.

Dhillon, B.S. (2006), *Maintainability, Maintenance, and Reliability for Engineers*, CRC Press, USA, doi: 10.1201/9781420006780.

Dinesh Kumar, U., Knezevic, J. and Crocker, J. (1999), "Maintenance free operating period – an alternative measure to MTBF and failure rate for specifying reliability?", *Reliability Engineering & System Safety*, Vol. 64, pp. 127-131, doi: 10.1016/S0951-8320(98)00048-9.

Ebrahimipour, V. and Sheikhalishahi, M. (2011), "Application of multi-objective particle swarm optimization to solve a fuzzy multi-objective reliability redundancy allocation problem", *2011 IEEE International Systems Conference. Presented at the 2011 IEEE International Systems Conference*, pp. 326-333, doi: 10.1109/SYSCON.2011.5929085.

Goel, H.D., Grievink, J. and Weijnen, M.P.C. (2003), "Integrated optimal reliable design, production, and maintenance planning for multipurpose process plants", *Computers & Chemical Engineering*, Vol. 27, pp. 1543-1555, doi: 10.1016/S0098-1354(03)00090-5.

Hockley, C.J. (1998), "Design for success", *Proceedings - Institution of Mechanical Engineers Part G Journal of Aerospace Engineering*, Vol. 212, pp. 371-378, doi: 10.1243/0954410981532342.

Hwang, H.-S. (2005), "Costing RAM design and test analysis model for production facility", *International Journal of Production Economics*, Production Research: Facing the Challenges in the New Millennium, Vol. 98, pp. 143-149, doi: 10.1016/j.ijpe.2004.05.022.

Karre, H., Hammer, M., Kleindienst, M. and Ramsauer, C. (2017), "Transition towards an industry 4.0 state of the LeanLab at graz university of technology", *Procedia Manuf., 7th Conference on Learning Factories, CLF 2017*, Vol. 9, pp. 206-213, doi: 10.1016/j.promfg.2017.04.006.

Kumar, N., Borm, J.-H. and Kumar, A. (2012), "Reliability analysis of waste clean-up manipulator using genetic algorithms and fuzzy methodology", *Computers & Operations Research*, Vol. 39, pp. 310-319, doi: 10.1016/j.cor.2011.04.005.

Kusiak, A. and Li, W. (2011), "The prediction and diagnosis of wind turbine faults", *Renewable Energy*, Vol. 36, pp. 16-23, doi: 10.1016/j.renene.2010.05.014.

Lesobre, R. (2015), "Modélisation et optimisation de la maintenance et de la surveillance des systèmes multi-composants - applications à la maintenance et à la conception de véhicules industriels", (phdthesis), Université Grenoble Alpes, France.

Lesobre, R., Bouvard, K., Bérenguer, C., Barros, A. and Cocquempot, V. (2014a), "Evaluation of decision criteria to optimize a dynamic maintenance policy based on Maintenance Free

Operating Period concept", *8th IMA International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR), Proceedings for 8th IMA International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR)*, IMA - Institute of Mathematics and its Applications, Oxford, UK, pp. 173-178.

Lesobre, R., Bouvard, K., Bérenguer, C., Barros, A. and Cocquempot, V. (2014b), *A Usage-Informed Preventive Maintenance Policy to Optimize the Maintenance Free Operating Period for Multi-Component Systems 12*.

Lesobre, R., Bouvard, K., Berenguer, C., Barros, A. and Cocquempot, V. (2013), "A maintenance free operating period policy for a multi-component system with different information levels on the components state", *Chemical Engineering Transactions*, Vol. 33, pp. 1051-1056, doi: 10.3303/CET1333176.

Long, J., Shenoi, R.A. and Jiang, W. (2009), "A reliability-centred maintenance strategy based on maintenance-free operating period philosophy and total lifetime operating cost analysis", *Proceedings - Institution of Mechanical Engineers Part G Journal of Aerospace Engineering*, Vol. 223, pp. 711-719, doi: 10.1243/09544100JAERO488.

Markeset, T. and Kumar, U. (2003), "Design and development of product support and maintenance concepts for industrial systems", *Journal of Quality in Maintenance Engineering*, Vol. 9, pp. 376-392, doi: 10.1108/13552510310503231.

Markeset, T. and Kumar, U. (2001), "R&M and risk-analysis tools in product design, to reduce life-cycle cost and improve attractiveness", *Annual Reliability and Maintainability Symposium. 2001 Proceedings. International Symposium on Product Quality and Integrity (Cat. No.01CH37179). Presented at the Annual Reliability and Maintainability Symposium*, IEEE, Philadelphia, PA, USA, pp. 116-122, doi: 10.1109/RAMS.2001.902452.

Mitchell, P. (2000), *What the Customer Wants. Maintenance-free and Failure-free Operating Periods to Improve Overall System Availability and Reliability*, Royal air force, Brampton Huntingdon.

Moghaddam, K.S. and Usher, J.S. (2011), "A new multi-objective optimization model for preventive maintenance and replacement scheduling of multi-component systems", *Engineering Optimization*, Vol. 43, pp. 701-719, doi: 10.1080/0305215X.2010.512084.

Mulder, W., Basten, R.J.I., Becker, J.M.J. and Van Dongen, L.A.M. (2013), "Work in progress: developing tools that support the design of easily maintainable rolling stock", *Procedia CIRP, 2nd International Through-life Engineering Services Conference*, Vol. 11, pp. 204-206, doi: 10.1016/j.procir.2013.07.034.

Nishijima, K., Maes, M.A., Goyet, J. and Faber, M.H. (2009), "Constrained optimization of component reliabilities in complex systems", *Structural Safety, Risk Acceptance and Risk Communication*, Vol. 31, pp. 168-178, doi: 10.1016/j.strusafe.2008.06.016.

Nourelfath, M. and Ait-Kadi, D. (2007), "Optimization of series–parallel multi-state systems under maintenance policies", *Reliability Engineering & System Safety*, Special Issue on ESREL 2005, Vol. 92, pp. 1620-1626, doi: 10.1016/j.ress.2006.09.016.

Okasha, N.M. and Frangopol, D.M. (2009), "Lifetime-oriented multi-objective optimization of structural maintenance considering system reliability, redundancy and life-cycle cost using GA", *Structural Safety*, Vol. 31, pp. 460-474, doi: 10.1016/j.strusafe.2009.06.005.

Olde Keizer, M.C.A., Teunter, R.H. and Veldman, J. (2016), "Clustering condition-based maintenance for systems with redundancy and economic dependencies", *European Journal of Operational Research*, Vol. 251, pp. 531-540, doi: 10.1016/j.ejor.2015.11.008.

Rawat, M. and Lad, B.K. (2016), "Simultaneous selection of reliability design and level of repair for fleet systems", *International Journal of System Assurance Engineering and Management*, Vol. 7, pp. 138-155, doi: 10.1007/s13198-016-0429-z.

Relf, M.N. (1999), "Maintenance-free operating periods—the designer's challenge", *Quality and Reliability Engineering International*, Vol. 15, pp. 111-116, doi: 10.1002/(SICI)1099-1638(199903/04)15:2<111::AID-QRE237>3.0.CO;2-2.

Roda, I. and Garetti, M. (2014), "The link between costs and performances for total cost of ownership evaluation of physical asset: state of the art review", *2014 International Conference on Engineering, Technology and Innovation (ICE). Presented at the 2014 International Conference on Engineering, Technology and Innovation (ICE)*, pp. 1-8, doi: 10.1109/ICE.2014.6871544.

Suman, B. (2003), "Simulated annealing-based multiobjective algorithms and their application for system reliability", *Engineering Optimization*, Vol. 35, pp. 391-416, doi: 10.1080/03052150310001597765.

Thiede, S., Spiering, T., Kohlitz, S., Herrmann, C. and Kara, S. (2012), "Dynamic total cost of ownership (TCO) calculation of injection moulding machines", in Dornfeld, D.A. and Linke, B.S. (Eds.), *Leveraging Technology for a Sustainable World*, Springer Berlin Heidelberg, Germany, pp. 275-280.

Tian, Z., Jin, T., Wu, B. and Ding, F. (2011), "Condition based maintenance optimization for wind power generation systems under continuous monitoring", *Renewable Energy*, Vol. 36, pp. 1502-1509, doi: 10.1016/j.renene.2010.10.028.

Torres-Echeverría, A.C., Martorell, S. and Thompson, H.A. (2012), "Multi-objective optimization of design and testing of safety instrumented systems with MooN voting architectures using a genetic algorithm", *Reliability Engineering & System Safety*, Vol. 106, pp. 45-60, doi: 10.1016/j.ress.2012.03.010.

Wang, Z., Chen, T., Tang, K. and Yao, X. (2009), "A multi-objective approach to Redundancy Allocation Problem in parallel-series systems", *2009 IEEE Congress on Evolutionary Computation. Presented at the 2009 IEEE Congress on Evolutionary Computation*, pp. 582-589, doi: 10.1109/CEC.2009.4982998.

Wani, M.F. and Gandhi, O.P. (1999), "Development of maintainability index for mechanical systems", *Reliability Engineering & System Safety*, Vol. 65, pp. 259-270, doi: 10.1016/S0951-8320(99)00004-6.

Zhang, Y.L., Yam, R.C.M. and Zuo, M.J. (2002), "Optimal replacement policy for a multistate repairable system", *Journal of the Operational Research Society*, Vol. 53, pp. 336-341, doi: 10.1057/palgrave.jors.2601277.

Zhao, X. and Nakagawa, T. (2012), "Optimization problems of replacement first or last in reliability theory", *European Journal of Operational Research*, Vol. 223, pp. 141-149, doi: 10.1016/j.ejor.2012.05.035.

Zoulfaghari, H., Zeinal Hamadani, A. and Abouei Ardakan, M. (2014), "Bi-objective redundancy allocation problem for a system with mixed repairable and non-repairable components", *ISA Transactions*, Vol. 53, pp. 17-24, doi: 10.1016/j.isatra.2013.08.002.

Corresponding author
Khaled Benfriha can be contacted at: khaled.benfriha@ensam.eu